SYSTEMIQ

ADVANCING SUSTAINABLE BATTERY RECYCLING: TOWARDS A CIRCULAR BATTERY SYSTEM

ABOUT THIS REPORT

This is the first comprehensive synthesis of the fragmented knowledge on sustainability in electric vehicle lithium-ion battery (LIB) recycling. The report aims to build a foundation for effective measures and supportive environments to optimise the sustainability impact of the battery recycling process and facilitate better partnerships between industry, the public sector and civil society. It examines sustainable battery recycling operations, evaluating their technical processes and sustainability performance, and emphasising the need for a careful balance of conflicting sustainability trade-offs. It investigates policy and industry levers for scaling and implementing sustainable battery recycling, and analyses broader circular economy practices that support a sustainable and circular battery system. Finally, the report proposes actionable principles for decision makers in the private and public sectors to optimise the sustainability impact of battery recycling. The study team would welcome questions, challenges, relevant data points and information about published or ongoing studies that are not referenced in this paper.

For more information or feedback, contact us at communications@systemiq.earth.

ABOUT SYSTEMIQ

Systemiq was founded in 2016 to drive the achievement of the Paris Agreement and the UN Sustainable Development Goals by transforming markets and business models in five key systems: nature and food, materials and circularity, energy, urban areas and sustainable finance. A certified B Corp, Systemiq works to unlock economic opportunities that benefit business, society and the environment; it does so by partnering with industry, financial and government institutions, and civil society. Learn more at systemiq.earth.

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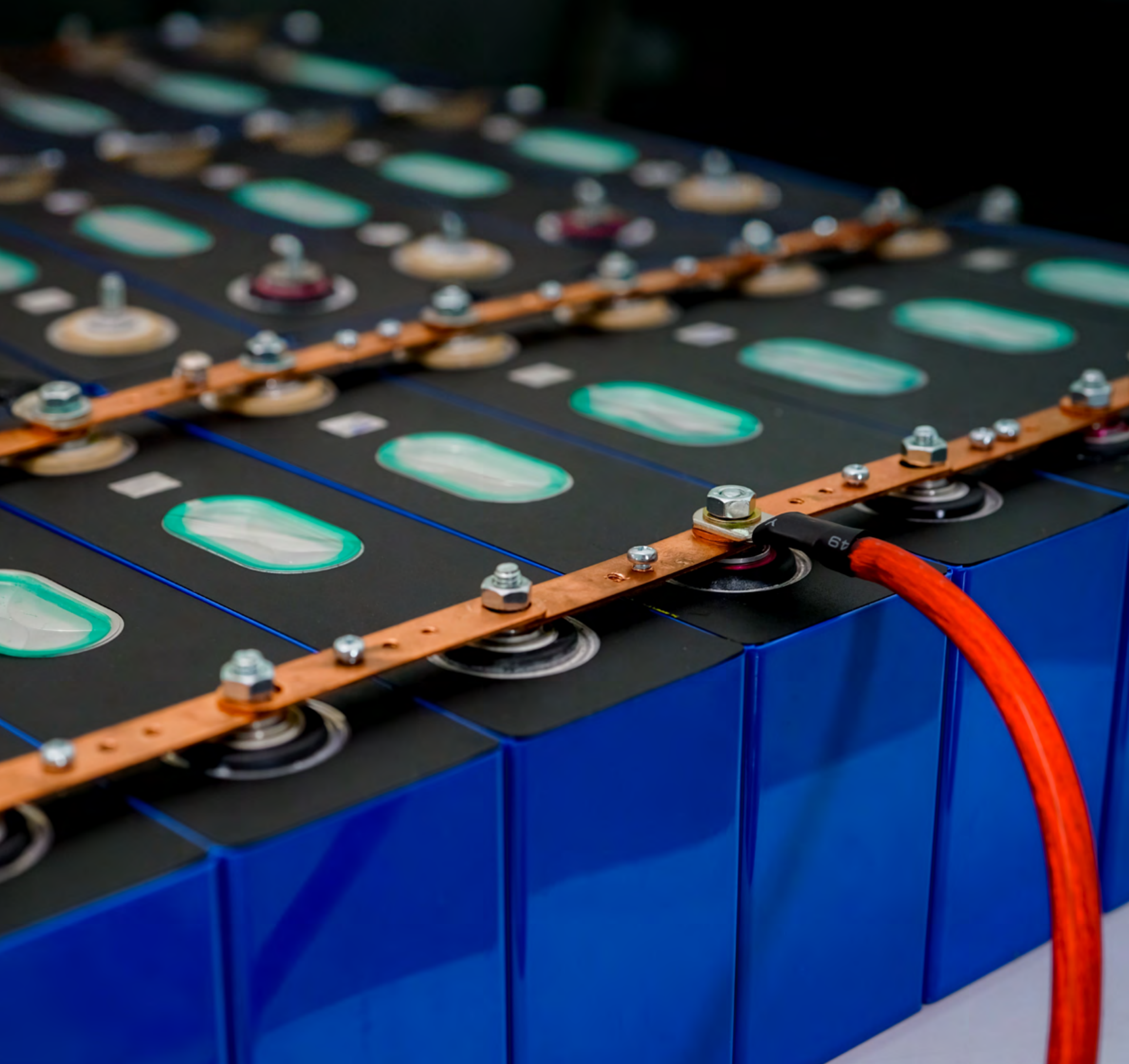

EXECUTIVE SUMMARY

Advancements in battery chemistry and recycling technologies are expected to have a dramatic impact on the sustainability and feasibility of battery recycling. This synthesis report assesses the most widely used current recycling processes and provides recommendations to ensure battery recycling meets sustainability standards, laying the foundation for ongoing monitoring and further evaluation of this rapidly evolving field. The report highlights seven key insights, as follows.

1. Battery use in electric vehicles is rapidly increasing and battery recycling is also scaling up fast

Global battery demand is anticipated to reach over 5.5 terawatt-hours by 2030, driven overwhelmingly (90%) by the mobility sector. Passenger electric vehicles (EVs) are close to a tipping point as they are expected to reach the cost parity required for exponential growth by 2025-2026; as a result, the global EV fleet could total 380 million by 2030.

If these forecasts are realised, carbon dioxide (CO_2) emissions from cars would be on a path in line with the International Energy Agency's (IEA) Net Zero Emissions by 2050 Scenario. This would translate to a net greenhouse gas (GHG) emissions reduction of 405.9 million tonnes of CO_2 equivalent by 2030 on a well-to-wheel basis compared to the equivalent use of internal combustion engine vehicles in the IEA's Sustainable Development Scenario.

The electrification of transport could also trigger a cascade of tipping points, with cheaper batteries facilitating the scale-up of solar and wind power through energy storage solutions. Global lithium-ion battery (LIB) recovery capacity has doubled in the last three years and is predicted to increase to more than 2.5 million tonnes per year by 2030 (46% China, 19% North America, 21% Europe).

Battery recycling presents a crucial opportunity to recover high-grade metals and other materials from spent batteries (particularly copper, nickel, cobalt and lithium). The growth of the battery recycling industry can help to reduce demand for mined metals and other primary materials (and their associated climate, nature and social impacts), boost supplies of critical raw materials and reduce dependence on global supply chains.

2. Battery recycling has a critical role to play in improving the overall sustainability performance of electrified mobility systems. However, design and operation of battery recycling systems should still be informed by a holistic sustainability mindset to mitigate potential negative effects

Optimising for economic performance or single sustainability parameters such as climate impact or maximum material recovery will not be enough; social dimensions and broader environmental factors – including water use, water discharge and emissions to air – should also be examined.

This report seeks to evaluate the sustainability of battery recycling operations from a holistic standpoint, qualitatively reviewing impact dimensions beyond the environmental key performance indicators that are ordinarily employed when conducting lifecycle analysis (LCA). A comprehensive list of key sustainability indicators, encompassing multiple impact dimensions, has been employed, and the most commonly cited risks and benefits have been synthesised.

Decisions on trade-offs should be data-driven: LCAs and other appropriate analysis should be conducted to avoid unintended consequences. Selected quantitative data from academic LCAs and techno-economic assessments (TEAs) has been referenced in this report to support the analysis.

3. LIB recycling is technically complex, demanding a multi-step approach. Process design varies between recyclers and significantly affects performance across different sustainability indicators

Diverse battery recycling technologies and routes are being adopted by recyclers worldwide. This gives rise to distinct sustainability considerations:

- There is no consensus on the 'best' technology or process due to variations in input materials, local conditions and market demand and prices for secondary materials.
- This picture is complicated further by evolving cathode chemistries, with different approaches suited to discrete battery recycling technologies and routes.
- Specific technologies and routes can vary considerably in terms of their environmental footprint and social, health and safety risks. The diverse impacts and risk dimensions are synthesised in this report.
- Battery recyclers thus have design choices with sustainability implications to make both at each step of the recycling process and when sequencing those steps within an end-to-end battery recycling route.

4. Despite the variation in recycling operations, universal sustainability principles can be applied across the whole battery recycling industry

These principles are identified in this report and apply to:

- Ensuring sustainable recycling operations
- Collaborate with responsible suppliers
- Engage the broader value chain

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5. Urgent action from both industry and government is needed to ensure that the burgeoning battery recycling industry is set up for sustainability

Sustainability should be an explicit criterion in private and public decision making, without slowing down the approval and permitting processes for new recycling operations. The report assesses a range of policy and market initiatives to integrate sustainable practices into these decision-making processes.

Traceable battery information across the value chain is crucial to ensure safe and efficient recycling, prevent greenwashing and mislabelling, and promote the efficient use of recovered materials.

A global standard on sustainable recycling, and consistent GHG footprint calculation and reporting rules, can prevent the externalisation of environmental costs in the battery trade and benefit responsible recyclers.

6. Sustainable battery recycling operations are a crucial step, but they are only one of the elements required to improve the overall sustainability performance of mobility systems

Recycling is just one component of the broader battery ecosystem, and decisions made beyond the control of battery recyclers will have significant implications both for them and for the overall sustainability impact of batteries and e-mobility:

- Wider mobility system trends (eg, increases in public transport or car sharing and the size and weight of cars) will have a significant impact on battery demand and the overall environmental impact of the system.
- The extension of battery life through second-life energy storage applications (once battery performance is no longer suitable for EV use) has the potential to reduce the overall environmental impact of the battery system and can contribute low-cost energy storage options to enable the wider decarbonisation of energy systems.
- The sustainability of a battery starts with its initial design. Design for durability and repair allows for a longer battery lifetime and helps to reduce overall battery use. Standardised and more straightforward designs (ie, easier to disassemble) could promote reusability and recyclability (increased material recovery; reduced energy and resource use in recycling processes).
- Ensuring safe, sustainable and efficient battery collection and transportation to recycling facilities is also essential to achieve high material recovery rates and scale sustainable battery recycling. Clear definitions and transport requirements for end-of-life EV batteries, along with improved information sharing, are needed. Supported by extended producer responsibility schemes, international recycling standards and clear instructions and incentives for battery takeback, these can help to prevent batteries from escaping the recycling system or being recycled irresponsibly.

7. Industry alignment is needed on certain topics of debate in relation to sustainable battery recycling

The report concludes by exploring key open questions relating to sustainable battery recycling and summarising existing viewpoints. The need to resolve ongoing debates through clear standards, regulations and guidelines is highlighted.

Ongoing innovation in battery cathode chemistries and recycling technologies is influencing both the economic and technical feasibility and the sustainability impact of recycling processes, and should be continuously monitored.

Pre-competitive collaboration between battery recyclers, alongside wider multi-stakeholder engagement, would be an ideal way to address these questions.

INDUSTRY PRINCIPLES FOR SUSTAINABLE BATTERY RECYCLING

The 10 principles outlined below provide practical recommendations for the recycling industry, in order of value chain steps. Industry participants should actively encourage their partners to adhere to these principles to ensure sustainable battery recycling across their value chain.

RECYCLING OPERATIONS

1

Safe operations: Prioritise stringent health and safety standards in recycling operations

Commit to the highest health and safety standards, ensuring that workers are appropriately trained and provided with high-quality protective equipment. For example, adhere to ISO 45001 – an international standard for health and safety at work – or relevant ILO standards and guidance on occupational health and safety in industrial operations. Ensure fair working conditions through regulated and licensed economic activity along the entire recycling value chain to rule out exploitative practices. This should take priority above all.

2

Technology selection and process design: Incorporate sustainability impact assessments into the selection of battery recycling technologies and processes

Recycling processes differ according to local situations, inputs and desired outputs; and no one process has a clear sustainability advantage in all dimensions. To make informed decisions, conduct in-depth data driven analyses of recycling routes, considering the advantages, disadvantages and trade-offs of the recycling flowsheet from a cradle-to-gate perspective and considering all inputs.

3

High-ambition recycling: Maximise material recovery and carbon efficiency, and prioritise recycling to high-grade materials

Optimise recycling operations for maximum recovery of key materials and minimum carbon footprint. This includes recovering energy during discharge and reclaiming non-active materials during disassembly and mechanical processing. Aim for high-purity secondary materials which allow for repeated reuse and recycling. Recovery of active and critical materials should take precedence. However, each material has its own optimal recovery rate, considering overall material yields and energy consumption. To determine the optimal material recovery rates, comprehensive evaluations comparing recycled and newly mined materials across various sustainability aspects are needed. To facilitate high-purity recycling, optimise disassembly and pre-processing steps and explore innovative recycling technologies.

4

Water management: Adopt best practices for water reduction and wastewater management

Aim to implement a closed water loop within recycling facilities – that is, a system that consumes no more water than is lost through evaporation or oxidation, and that recycles and purifies water processes. If this is not feasible, establish treatment systems to ensure that the quality of water entering the facility matches that of the water leaving it and minimise overall water consumption.

5

Minimal waste: Design and operate recycling processes to minimise waste streams and ensure that all waste is treated and disposed of in accordance with international standards

Minimise solid waste generation by exploring reuse options wherever possible – for example, repurposing hydrometallurgy sulphate by-products for the detergent industry or using slag produced in pyrometallurgy for road construction. Where this is not feasible, ensure that responsible disposal practices are in place, adhering to the highest environmental and safety standards – for example, ISO 14001 on environmental management systems, including waste management procedures; and ISO 24161 on waste collection and transportation management.

6

Energy usage and GHG emissions: Decarbonise recycling operations

Reduce the overall energy intensity of operations to the minimum. Ensure that the electricity used is sourced from renewable sources. Consider investing in renewable energy generation infrastructure such as photovoltaic systems or wind turbines. If complete electrification is not feasible for certain operations, transition to low-carbon fuel alternatives. For any unavoidable air emissions, employ reduction and control measures that align with the strictest carbon, environmental and health standards. Where feasible, minimise the direct release of GHGs – for example, by implementing effective capture methods.

RECYCLING VALUE CHAIN

7

Auxiliary materials: Minimise consumption and GHG emissions of used chemicals, gases and other input materials

Reduce the auxiliary materials consumption of recycling processes. If possible, recycle or regenerate the inputs – for example, recover used acids via regenerative chemistry or scrub and reuse inert gas used in shredding. Procure auxiliary materials such as chemicals with low environmental footprints – including considerations such as climate (eg, carbon footprint), freshwater and land impacts – in alignment with the planetary boundaries.

8

Supplier engagement: Apply sustainability assessment criteria and robust controls to ensure that suppliers of auxiliary materials adhere to internationally accepted environmental, social and labour standards

When procuring end-of-life batteries, black mass or auxiliary materials, conduct rigorous due diligence on suppliers to ensure that their materials have not caused adverse social and environmental impacts. Adhere to established international safety and environmental standards, follow due diligence regulations and refer to guidance such as the OECD's Due Diligence Guidance for Responsible Business Conduct. Verify supplier provenance to prevent materials from uncertified or problematic sources – ideally through established certification schemes.

BROADER VALUE CHAIN

9

Transport: Optimise transport routes and electrify modes of transportation

Prioritise the decarbonisation of all transportation relating to recycling operations, extending this effort beyond primary suppliers whenever feasible. Optimise transport routes to minimise distances and enhance the efficiency and scalability of dismantling and recycling networks. Invest in comprehensive training and equip personnel to uphold strict transport protocols, ensuring safety and environmental responsibility. When outsourcing transportation services, hold partners to these same high standards, including by requesting relevant certifications.

10

Data availability: Implement digital tools and enhanced traceability in line with the digital ecosystem along the value chain

Deploy digital tools such as battery passports, battery analytics and intelligence software to access information about battery history and composition. This will also enhance the recovery rates of valuable materials and facilitate sustainable recycling processes.

CHAPTER 1

CONTEXT: ENSURING SAFE AND SUSTAINABLE RECYCLING OF EV BATTERIES

1. CONTEXT: ENSURING SAFE AND SUSTAINABLE RECYCLING OF EV BATTERIES

CHAPTER 1 KEY TAKEAWAYS

Increasing demand for batteries

- Battery demand is expected to increase exponentially to over 5.5 terawatt-hours (TWh) by 2030 and 6.5 TWh by 2040.
- The mobility sector is driving 90% of this demand, as passenger electric vehicles (EVs) are close to a tipping point and are expected to reach the cost parity required for exponential growth by 2025-2026.
- Demand is highest in China, followed by Europe and the US.

Evolving cathode chemistries

- While nickel-rich chemistries such as nickel manganese cobalt (NMC) currently predominate, nickel-free lithium iron phosphate (LFP) batteries are expected to significantly increase their market share, driven by demand in China.
- The materials used in the cathode determine the economic attractiveness of recycling. As LFP batteries contain neither cobalt nor nickel, sourcing costs are low, thus challenging the economic attractiveness of recycling efforts.
- As battery chemistries evolve, the recovery rates for reclaiming essential materials through recycling will vary. As recycling may not always be profitable for certain chemistry types, there is a risk of irresponsible disposal of lower-value cell chemistries.

Recycling to build supply chain resilience

- Battery recycling is critical to reduce long-term dependence on primary mining.
- Battery recycling can build resilience against supply chain disruptions caused by geopolitical tensions.

Global expansion of recycling capacity

- China has the greatest recycling capacity today, accounting for two-thirds of current global capacity (1.5 million tonnes). Total global lithium-ion battery (LIB) material recovery capacity will reach over 2.6 million tonnes by 2030.

Increased regulatory focus on recycling

- The new EU Battery Regulation sets strict recovery and recycling targets.
- The upcoming EU battery pass will enhance transparency and traceability across the entire lifecycle from 2027.
- China is also working on a digital battery passport to facilitate international trade, having first set up a tracing system for end-of-life (EoL) batteries and recycling in 2018.
- The US is seeking to regionalise the battery recycling industry through the Inflation Reduction Act (IRA).

1.1 EXPONENTIAL GROWTH IN BATTERY DEMAND

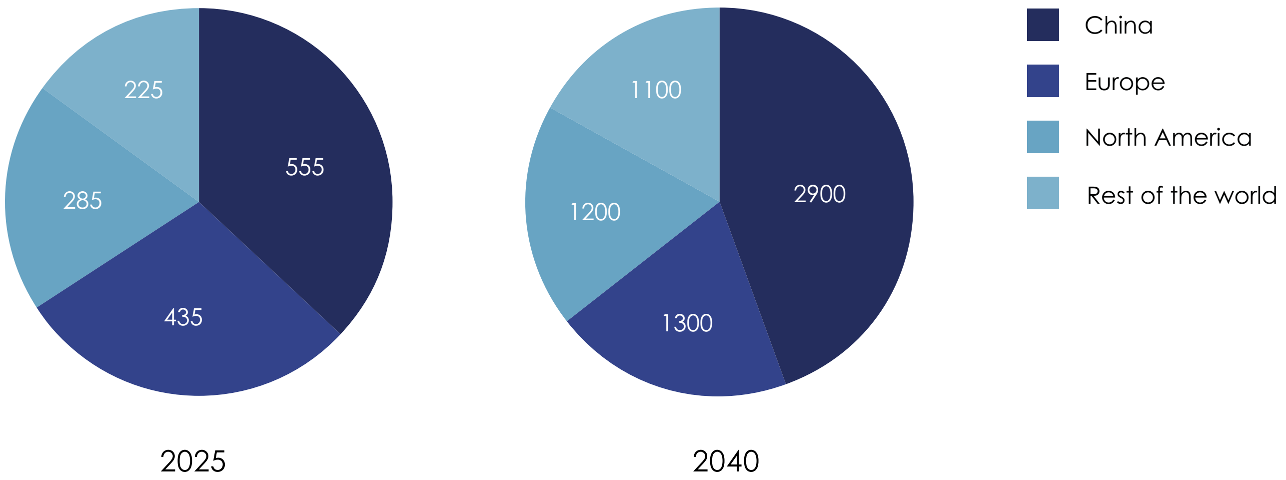
Global battery demand is anticipated to reach over 5.5 TWh in 2030. The mobility sector is driving 90% of this demand – passenger EVs are close to a tipping point and are expected to reach the cost parity required for exponential growth by 2025-2026.

Batteries have a key role to play in decarbonisation and in achieving the Paris Agreement targets. They will help to accelerate the green transition, especially in the mobility and energy sectors. The International Energy Agency (IEA) forecasts that global battery demand will reach 5.5 TWh in 2030 according to its Net Zero Emissions by 2050 Scenario.[1] The mobility sector will drive most of this demand – particularly for LIBs, which are expected to account for more than 90% of total demand by 2030.[2] In 2022, demand for EV batteries totalled 550 gigawatt-hours (GWh) – a 65% increase on the previous year;[1] while the global EV fleet stood at 30 million – a figure which is estimated to reach 240 million by 2030 under the IEA's Stated Policies Scenario.[1] In the IEA's ambitious Net Zero Emissions by 2050 Scenario, this number would increase almost 1.6-fold to 380 million. [1] This anticipated surge in demand is primarily due to substantial investments by innovators and incumbents alike, as well as economies of scale and favourable regulatory measures.[2]–[4] Particularly in China, the world's largest car market, there is a growing consumer preference for EVs. EVs are also predicted to reach cost parity with internal combustion engine (ICE) vehicles in 2025-2026. As more EVs are sold, this cost-parity tipping point will lead to further economies of scale in battery production, which in turn will enhance their cost advantage.[4]

Demand for EV batteries is highest in China, followed by Europe and the US.

China is currently the world's largest EV market and domestic demand is expected to increase fivefold by 2040.[5] The share of EVs manufactured in China and traded to Europe grew to 16% in 2022[1] Although Europe's demand for EV batteries is forecast to soar from 435 GWh in 2025 to 1,300 GWh in 2040, its overall share of demand will decrease from one-third to one-fifth during that same period. North America's share of overall demand should stay consistent even as demand increases to 1,100 GWh.

Figure 1: Global EV demand forecast by region[5]



INFORMATION BOX 1: LIB CHEMISTRIES

Batteries are differentiated by their cathode chemistries, which influence their performance.

LIBs are comprised of cells, modules and packs. The smallest unit – the battery cell – serves as an individual electricity-generating entity and consists of a cathode, an anode, a separator and an electrolyte solution, encased in a sturdy housing.[8] Depending on the cathode chemistry, characteristics such as capacity, energy density, power density, lifecycle, charging time, self-discharge rate and efficiency vary.[8] The optimal chemistry type is determined by trade-offs between these characteristics. LIBs are typically classified based on the composition of their cathodes. A general distinction is made between nickel-rich chemistries (eg, NMC 622, NMC 811, NCA, NCMA) and low-nickel chemistries (NMC532 and NMC 111).[9] The number in the chemistry abbreviation stands for the ratio of materials used – for example, NMC 811 contains eight parts nickel, one part manganese and one part cobalt.

Common chemistries include the following:[10],[11]

- Lithium cobalt oxide (LCO) has the advantage of high specific energy. The primary drawbacks of LCO batteries are the costs, the relatively short lifecycle and safety concerns.
- Lithium manganese oxide (LMO) batteries have high specific power, a longer lifecycle and significantly improved thermal stability compared to LCO batteries. The absence of cobalt is another notable advantage. However, this is the least common chemistry for EV batteries due to its low energy density and instability.
- The advantages of LFP batteries include thermal stability, low cost, long lifecycle and durability while maintaining performance. Their main drawback is lower specific energy. This notwithstanding, they are the second most common chemistry for EVs. Especially in China, they are popular due to their cost effectiveness and independence from cobalt and nickel.
- Lithium nickel cobalt aluminium oxide (NCA) batteries have the highest specific energy, along with high specific power and a long lifecycle. This technology is favoured by manufacturers such as Tesla and presents significant potential for applications in power systems for backup and load shifting. However, NCA batteries tend to be costlier than other battery chemistries.
- NMC batteries have dominated the EV market since their introduction in the early 2000s – not least thanks to their higher specific energy and long lifecycles.

Other potential battery chemistries such as sodium-ion (Na-ion) could complement LIBs in the future. Na-ion batteries have environmental advantages and are considered safe and cost efficient. Their performance thus far is promising and density and cycle rates are improving. As sodium is vastly more abundant than lithium, extraction and purification costs are significantly lower.[12] However, this could influence the recycling landscape, as materials recovery may not be as economically attractive. The primary challenge lies in scaling up the technology to a level where Na-ion batteries can be used for storage and entry-level EVs.[13] Contemporary Amperex Technology Co., Ltd (CATL) recently announced that its Na-ion batteries will power Chery EV models, although no further information is available on exactly when these EVs will enter the market.[14]

While nickel-rich chemistries currently predominate, nickel-free LFP batteries are expected to significantly increase their market share, driven by Chinese demand.

Today, nickel-rich battery chemistries dominate the market, with a share of 66%, while low-nickel chemistries account for just 4%. NMC is the leading battery chemistry, making up 60% of the market in 2022; while nickel cobalt aluminium oxide (NCA) had a share of around 8%. LFP batteries currently account for 33% of the market,[1] but this figure is projected to rise to 45% by 2030.[6] This will be driven by demand from China, where approximately 95% of LFP batteries are manufactured for light-duty EVs.[1] LFP batteries do not rely on nickel, manganese or cobalt are and are thus a preferred chemistry type, being cheaper to produce.[6],[7]

The chemistry shift has been influenced by performance, as well as the price and accessibility of key raw materials (lithium, nickel and cobalt).

In recent years, price fluctuations and availability of critical minerals have driven changes in battery chemistry. Low-nickel chemistries were popular until 2015, when the rising cost of cobalt and concerns about the social impact of cobalt mining prompted a transition towards lower-cobalt, higher-nickel chemistries. However, in 2022, the price of nickel soared to double the average observed between 2015 and 2020, due to a demand-supply imbalance, leading to a shift towards chemistries with reduced dependence on nickel, such as LFP.[1],[2],[15] Global commodity prices have also risen in recent years due to disruptions caused by COVID-19 and geopolitical events such as Russia's invasion of Ukraine in February 2022, among other factors.[1]

The economic feasibility of recycling is determined by the potential to recover valuable metals, particularly cobalt and nickel.

As battery chemistries evolve, recovery rates from recycling will vary.[6],[16] Recycling might not always be profitable for certain chemistry types, leading to a risk of irresponsible disposal of lower-value chemistries.[6] While lithium has the greatest influence on the price of batteries, it also has the lowest weight. LFP and LMO batteries are currently the least profitable to recycle,[17] as they contain only small amounts of lithium – which is difficult to recover – and no cobalt or nickel. Meanwhile, NCA and NMC batteries are the most economically attractive to recycle, as they contain more cobalt and nickel.[15] Based on market values from May 2023, one tonne of LFP cells was worth $3,170 in material prices, while one tonne of NCM was worth $8,700 and one tonne of LCO was worth $11,130.

Although resource demand for the energy transition will be significant, it will be 50 times less than that required for the current global fossil fuel-based system.

Despite the substantial resource demand that the burgeoning battery industry will require, this will still be 50 times less than what is needed for the current global fossil fuel-based energy system.[15] This underscores the environmental benefits of transitioning to battery-powered technologies such as EVs. Shifting from the consumption of finite fossil fuels – which require continuous extraction – to long-lasting metals that can be repurposed and recycled paves the way for a significantly more sustainable energy system.[15] This point is further illustrated by a comparison of the amount of raw materials needed to run ICEs and EVs. A study by Transport and Environment revealed that ICE vehicles can burn 17,000 litres of gas or 13,500 litres of diesel throughout their lifetimes; while the volume of raw materials required for the battery of a comparable EV run on green energy is only around 30 kilograms (kg).[18]

1.2 GROWING NEED FOR SAFE AND SUSTAINABLE MANAGEMENT OF SPENT BATTERIES

As an increasing number of batteries reach end of life EoL, safe and sustainable management is urgently needed.

Given the soaring demand for EVs, it is anticipated that over 1.9 million tonnes of LIBs – more than half of them in China – will reach EoL by 2030.[19]. Recycling capacity is urgently needed to ensure safe EoL management and keep valuable materials in the loop.

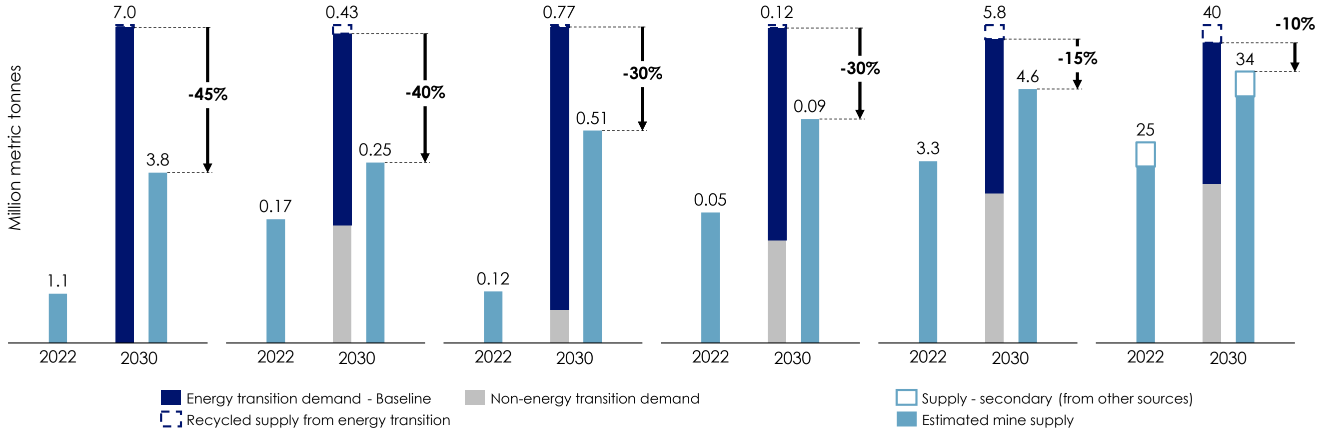
While production scrap currently predominates recycling input, EoL batteries will account for the vast majority of recycling feedstock by 2040.

Currently, recycling facilities predominantly rely on production scrap as their primary input, due to the limited number of EoL EVs on the market. This will change by 2025, when EoL and production scrap will each account for half of the total feedstock. After 2030, EoL materials will exceed production scrap, accounting for 57% of the global recycling volume of 1,850 kilotons (kt). This figure will rapidly increase to 94% of global recycled supply (20,500 kt) by 2040.[20]

The export of EoL EVs is likely to decrease as domestic recycling capacity is built up.

In countries where recycling is not profitable, EoL vehicles are sometimes exported to countries with laxer environmental regimes, making them cheaper to discard.[21],[22] In particular, this has been the case for ICE vehicles: between 2015 and 2018, 14 million used light-duty vehicles were exported worldwide. Eighty per cent of these were exported to low and middle-income countries, with more than half ending up in Africa, according to a United Nations Environmental Programme (UNEP) report.[23] To prevent incorrect disposal and environmental pollution, safe and sustainable management is needed.

Figure 2: Energy Transition Commission's demand/supply estimations for 2023 (nickle, cobalt, lithium)[15]



Note: the ETC's Baseline Decarbonisation scenario assumes the aggressive deployment of clean energy technologies for global decarbonisation by mid-century, but materials intensity and recycling trends follow recent patterns. Supply only shown for natural graphite – it is likely that synthetic graphite could close most of the remaining supply gap.
Source for Energy transition demand: SYSTEMIQ analysis for the ETC.
Source for Non-energy transition demand: Copper – BNEF (2022), *Global copper outlook*; Nickel – BNEF (2023), *Transition metals outlook*; Lithium, cobalt, neodymium – IEA (2021), *The role of critical minerals in clean energy transitions.*
Source for Primary supply: Copper, nickel – BNEF (2023), *Transition metals outlook*, and assuming recycled copper from non-energy transition sources is 10% of primary supply; Graphite Anodes, lithium, cobalt – BNEF (2022), *2H Battery metals outlook*; Neodymium – estimated assuming continued CAGR in rare earth oxide production from 2010-21 to 2030, with neodymium making up 17% of total supply.

[17] As a result of the EV transition and respective regulations, exports of EoL EVs will likely be reduced as domestic recycling capacities are built up. Recycling must be scaled to recover materials from LIBs, thus establishing a sustainable resource supply.[6],[17] This highlights the importance of both closed-loop regional recycling and infrastructure and knowledge transfer to importing countries.[24]

Growth in the recycling market will remain modest in the near to mid-term, supplied mostly by battery manufacturing waste. Global revenues are estimated to reach $40 billion by 2040.

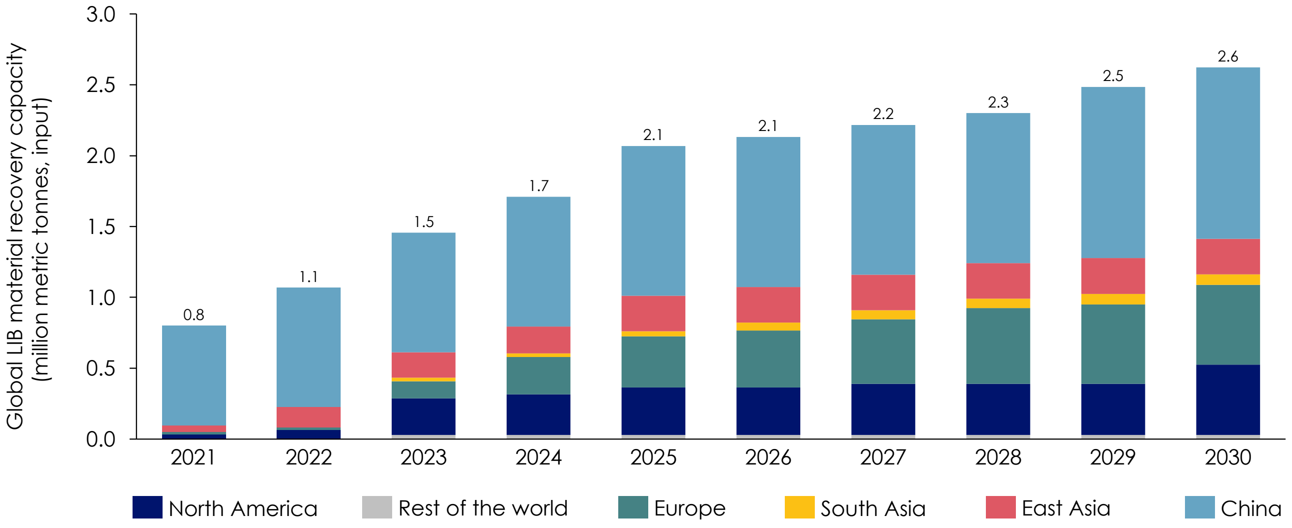
The total market value of the LIB recycling industry in terms of sales revenues was estimated at $6.5 billion in 2022 and is projected to reach $35.1 billion by 2035.[25] A report published by McKinsey and the Global Battery Alliance (GBA) anticipates that that this figure could reach $40 billion by 2040. [2] The greatest revenue opportunities, in terms of both reuse and recycling, are expected in China, where the market is forecast to hit $6 billion by 2030. Medium-term supply constraints associated with cobalt, lithium and nickel could further accelerate the recycling market: as the Energy Transitions Commission (ETC) estimates that 40% of cobalt demand, 30% of lithium demand and 15% of nickel demand will not be covered by primary supply by 2030,[15] scaling up recycling could help to mitigate these shortfalls.

The largest LIB material recovery capacity is and will remain in China, accounting for 33% of global capacity (1.5 million tonnes) by 2023. Total global capacity has nearly doubled in the last three years and will rise to over 2 million tonnes by 2025.

Recycling capacity is expected to almost quadruple globally from 2020 to 2030. China currently predominates, with a market share of almost 90% in 2021; however, this is expected to fall to 46% by 2030 as North America and Europe increase capacity to roughly 20% apiece. North America's capacity will almost double from 250,000 tonnes in 2023 to around 500,000 tonnes by 2030. Europe's capacity will increase fivefold in the same period to reach 561,500 tonnes. It is important to note that these estimations refer to the ability to process input, rather than actual production.[26]

Automotive original equipment manufacturers (OEMs) and cell producers are increasingly entering into partnerships to ensure the stability of their supply chains of local raw materials. Through vertical integration, sufficient volumes of recycled content can be secured. For example, Volkswagen (VW) is collaborating with Redwood Materials in the United States; while General Motors (GM) has entered into partnerships with Li-Cycle and Cirba Solutions.[20] Other partnerships include those between BASF and SVOLT and Mercedes Benz and Brunp.[27],[28]

Figure 3: Global LIB material recovery capacity



INFORMATION BOX 2: BLACK MASS

'Black mass' is a fine powder that contains valuable cathode and anode materials. First, EoL batteries are discharged and dismantled. Once the residual electrolyte has been removed, black mass is produced through a thermomechanical process.[29] This shredded material serves as feedstock for hydrometallurgical or pyrometallurgical processing to recover valuable materials which can subsequently be used for the production of new batteries.[30] Black mass composition can differ significantly between different OEMs depending on the chemistry used in the battery. Black mass is especially valuable for cobalt and nickel-rich chemistries.

Future exports of black mass will be influenced by the classification of the material: depending on whether black mass is classified as a product or as hazardous waste, different border regulations will apply.[31] In **China**, black mass is considered a **toxic substance** and its import was prohibited in the past. However, a new regulation will allow hydrometallurgical recyclers – particularly in Southeast Asia and South Korea – to export their nickel, cobalt and lithium carbonate products to China.[32] In the **EU**, the classification of black mass **lacks consistency**. The European Commission has thus proposed the addition of waste codes for LIBs and black mass to the European List of Waste in 2024. This means that black mass would be defined as hazardous waste, necessitating permits for cross-border transportation.[33]

1.3 REDUCING DEPENDENCE ON PRIMARY MINING

Secondary materials recovered through recycling circumvent many of the sustainability concerns related to the sourcing of primary battery materials.

The dramatic rise in battery demand has driven an increase in critical material extraction, intensifying the negative environmental and social impacts of primary mining.[15] These include impacts on nature and biodiversity; social impacts in resource-rich regions; generation of mining waste; high water usage and risk of water contamination; and GHG emissions during mining operations and mineral/metal processing. Secondary materials from battery recycling can reduce demand for primary metals and reduce the pressure to open new mines. From a climate perspective, a study by McKinsey estimates that the use of recycled raw materials could result in four times less emissions than the use of primary raw materials: while virgin nickel-based batteries were estimated to emit 29 kg of carbon dioxide equivalent ($kgCO_2e$) per kilowatt-hour (KWh), recycled materials emitted only approximately 8 $kgCO_2e$ per KWh. Considering the long lifetime of recycling facilities, sustainability ought to be made a priority from the outset.[20]

Recycling battery materials can reduce dependences on mining and increase resilience against supply chain disruptions.

Diversification of supply through the scale-up of battery recycling would reduce reliance on mining regions from which primary battery materials are sourced. For example, dependence on primary cobalt sourced from the Democratic Republic of Congo can be mitigated by reusing cobalt from recycled batteries.

Recycling alone cannot meet material demand until the battery market slows in the 2050s. Therefore, more sustainable mining management is also crucial.

Until recycled materials can meaningfully cover demand in the long term, mining will have to expand,[15] making it crucial to enforce sustainable mining practices. UNEP has acknowledged the negative impacts associated with mining and has carried out five regional consultations within the context of the UN Environmental Assembly 5/12 Resolution on Environmental Aspects of Minerals and Metals Management, bringing nations together to discuss the negative impacts of mining and take stock of best practices to mitigate them.

1.4 REGULATORY MANDATES DRIVE BATTERY RECYCLING

Regulatory mandates require full collection of vehicle batteries and incentivise improved material recovery.[1]

Across different regions, a growing number of policies aimed at achieving a more sustainable battery value chain are being put in place. For example, the US is seeking to reduce its dependence on imports by regionalising its industry through the IRA and a budget of $3 billion has been allocated to a programme focused on the processing of battery materials. A further $3 billion has also been earmarked to support domestic battery manufacturing and recycling. In Europe, the new EU Battery Regulation was adopted in July 2023, setting strict recycling and recovery targets. Additionally, the mandatory 'battery passport' will enhance traceability and transparency across the entire lifecycle from 2027.[36] China is also working on a digital battery passport to facilitate trade, having first set up a system for the tracing and recycling of batteries in 2018.

The new EU Battery Regulation sets strict recycling and recovery targets for lithium, cobalt and nickel.

Anchored in the EU Green Deal and its Strategic Action Plan for Batteries, the EU Battery Regulation was first proposed in 2020 and entered into force on 17 August 2023, replacing the EU Battery Directive (2006/66/EC).

Three overall objectives have been set: reducing the environmental and social effects across all phases of the battery lifecycle; advancing the concept of a circular economy; and enhancing the operational efficiency of the EU market. The EU Battery Regulation requires due diligence of supply chains across the entire battery lifecycle, accessing social and environmental impacts. It also sets stricter recovery and recycling targets of 50% for lithium and 90% for cobalt and nickel from 2027, which will increase to 80% and 95% respectively in 2031. The Battery Regulation also stipulates that by 2031, at least 6% of all lithium and nickel used and 16% of all cobalt used must be recycled; in 2036, these targets will increase to 12% for lithium, 15% for nickel and 26% for cobalt. Recycling efficiency for LIBs is also targeted to increase from 65% in 2025 to 70% in 2030.[37]

Around 100 distinct metrics relating to the safety, sustainability, performance and circularity of EV batteries will become reportable through a mandatory digital 'battery passport' from 2027.[36] This passport will contain crucial details regarding battery type, chemistry, health status and charge level, thus simplifying disassembly and recycling. This is also in alignment with the EU Taxonomy Regulation, which entered into force in July 2020. The regulation sets out a list of environmentally sustainable economic activities that require increased investment in order for the EU economy to meet its Green Deal objectives. Therefore, to become more attractive investment targets, manufacturers are encouraged to make batteries that can be easily recycled and that incorporate recycled components.[38] The Critical Raw Materials Act was adopted by the European Council in June 2023. It aims to increase and diversify the EU's critical raw materials supply; strengthen circularity, including recycling; and support research and innovation on resource efficiency and the development of substitutes. The Proposal Regulation Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical

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[1] An overview of main regulation mandates can be found in **Annex I** to the report.

Raw Materials further aims to expand EU capacity and strengthen circular supply chains of critical materials.[39] This is also highly relevant to the Net-Zero Industry Act tabled by the EU in March 2023, which proposes that close to 90% of battery demand in the EU be met by EU manufacturers, accounting for at least 550 GWh, by 2030.[40]

1.5 ACCESSIBLE INFORMATION IS NEEDED FOR DECISION MAKERS

Public perceptions of EV battery recycling have shifted significantly in recent years and the topic has evolved from a relatively niche issue to one of growing importance and concern. People are now more cognisant of the fact that while EVs help to reduce GHG emissions, their batteries contain valuable and potentially harmful materials that must be handled responsibly at the end of their lifecycle. This awareness has driven heightened interest in battery recycling technologies and processes. While there are optimistic views on the potential for recycling to minimise resource depletion and reduce waste, there are also questions and scepticism about the efficiency and environmental benefits of recycling methods. This knowledge gap is reflected in the findings of a US study carried out in 2022 which revealed that nearly half of respondents falsely believed that EV batteries cannot be recycled; while over one-third believed that EV batteries cannot be manufactured with recycled minerals and metals.[41] As the EV market continues to expand and technology continues to advance, public perceptions of EV battery recycling will likely be shaped by ongoing developments in recycling infrastructure, regulatory efforts and the transparency of the industry in addressing both environmental and ethical concerns. It is essential to provide sufficient accessible information on the subject to educate the public accordingly.

Industry decision makers and policy makers need more accessible information about recycling trade-offs and ways to develop a better battery system

Battery recycling processes are diverse and continually evolving, and differ between facilities. Given the variety of performance parameters in battery recycling, trade-offs are inevitable, as is discussed in the following chapters. One key challenge is the proprietary information of recycling companies, which limits the availability of reliable and transparent data. The competitive landscape and ongoing advances in recycling technologies add a further layer of complexity for decision makers seeking the optimal approach. Often, the relationship between the battery value chain and battery recycling is not fully taken into account. Consequently, a lack of accessible information may inhibit decision-making on policy, industry strategy and investment direction.

This report seeks to break down the complexity, providing a comprehensive yet accessible overview of the **critical sustainability parameters** involved in battery recycling and **how the main recycling routes perform against them**. It also **recognises the role of the battery system in achieving sustainable battery recycling** and how **policy makers and industry leaders can support this**. By bridging the gap between highly specialised academic studies on battery recycling and the overarching principles, this report seeks to provide foundational and implementable knowledge to policy makers and industry.

CHAPTER 2

SCOPE AND METHODOLOGY

2. SCOPE AND METHODOLOGY

2.1 OBJECTIVES

This report has three main objectives:

1. **Establish a fact base and uncover research gaps** on the sustainability performance of battery recycling operations. A thorough assessment of existing recycling methods and technologies is conducted, examining the associated benefits and risks to highlight the current status of battery recycling. Furthermore, the report identifies gaps in public knowledge and proposes research directions to close these gaps.

2. **Provide recommendations to policy makers and industry leaders** on how best to promote sustainable battery recycling. The report examines key enablers such as investments, policy targets, standards and skills and jobs; and summarises recommended public and private sector actions to unlock these enablers. It also examines the wider battery system within the circular economy framework (eg, battery design and transportation of spent batteries), and explores how sustainable recycling may be scaled.

3. **Outline a set of guiding principles** from which industry stakeholders can develop a unified position on sustainable battery recycling. The analysis identifies where voluntary industry action could optimise the sustainability impact of battery recycling, aligning the sector with broader environmental and social goals.

The target audience for this report has been intentionally defined broadly to ensure that the content and recommendations can be applied by a wide array of stakeholders. The information and recommendations are directed towards policy makers and standards setters, defining their crucial role in regulating and incentivising sustainable battery recycling. The report also addresses industry and academia, providing insights into how they can improve technical processes to minimise environmental consequences, establish a cohesive and efficiently coordinated value chain through cooperation, and address areas that require further research and development (R&D) efforts.

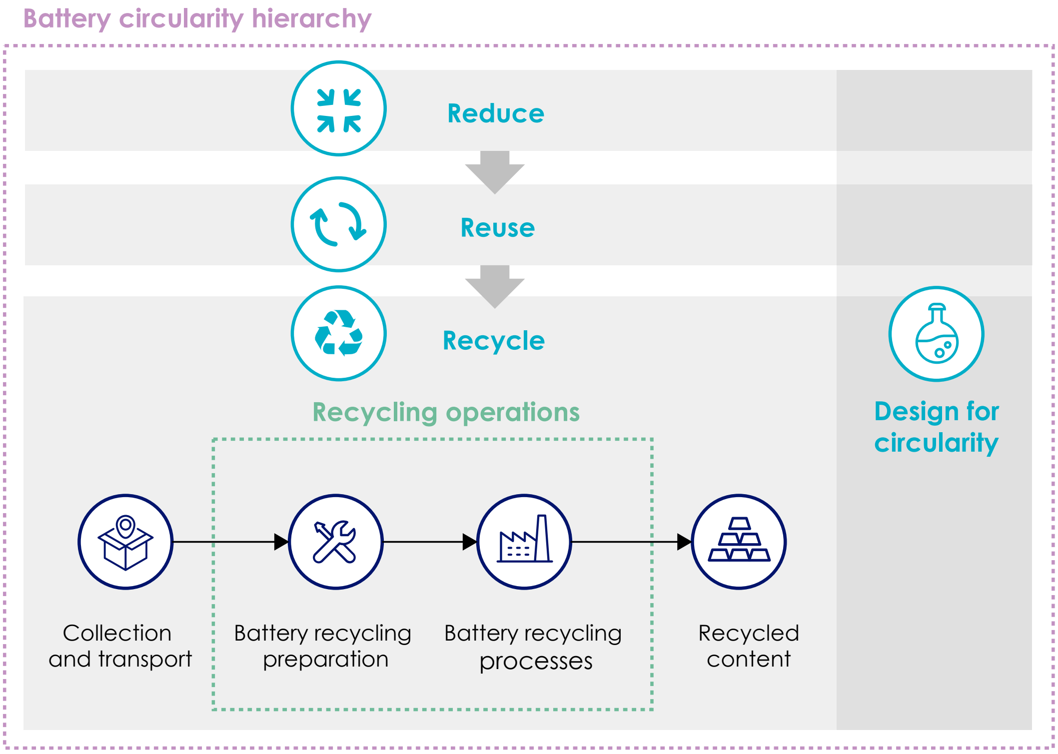
2.2 SCOPE

This report explores three crucial aspects for understanding the current state of sustainable battery recycling, and the obstacles and drivers that are shaping its development. As illustrated in Figure 4, battery recycling is examined within the context of the broader battery value chain.

- **Sustainable battery recycling operations:** To determine how the battery recycling industry can be optimised for sustainability, the diverse technical processes utilised and their potential benefits and drawbacks must be evaluated. Chapter 3 outlines the existing recycling methods, while Chapter 4 examines their sustainability performance. Acknowledging that sustainability aspects may occasionally conflict, recyclers must carefully balance these factors when designing a sustainable recycling process.

- **Enablers to scale and implement sustainable battery recycling:** While the recycling process can be assessed from a technical standpoint, it cannot be viewed in isolation. Chapter 5 explores the critical factors that will enable the establishment and expansion of a sustainable battery recycling system. These include investment and R&D; ambitious recycling targets, standards and certifications; and environmental footprints. Achieving safe and sustainable battery recycling also depends on the availability of comprehensive data and the creation of new skills and job opportunities.

Figure 4: Methodological framework of the study



Chapter 3: Industrial battery recycling operations
Chapter 4: Recycling operations sustainability assessment
Chapter 5: Enablers to scale and implement sustainable battery recycling

Chapter 6: Circular economy practices for a sustainable battery system

- **Circular economy practices for a sustainable battery system:** Chapter 6 outlines the battery circularity hierarchy, including battery demand reduction, lifespan extension via reuse and battery design for circularity. Additionally, it examines the impacts of efficient, safe and sustainable battery collection and transportation and the use of recycled content on the sustainability of the recycling process.

- **Next steps for the recycling industry:** The 10 principles outlined in Chapter 7 provide practical recommendations for the recycling industry. Participants should actively encourage their partners to adhere to these principles to achieve sustainable battery recycling within their value chain. Open and debated topics in sustainable battery recycling on which industry alignment is needed are also summarised in this chapter.

The scope of the various study elements was determined based on their alignment with the report's objectives and their relevance to a broad audience.

In potential future phases of this study, there will be an opportunity to examine specific technical or value chain issues to provide more detailed guidance and offer specific recommendations that could serve as a roadmap for the industry and policy makers.

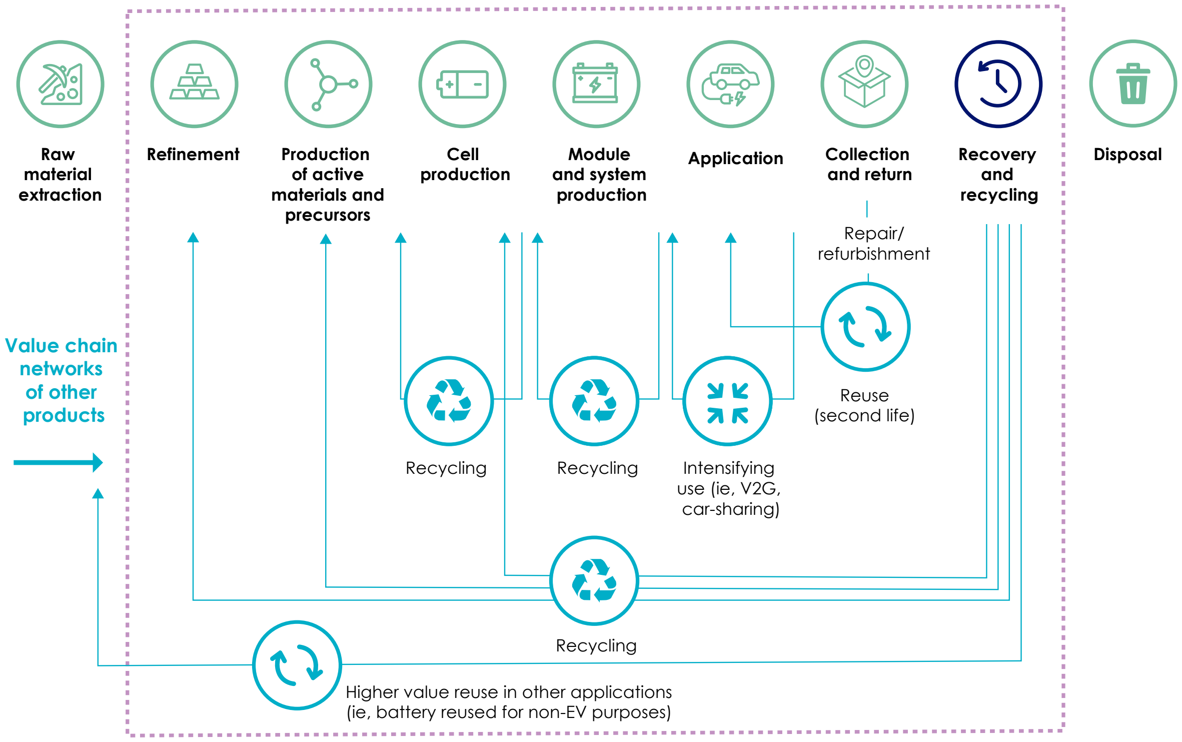
Geographical scope

Globally applicable insights and principles for sustainable battery recycling have been developed to ensure the report's relevance for a broad and diverse stakeholder base. Regional and national distinctions in battery recycling practices and supply chain dynamics have been acknowledged where appropriate.

Battery scope

Applications: EVs were selected for examination in this study as light-duty EVs will account for around 80% of additional global battery capacity over the next two decades.[42]

Figure 5: The circular economy for EV batteries.[43]



Chemistries: The report focuses on LIBs due to their predominant use in EVs and their significant expected contribution to the EoL battery pool in the coming decades. All LIB cathode chemistries are within scope. Select reference to other battery chemistries (eg, Na-ion) is made where appropriate.

Recycling scope

Recycling operation phases: The analysis encompasses the complete battery recycling system after the point of collection, including the preparation, pre-treatment and main treatment phases. For further detail of the system boundaries, see Chapter 3.1.

Technology: The most widely adopted industrial technologies are examined: discharge, dismantling, mechanical processing, thermal pre-treatment, pyrometallurgy and hydrometallurgy. These technologies have been successfully scaled and implemented in the current context. Direct recycling is also briefly touched upon, in light of growing interest in its sustainability potential.

Broader battery system: Beyond recycling operations themselves, the broader battery system is taken into account. This includes both the full recycling system (ie, including the steps before and after the recycling process itself) and other circular economy levers, as outlined in Figure 4.

2.3 METHODOLOGY

Knowledge-gathering approach

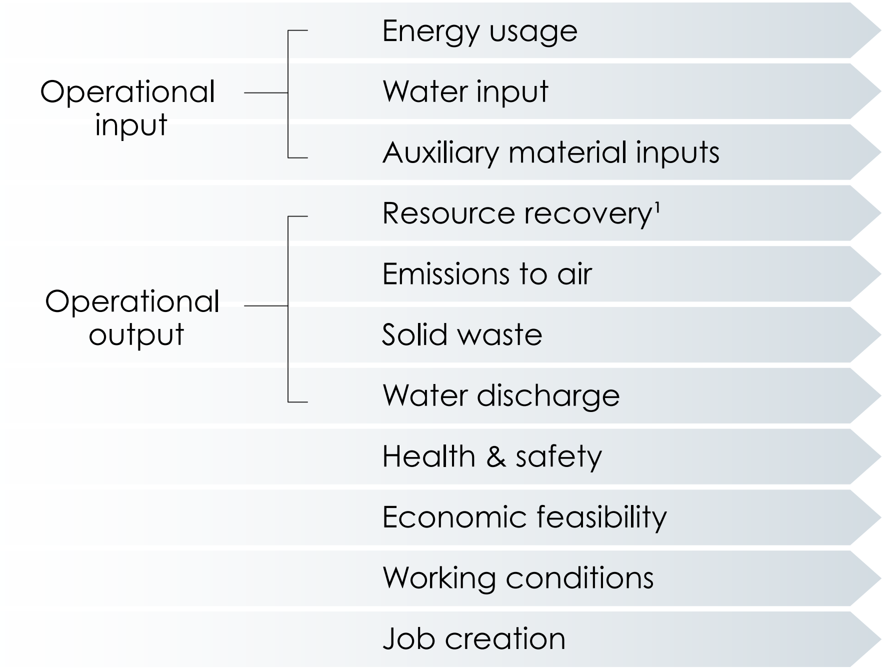
The analysis was conducted following a strict evidence-based approach and encompassed 100-plus reputable studies in peer-reviewed academic journals and publications from government agencies, consultancies, think tanks and civil society organisations. This literature review was complemented and validated by 20-plus interviews with experts in LIB battery recycling and critical metals from diverse geographies as well as a wide range of stakeholders from across the value chain.

Analysis framework

The analysis of technical recycling operations detailed in Chapter 4 employs the sustainability indicators shown in Figure 6. These indicators were used to methodically analyse the commentary provided in literature and interviews. The analysis is primarily qualitative but also incorporates quantitative data from academic lifecycle analyses (LCAs) and techno-economic assessments (TEAs) to support the findings.

LCA data is included where relevant to the context and when useful in supporting qualitative insights. The intention is not to undertake a direct comparison between LCAs or to collate results. This is due to the considerable variability in the analysis approach (eg, choice of scope, methodology, boundaries). This issue of disparities between LCAs is discussed in more detail in Information Box 4 in Chapter 4.

Figure 6: Recycling operations sustainability performance indicators



Notes: (1) In this context, the term 'resource recovery' serves as a comprehensive indicator of the effectiveness of the recycling steps in terms of quantity of resource recovery (eg, mass, volume, percentage of critical material) and quality of resource recovery (eg, purity, impurity conc.).

As the analysis seeks to evaluate the sustainability of battery recycling operations from a holistic standpoint, it was important to review impact dimensions beyond the environmental key performance indicators that are ordinarily employed in LCAs. Therefore, a set of indicators was developed by collating impact categories used in reputable sources such as the EU Battery Regulation and *Measuring Sustainability: A Consistent Metric for Sustainable Batteries,* a report by the German Federal Ministry for Economic Affairs and Climate Action.[44] Indicators often encountered in peer-reviewed papers and LCA reports were also considered and included. The framework was validated and reviewed in interviews with industry experts.

The 11 key sustainability indicators encompass circular economy, environmental, social and economic impact dimensions. They were used to assess sustainability through the following steps:

1. The potential benefits and risks linked to each indicator were identified for each recycling step, establishing a comprehensive fact base of sustainability considerations associated with each discrete recycling step.

2. This information is condensed and synthesised in Chapter 4, focusing on the most commonly referenced risks and benefits for each stage of operations.

3. The process was then repeated for features of recycling routes that lead to distinct additional sustainability considerations (eg, the omission of an optional operational step or the ordering of steps).

Notably, economic impact and job creation indicators are not analysed in detail in the technical operations analysis in Chapter 4. While these factors are crucial for the industry's overall sustainability and have been included for completeness, there is limited academic research available on LIB battery recycling specifically, which would add value to the analysis provided. However, job creation and shifts are detailed in the discussion of industry enablers in Chapter 5.

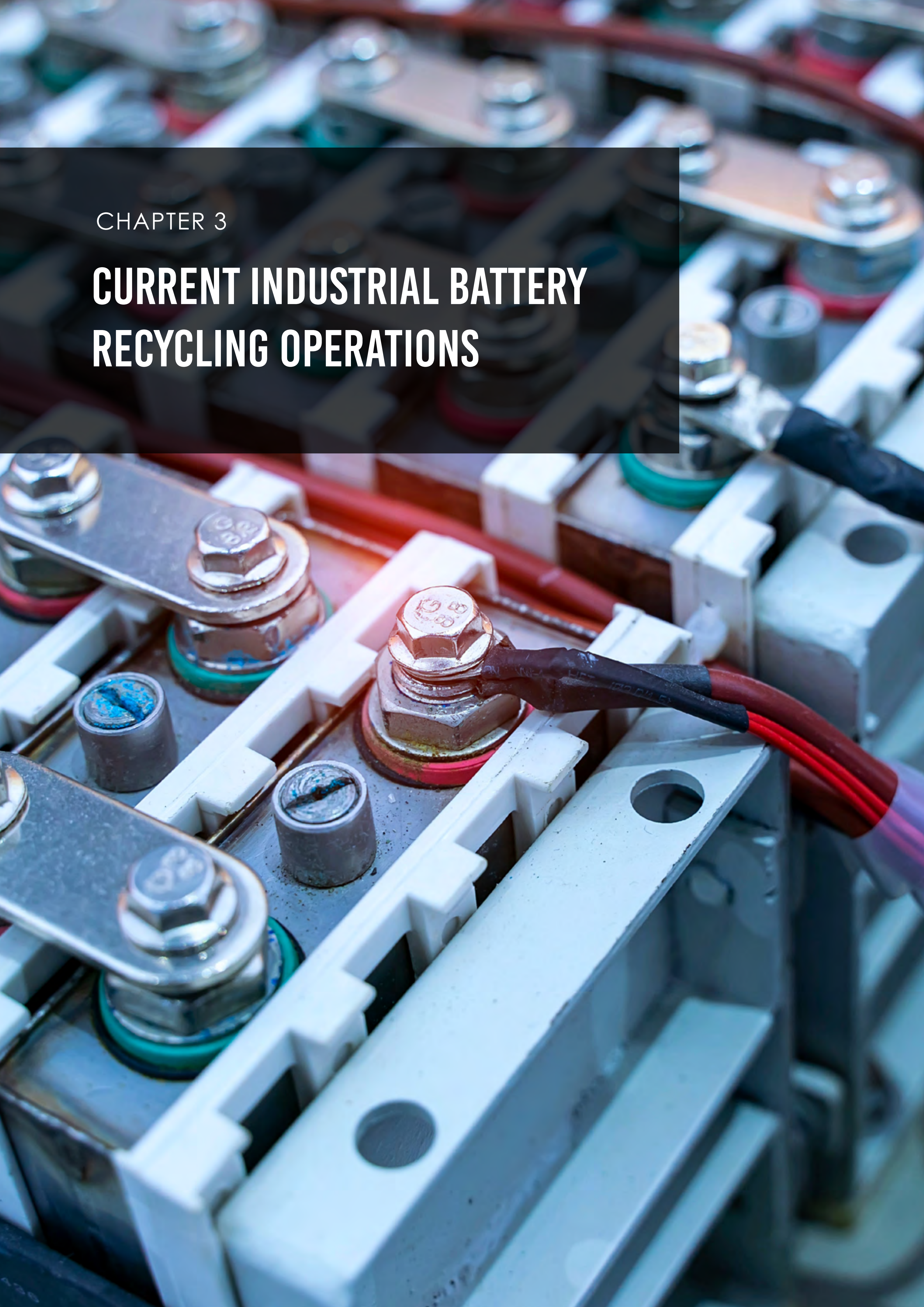
Development of industry principles and the way forward

Based on the findings from the literature review and expert interviews, in-depth analysis of technical recycling operations, their facilitating factors and complementary value chain practices was conducted.

Finally, a set of industry principles was formulated to promote sustainable battery recycling. These principles are intended to serve as a compass for battery recyclers, enabling them to translate the analytical insights into actionable strategies. It is recommended that these principles be further refined and implemented through a multi-stakeholder dialogue, as outlined in Chapter 7. This dialogue should also encompass a comprehensive exploration of unresolved issues and ongoing debates affecting battery recycling, which are further summarised in Chapter 7.

CHAPTER 3

CURRENT INDUSTRIAL BATTERY RECYCLING OPERATIONS



3. CURRENT INDUSTRIAL BATTERY RECYCLING OPERATIONS

The battery recycling industry is continually evolving due to technological advancements, changing stakeholder engagement and shifting market dynamics. Its rapid evolution has resulted in diverse definitions of the battery recycling system in the academic, regulatory and industrial contexts. These definitions often differ in terms of the point at which recycling operations commence in the value chain and which materials enter and exit the system. Therefore, this chapter aims to build a common understanding among audiences, establishing the current state of industrialised and scaled recycling techniques in order to familiarise readers with the concepts discussed in Chapter 4. Additionally, the capacities of global recyclers are mapped to their respective recycling routes to highlight industry trends.

CHAPTER 3 KEY TAKEAWAYS

LIB recycling is technically complex and involves a multi-phase approach:

- Preparation: Steps to ensure safe and efficient further treatment; includes discharge and dismantling.
- Pre-treatment: Steps to optimise feedstock for refinement in the main treatment phase; includes mechanical processing and thermal pre-treatment.
- Main treatment: Steps to refine waste into useable secondary materials; includes pyrometallurgy and hydrometallurgy.

Industrial battery recycling routes can be summarised by five representative routes, categorised primarily by the approach to main treatment – either pyrometallurgy followed by hydrometallurgy or hydrometallurgy only.

Mapping the capacities of recyclers to their associated recycling routes and regions reveals the following:

- Routes using hydrometallurgy only in the main treatment phase have 6.5 times the capacity of those using both pyrometallurgy and hydrometallurgy, globally.
- Asia has twice the overall capacity of the EU and North America combined.
- The EU has almost four times more pre-treatment capacity than main treatment capacity, suggesting black mass produced in the EU must undergo further processing internationally.

3.1 DEFINING THE SYSTEM

Recycling definition

'Recycling' is defined in Article 3 of the EU Waste Directive as 'any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes'.[45] This definition encompasses both closed-loop and open-loop operations. In closed-loop recycling, recyclates are reused in the same application as the input materials (ie, they are used to produce new batteries); whereas in open-loop recycling, recyclates are used in different applications (eg, repurposing nickel from batteries to produce steel alloys).[43] The sustainability of closed-loop operations versus open-loop operations is often debated in the recycling industry, as concerns over downcycling are counterbalanced by the challenges of meeting fluctuating market demand for secondary materials. Points of discussion and unanswered questions such as closed-loop versus open-loop recycling are discussed further in Chapter 7.

In this report, co-production is not considered within the definition of 'recycling'.[2] However, this issue is contentious, as some stakeholders in the battery recycling industry argue that co-production should fall under the umbrella of recycling to expand secondary material processing capacity and improve the economic viability of battery recycling (see Chapter 7 for further details).

System boundaries

The system boundaries of battery recycling are commonly set after the waste batteries have been collected.[43] Hence, the recycling system boundaries encompass all battery treatment phases post-collection,[3] including preparation, pre-treatment and main treatment (illustrated in Figure 7):

- **Preparation:** This ensures that materials can be safely and efficiently processed. The steps involved are discharge and dismantling.[47]
- **Pre-treatment:** Battery materials are physically separated or chemically modified into optimised feedstocks for the main treatment phase. The steps involved are thermal pre-treatment and mechanical treatment.[47]
- **Main treatment:** Materials are separated, converted and refined into recyclates.[48] The main treatments examined are pyrometallurgy and hydrometallurgy.

(Note: Direct recycling is still in the relatively early stages of development and thus is not examined in depth; however, a high-level analysis of direct recycling is presented in Information Box 3).

The preparation phase is distinguished from pre-treatment and main treatment in the EU Battery Regulation, which states: 'the recycling process does not include sorting and/or preparation for

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[2] 'Co-production' refers to the refinement of pre-processed waste materials alongside primary materials. An example of co-production is the processing of black mass together with primary metal ores in a nickel/cobalt refinery process.[46]

[3] Post-collection implies that transport and reverse logistics are not included within the system boundaries.

recycling/disposal.' Nonetheless, the preparation phase has a significant influence on the subsequent recycling processes, making it crucial to include these steps in the technical assessment of overall battery recycling sustainability. Therefore, preparation is included within the analysis of recycling operations but is not considered a 'recycling process', as depicted by the green boundary and yellow shading in Figure 7.

System inputs

Three inputs for the battery recycling system are considered: battery materials, auxiliary materials and energy. 'Battery materials' are defined as the 'mass of collected waste batteries … entering the recycling process',[49] encompassing both pre-consumer and post-consumer materials. Pre-consumer materials include manufacturing scrap generated during the production of cells/modules/packs as a result of process start-up, trimmings and off-spec components. Post-consumer materials are LIBs which have been removed from the host product, potentially after multiple reuse lives and ideally having reached the end of their serviceable lifespan (see Chapter 5 for further details on the hierarchy of EoL destinations).[50] 'Auxiliary materials' are additional material resources required for battery recycling treatments, such as acids and reducing agents. 'Energy' is the input needed to power machinery in the recycling facilities.

System outputs

The outputs of the battery recycling system are categorised as either products, by-products or waste. 'Products' are the outputs 'that the process is operated for and optimised to produce'.[46] As the definition of 'recycling' used in this report includes both open-loop and closed-loop operations, this term can include both battery-grade materials ready for use in the manufacture of new batteries and technical-grade materials that may be used in other industries. 'By-products' are defined as outputs 'with an economic value above zero, for which demand at the specific production site is available, and evidence can be given that the byproduct is used as intended. This term is used to distinguish from waste'. Finally, an output is considered waste if zero or negative economic value can be proven and disposal is thus required.[46]

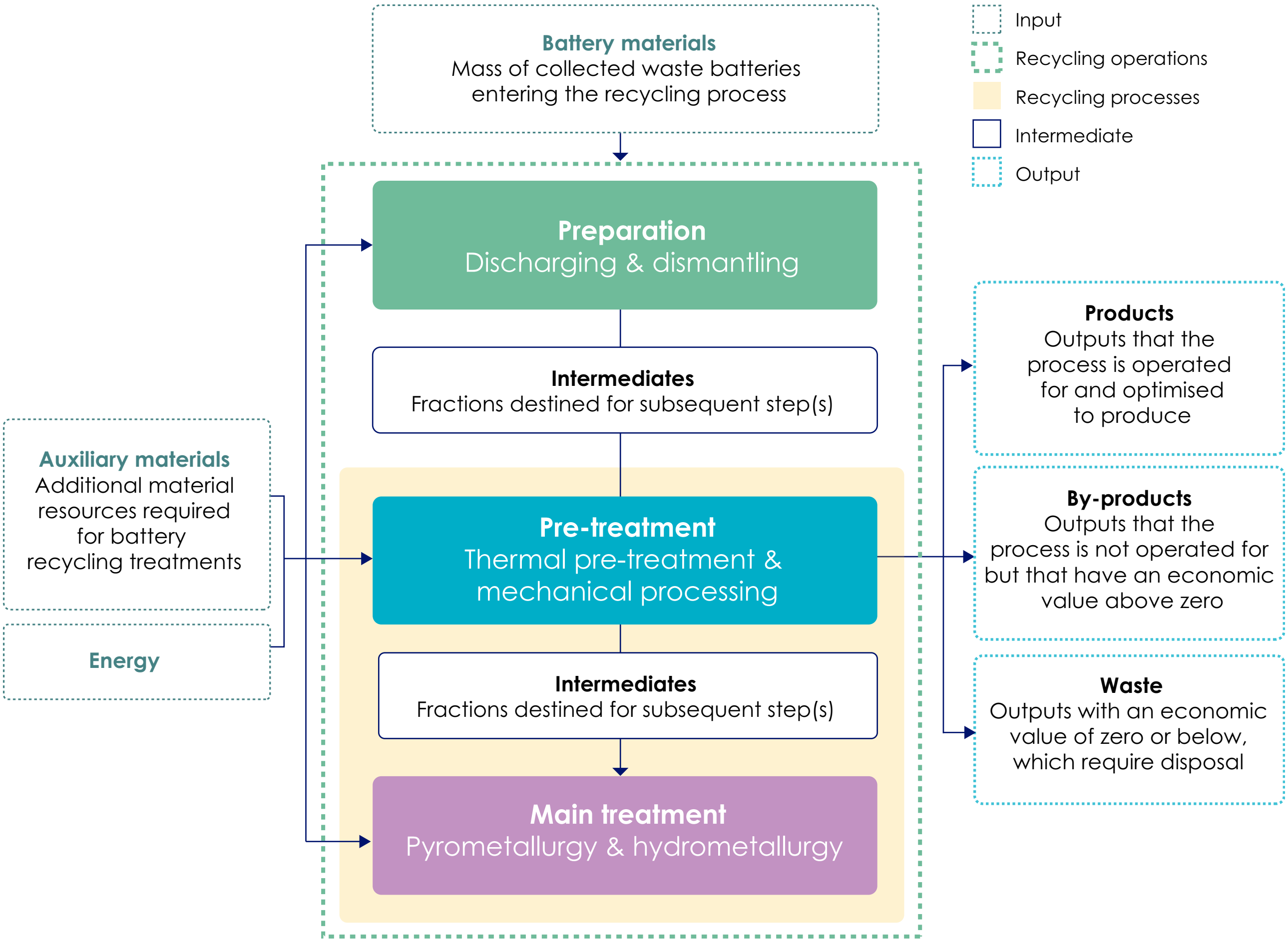
Intermediates

'Intermediates' are materials and substances produced through recycling that require further recycling processing before they can become products.[43] They can be described as 'fractions destined for subsequent step(s) in the recycling process'.[49]

Stakeholder division of the recycling value chain

Materials treatment steps may be undertaken by different stakeholders, as described in the EU Battery Regulation, which states that recycling 'may be carried out in a single facility or in several facilities'. Therefore, within the system boundaries, a single recycler may have integrated facilities designed to provide end-to-end recycling operations; or alternatively, its capabilities may be limited to producing intermediates, with multiple stakeholders managing different stages of the battery recycling value chain. The relative sustainability of end-to-end or partial recycling operations is another subject of debate. While comprehensive recycling facilities may streamline processes, their inability to adapt to diverse feedstocks and changing market dynamics could impact their economic feasibility (please see Chapter 7 for further discussion).

Figure 7: System boundaries of battery treatment and recycling including recycling steps and materials



3.2 RECYCLING OPERATIONS

Recycling complex waste such as LIBs requires a multi-step approach. The steps used in recycling processes today can be categorised into three distinct phases: preparation, pre-treatment and main treatment.

3.2.1 Preparation phase

Discharging

This step involves rendering a battery safe for subsequent handling, mitigating the electrical and thermal hazards associated with high voltages. Two common industrial methods for battery deactivation are the use of a discharge device and immersion in an aqueous solution[4] (eg, brine). In the former case, a discharge device is employed to convert the battery's residual charge into

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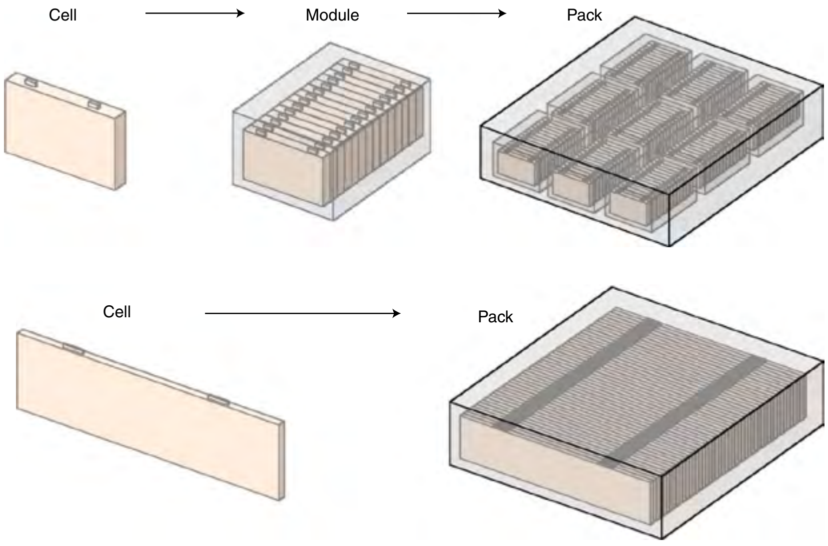
[4] Discharging can also be carried out prior to removal from an EV; however, this is outside the boundaries of recycling operations studied in Chapters 3 and 4.

Figure 8: Internal LIB structure[54]



electrical energy, thereby recovering it. This energy can then be fed back into the electrical grid or used for localised power generation.[51],[52] In the latter case, a salt solution is used to safely and gradually deplete the residual electrical energy within the battery. The salt increases the solution's electrical conductivity, allowing a conductive pathway to form between the positive and negative electrodes, which neutralises the battery's stored charge.[53]

Dismantling[5]

Battery packs have complex and variable internal structures. In a conventional cell-to-module LIB, the outer housing of the pack contains several battery modules, as well as multiple electrical, mechanical and thermal parts (eg, a cooling system and a battery management system (BMS)). The battery modules themselves contain numerous components, including the battery cells.[52] As the critical metals are contained within the battery cells, packs are often disassembled to either the module or cell level to facilitate more targeted recovery of these materials. In recent years, a cell-to-pack structure (as shown in Figure 8) has become increasingly popular, to reduce cost and increase the volumetric density of the battery.[54] Some manufacturers go one step further, using cell-to-body LIBs in which all additional internal casings have been removed. Battery producers also utilise different methods to assemble battery packs – for instance, the components may be screwed or glued together. The wide range of battery designs and chemistries available on the market, and the lack of LIB-specific dismantling manuals, necessitate a manual disassembly process conducted by trained technicians.[53] The components that are separated by hand from the modules or cells in the disassembly process can then be further treated through established recycling routes; more than 30% of the battery's total mass can typically be recovered as outputs in the dismantling process.[55] For some cells that are in sufficiently good condition, the reuse of components in new battery packs may be viable; although the feasibility of scaling such solutions is debated.

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[5] Dismantling refers to the deconstruction of the battery and not to the removal of the battery from the host vehicle, which occurs outside the recycling operations system boundaries.

3.2.2 Pre-treatment phase

Mechanical processing

Mechanical treatment involves physically breaking down battery packs, modules and/or cells through a shredding process. The result is a fragmented mixture of their components which requires separation into the various material fractions that can be further recycled. This is achieved by leveraging the distinct physical, mechanical and magnetic properties of the constituent materials (eg, via froth flotation or sieving/sifting).[56] The fraction containing processed active materials, derived from the electrode coatings (it may also contain impurities such as foil particles and residual electrolyte), is referred to as 'black mass' and must undergo further processing to recover valuable metals such as cobalt and nickel (see Information Box 2 in Chapter 1 for further information on black mass).[52]

Thermal pre-treatment

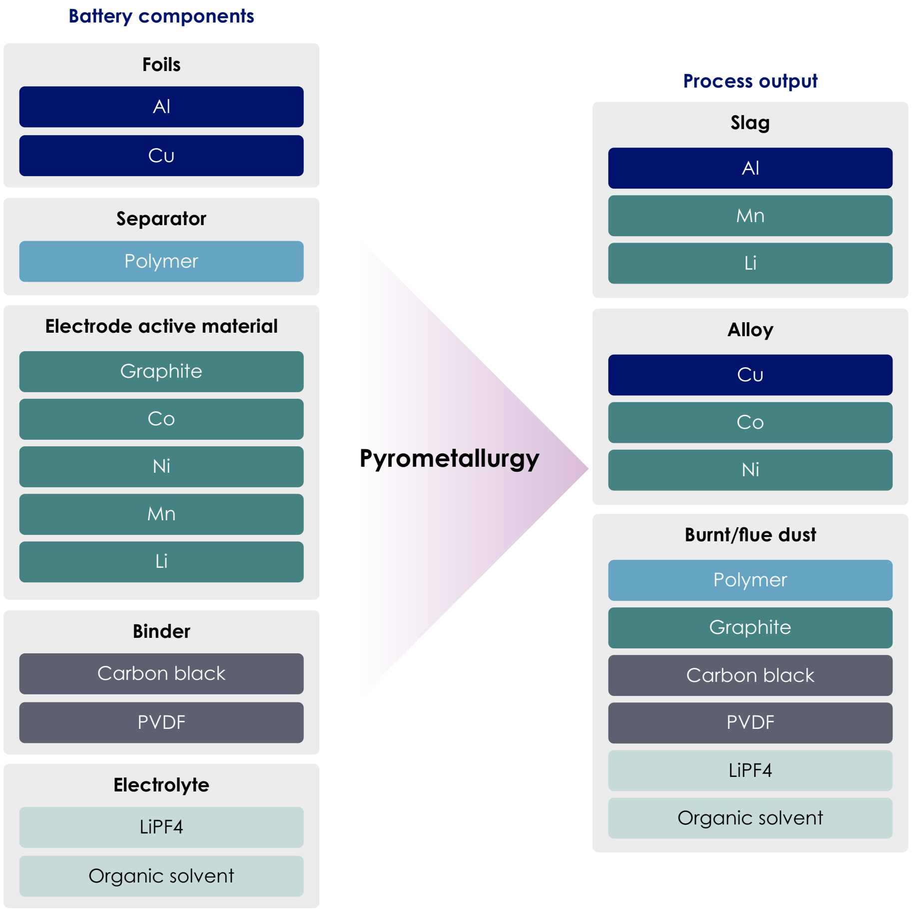
Thermal processes are used to treat either battery cells or the black mass output from mechanical processing. Multiple thermal processes are used for battery pre-treatment, which differ by parameters such as temperature range and atmospheric conditions. However, pyrolysis is the most common; and as such, the generalised term 'thermal pre-treatment' used throughout this report refers to this technique. Pyrolysis involves decomposing materials by heating them in the absence of oxygen.[48] The temperature varies according to the input material, adapted to enhance recovery rates and minimise the safety risks associated with specific feedstocks. For instance, cells are processed up to 400°C; while black mass can be pyrolysed up to 700°.[52] Thermal pre-treatment has several functions, including removing organic elements (eg, electrolyte solvents) and decomposing the polymeric binder (eg, polyvinylidene fluoride (PVDF)). It is preferable to eliminate organic solvents to avoid contamination in subsequent recycling steps and reduce the hazard potential, as these solvents are often highly flammable. Binder decomposition involves breaking down the polymeric substance that is used to bind the materials to the electrode coating and fix them to the current collectors. The aim is both to avoid contamination later in the recycling process and, importantly, to liberate the active materials in the electrode.[47] As the electrolyte is depleted during this procedure, the battery becomes fully discharged. Consequently, certain recyclers opt for pyrolysis as an alternative to the discharge methods outlined in Chapter 3.2.1.[11],[51]

3.2.3 Main treatment phase

Pyrometallurgy

Pyrometallurgy is a well-established metal extraction and purification technique which has been utilised in the metals industry for decades. In the case of battery recycling, metals are extracted by smelting the battery materials. Minimal pre-processing is required and pre-treatment steps are not essential, meaning that battery packs, modules, cells and black mass can be treated.[57] Smelting involves decomposing the input materials by heating them in a furnace at around 1500˚C in the presence of a reducing agent (commonly a source of carbon) and additives such as quicklime and silica dioxide ('slag formers').[55],[57] The process has several output fractions: for a typical NMC battery, these include an alloy containing nickel, cobalt and copper; slag containing aluminium, manganese and lithium; and a fly ash of fine particles which may include metal oxides, carbon residues from organic battery components and inorganics such as fluorine (see Figure 9). Other non-metallic materials (eg, graphite anode and polymers from the housing and separator) burn up in the furnace and are thus not recovered.[11] However, their combustion provides heat energy for the process, displacing other fuel sources. To be returned to materials, the products of pyrometallurgy require additional processing via hydrometallurgical techniques. Some of these intermediates can be used for lower value applications in other industries (eg, slag in the construction industry).[53],[58]

Figure 9: Simplified material flow of the typical cell components in an NMC battery when treated with pyrometallurgy[57]



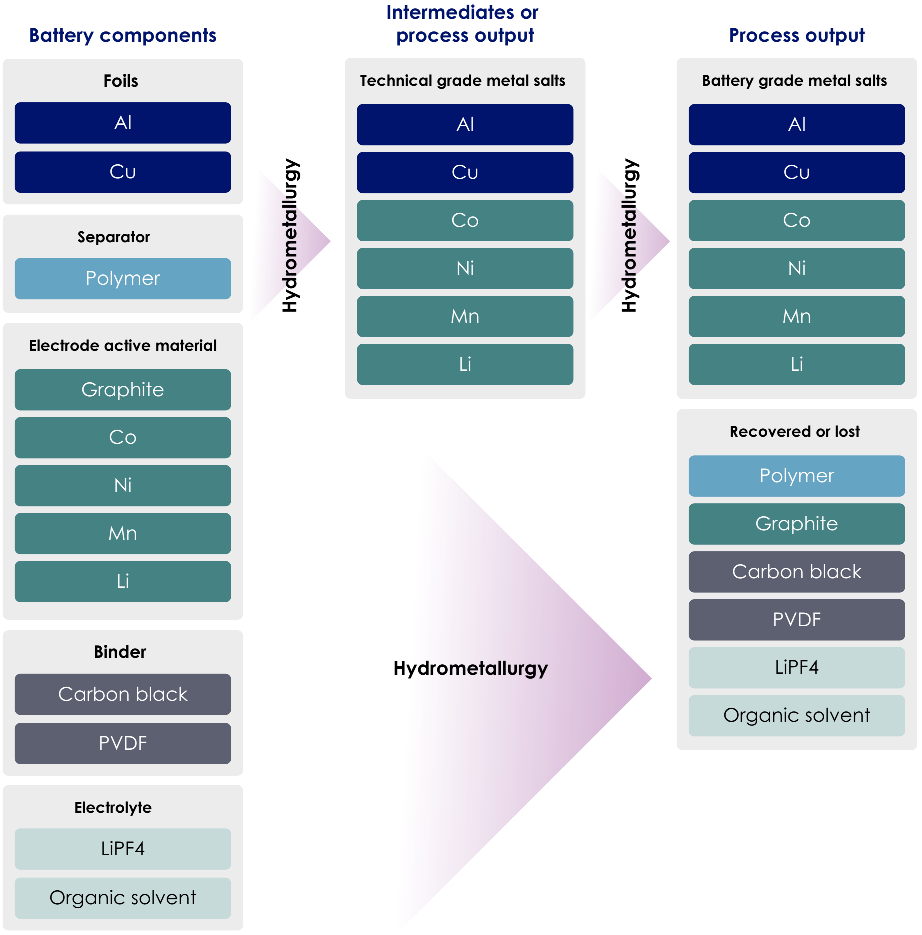
Hydrometallurgy

Hydrometallurgy recovers metals via wet chemical processes. The inputs for this technique may be intermediate materials produced through pyrometallurgy (alloy or slag) or black mass following pre-treatment steps. Intact cells or modules cannot be directly fed into this treatment, as the active materials must be exposed for effective processing.[57] Hydrometallurgy uses three general processes to extract outputs from black mass:

- **Leaching:** An acid, base or salt is used to dissolve the input LIB materials.
- **Purification:** Impurities are removed and metals in solution are separated via selective chemical processes (eg, ion exchange or solvent extraction).
- **Recovery from solution:** Separated metals are recovered as solid products through techniques such as precipitation, crystallisation or electrowinning.[11]

The specific product composition of the treatment is determined by the flowsheet, the reagents used and the extent of the processing applied, making it possible to produce both battery-grade materials and intermediate products.[59] For example, the lithium content in black mass may be processed to battery-grade lithium hydroxide/lithium carbonate or to non-battery-grade lithium sulphate. Lithium sulphate can be categorised as an intermediate product if it undergoes additional hydrometallurgical processing by another recycler to achieve battery-grade quality; otherwise, it is categorised as a lower technical-grade material.[59]

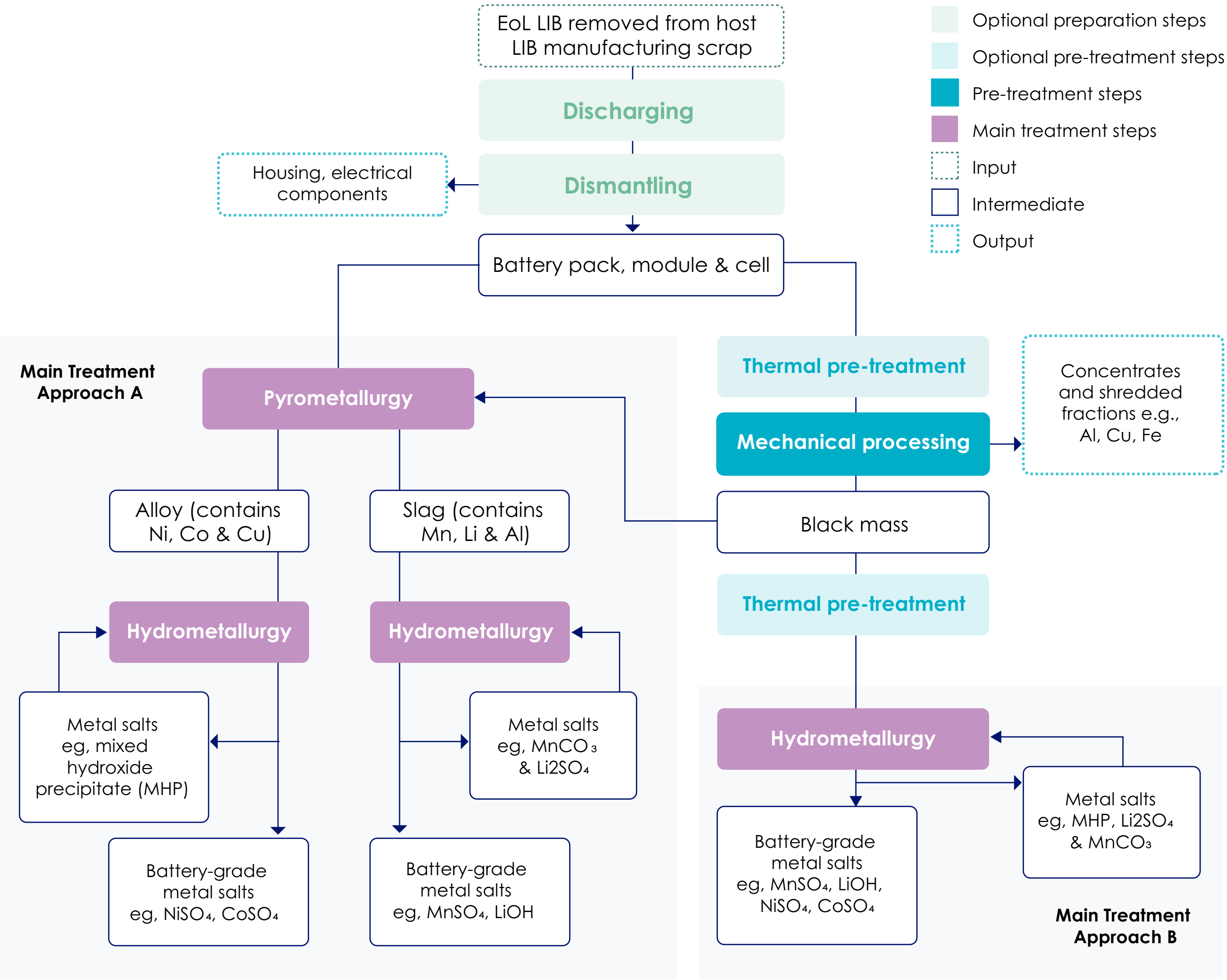
Figure 10: Simplified material flow of the typical cell components in an NMC battery when treated with hydrometallurgy[57]



3.3 RECYCLING ROUTES

A wide range of possible treatment combinations exists for LIB recycling routes. Figure 11 provides a flowchart of how recycling routes can be structured. There are multiple options through which recycling steps can be combined and some of the steps are optional. Additionally, each individual step may encompass multiple sub-steps that can also be structured in numerous ways. This results in many different permutations of recycling routes.[58]

Figure 11: Flow chart for possible recycling routes in the recycling of LIB materials.



Note: auxiliary material and energy input, as well as waste and by product output, are not shown (adapted from chart proposed by[11])

The primary divergence between the various routes concerns the steps used in the main treatment phase. The flowchart illustrates how battery-grade products can be obtained using two different approaches:

- **Main Treatment Approach A:** Pyrometallurgy followed by hydrometallurgy; or
- **Main Treatment Approach B:** Hydrometallurgy only.

The suitability of each main treatment approach varies depending on the battery chemistry. For instance, LIBs with a high nickel and cobalt content align well with Main Treatment Approach A, as these critical metals will be recovered in the alloy output of pyrometallurgy. In contrast, chemistries such as LFP are less compatible with Main Treatment Approach A, as the cathode metals are sent to the slag during pyrometallurgical processing.[11]

The pre-treatment steps employed vary according to the main treatment approach. Pyrometallurgy can accept both intact cells/modules/packs and black mass, affording flexibility in the choice of pre-treatment method. In contrast, hydrometallurgy can only accept black mass or metal alloys, meaning that mechanical processing or pyrometallurgy is essential.

The output of a recycler's operations depends on the extent of refinement applied and the phase at which materials are obtained as products. It is possible to produce battery-grade metal salts via hydrometallurgy. However, recyclers face a trade-off between achieving high-grade metal recovery and managing resource input requirements. As a result, producing battery-grade materials may not be cost effective, meaning that recyclers end up processing up to the point of intermediates and then selling them on for further treatment. Additionally, the output fractions vary based on the phase of the operations at which they are collected. For example, the copper that makes up the electrode foils may be separated after mechanical processing and output in the pre-treatment phase as a copper/aluminium concentrate.[11] Alternatively, the hydrometallurgy process might be engineered to include copper refinement and output a copper solution or compound.[55]

Recyclers must consider the following factors when choosing a recycling route in order to ensure its effectiveness, efficiency and feasibility:

- **Economic:** Upfront cost of equipment and facilities; operational costs (eg, labour, energy, waste disposal); market price of recovered materials.
- **Technical:** Operational scalability; flexibility to input material and chemistries to the EoL battery pool.
- **Regulatory:** Waste management and recycling policies; environmental policies (eg, carbon taxes, pollution standards).
- **Geographical:** Availability of resources and infrastructure; access to suppliers and customers.

Five distinct and representative industrial routes for LIB recycling have been identified. Through a comprehensive literature review and in-depth examination of recyclers' flowsheets,[6] five archetypal routes have been defined, as depicted in Figure 12. The routes have been categorised based on the main treatment approach used. In Table 1, recycling facilities accounting for almost

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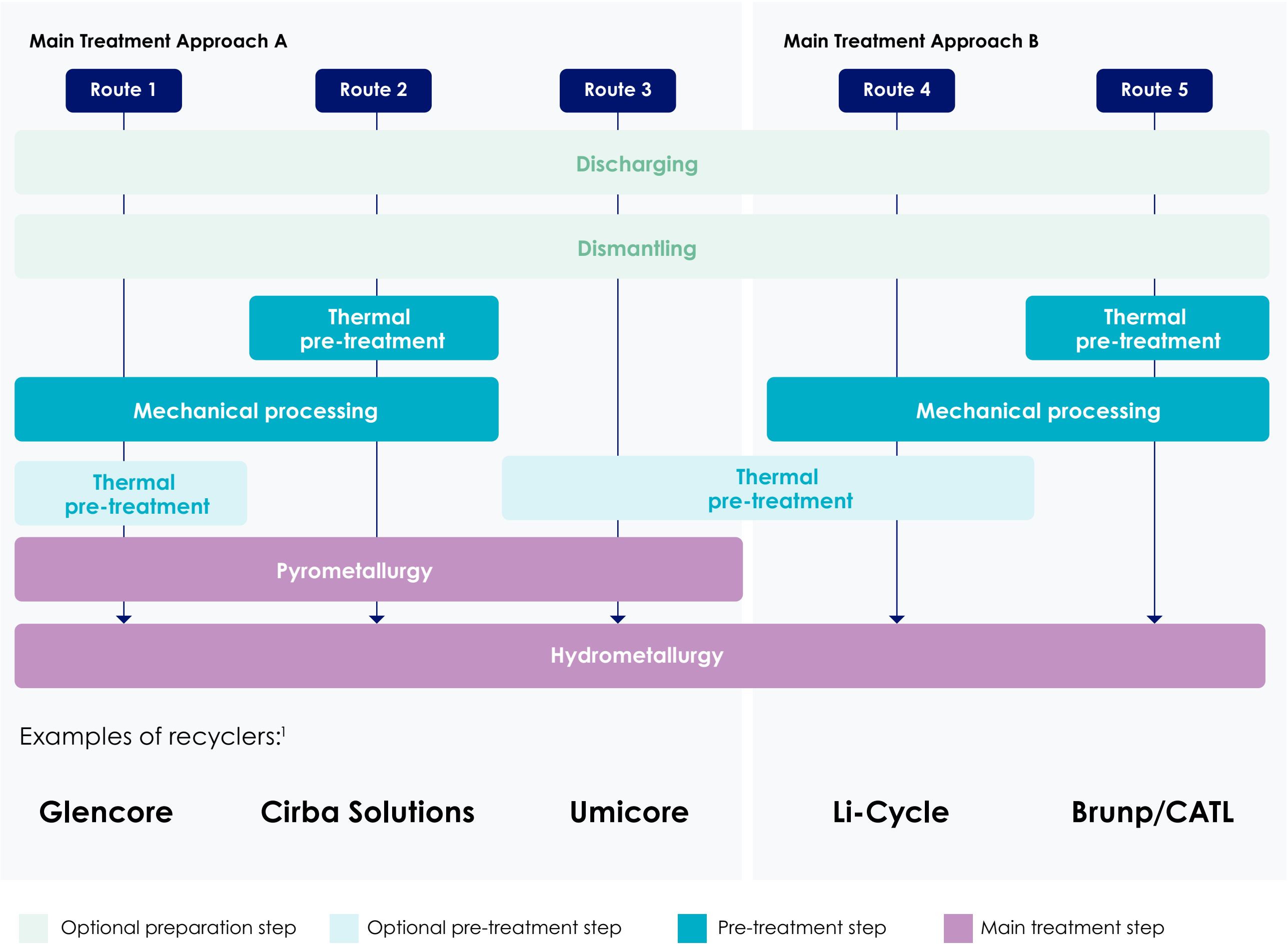
[6] A 'flowsheet' is a visual representation used by recyclers that outlines the sequence of recycling steps, phases and techniques used in its recycling operations.

60% of global main treatment recycling capacity have been mapped to the recycling route employed by each respective facility (see **Annex II** for a full list of mapped recyclers and capacities). The main treatment capacity for each of the archetypal routes identified is shown in Figure 13(I). Main Treatment Approach B has around 6.5 times the capacity of Approach A, with Route 4 leading in terms of processing volume. This suggests a stronger preference for the exclusive use of hydrometallurgy over pyrometallurgy followed by hydrometallurgy. Additionally, Figure 13(II) illustrates that the combined pre-treatment and main treatment capacity of the EU and North America is half that of Asia. Notably, the EU has much greater pre-treatment capacity, indicating an oversupply of black mass in this region which requires export for further processing.

Figure 12: Archetypal recycling routes identified from academia and recyclers' flowsheets

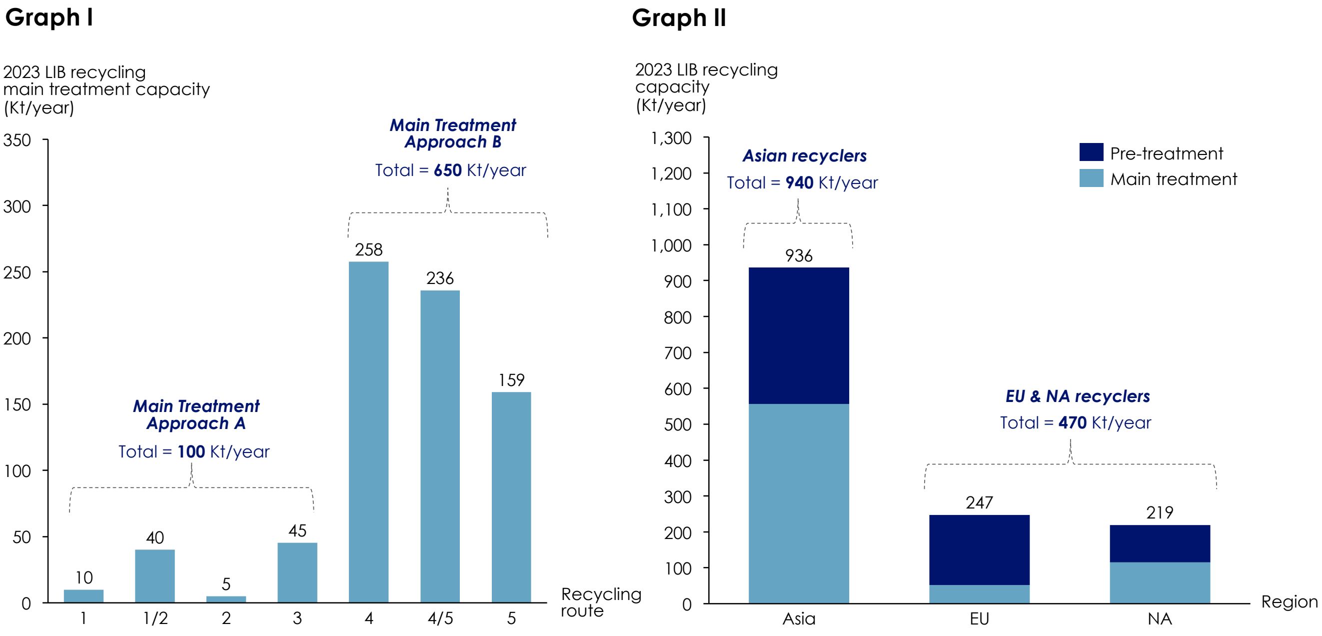


Note: Recyclers' routes as identified in the Circular Energy Storage database – please note routes may have changed since the date of entry into the database and companies may use different routes at different facilities.

Table 1: Industrial recyclers mapped to their respective archetypal recycling route, sorted by region according to headquarters.[7]

	North America	Asia	Europe
Route 1	• Glencore	-	-
Route 1/2	• Aleon • American Battery Tech.	-	-
Route 2	• Cirba	-	• SNAM
Route 3	-	• Dowa	• Nickelhütte • Umicore
Route 4	• Li-Cycle	• Ganfeng Lithium • GEM • Huayou Cobalt	• BASF • Fortum • Primobius
Route 4/5	• Ascend Elements • Electra Battery Materials	• Ecopro CNG • Fangyuan Env. Protec. • Miracle Auto. • POSCO • Shangong Weineng • Tata Chemicals • Xiongtao (vision)	• Attero • Erlos • Kyburz Group • Revolt • TES- Recupyl
Route 5	• Redwood Materials	• Brunp • SungEel HiTech	-

Figure 13: (I) 2023 main treatment capacity by process route; (II) 2023 main treatment and pre-treatment capacity by main treatment approach and region



Graph I

Graph II

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[7] Some recyclers do not explicitly disclose the order of pre-treatment steps; therefore, these have been mapped to '1/2' or '4/5'.

INFORMATION BOX 3: DIRECT RECYCLING

Interest in direct recycling of LIBs has grown over the past decade due to its potential to offer a closed-loop battery recycling solution.[57]

The process involves recovering cathode and anode active materials without breaking down their crystalline structure.[52] The recovered active materials can then be incorporated into new electrodes with minimal additional, resource-intensive processing. The exception to this is the need to replenish the lithium content to counteract losses from material degradation during battery use.[53]

During direct recycling, battery components are segregated through physical, magnetic and/or thermal separation techniques. The separation methods are designed to minimise the chemical degradation of the target materials. The recovered active materials then undergo purification, re-lithiation or hydrothermal treatment to repair any surface or bulk defects.[60] This technique appears to have greatest relevance for production scrap as by the time batteries reach EoL and are returned to recycling (10-20 years), the original cathode and anode material may have become outdated, meaning direct recovery would yield no benefits.

As direct recycling involves fewer processing stages and fewer material inputs, it can result in lower operational expenses compared to pyrometallurgical and hydrometallurgical treatment methods. This is especially relevant in light of the growing prevalence of LFP batteries. In the past, the high nickel and cobalt content allowed for economically viable returns from pyrometallurgy and hydrometallurgy recycling routes, despite the high operational costs. However, this may no longer hold true in future years, as cathodes made from more inexpensive metals (eg, iron) are increasingly accounting for a greater share of the LIB battery pool, creating a need for more efficient low-cost recycling techniques.[62]

Direct recycling has not yet been fully industrialised due to various technological challenges. One major obstacle is the need for the precise separation of the cathode and anode materials. However, for production scrap with anode and cathode materials being available separately, this is less of an issue. Another barrier is limited scalability, as the technique is chemistry specific.[57] However, with further research on the potential automation of electrode material separation and the recovery of mixed cathode materials, direct recycling may be one viable answer to sustainable LIB recycling.[60]

CHAPTER 4

SUSTAINABILITY ASSESSMENT OF RECYCLING OPERATIONS

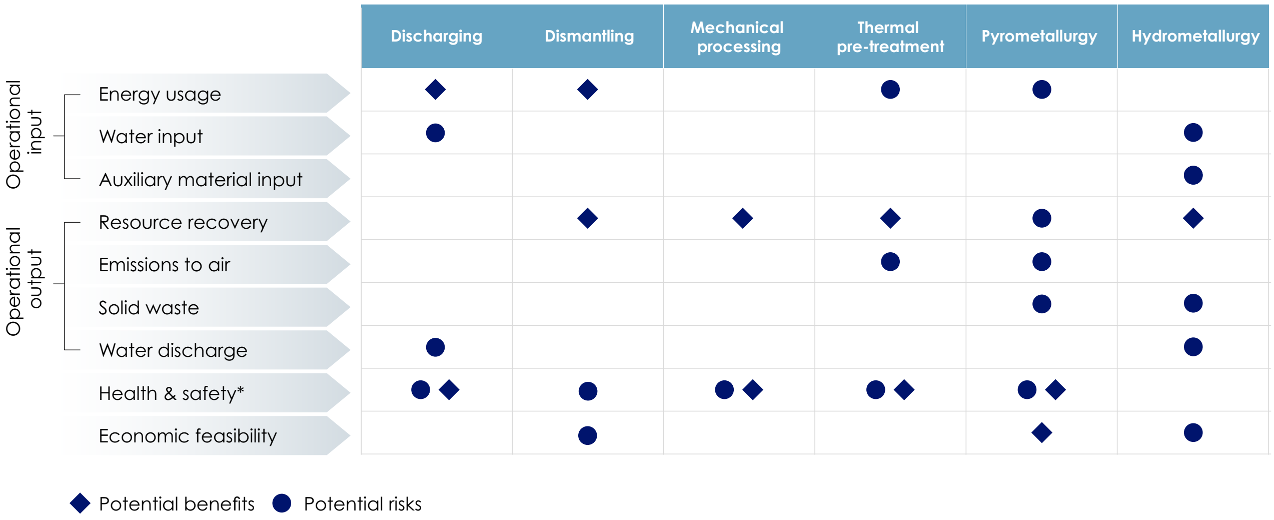
4. SUSTAINABILITY ASSESSMENT OF RECYCLING OPERATIONS

From a circular economy perspective, battery recycling is crucial for addressing waste streams, avoiding environmental impacts tied to primary material extraction and mitigating potential future resource constraints.

The findings from several trusted LCA studies demonstrate that GHG emissions for recycling routes using the most common approach to main treatment[8] range from 1.2 to 2.2 kgCO_2e per kilogram of LIB (kgLIB).[9][63]-[66] However, the same studies estimate the emissions avoided from reduced primary material production due to the use of recycled materials to be three times higher (4.2-5.4 kgCO_2e/kgLIB), reflecting the environmental advantage of recovering materials through recycling. To contextualise the results of these studies, according to battery circularity advisory firm Circular Energy Storage, if all EoL LIBs in the EU were assumed to be recycled in 2030, the net benefit would be almost 1 million tons of GHG emissions avoided. However, the industry faces sustainability challenges due to the complex nature of LIB recycling, safety risks and the substantial resource volumes required. For instance, studies have shown that hydrometallurgy treatment can use around 20 litres of process water for every kilogram of LIB processed.[32],[67]

This chapter explores the sustainability considerations associated with current industrialised LIB recycling operations by analysing performance indicators relevant to individual operational steps and combined routes.[10] It offers best practices for enhancing operational sustainability, which are also summarised and included in the key principles for sustainable battery recycling found in Chapter 7. The analysis

Figure 14: Summary of recycling operations sustainability assessment



		Discharging	Dismantling	Mechanical processing	Thermal pre-treatment	Pyrometallurgy	Hydrometallurgy
Operational input	Energy usage	◆	◆		●	●	
	Water input	●					●
	Auxiliary material input						●
Operational output	Resource recovery		◆	◆	◆	●	◆
	Emissions to air				●	●	
	Solid waste					●	●
	Water discharge	●					●
	Health & safety*	● ◆	●	● ◆	● ◆	● ◆	
	Economic feasibility		●			◆	●

◆ Potential benefits ● Potential risks

Potential risks and potential benefits are illustrated for each indicator and considered independently across the six process steps. Potential risks and potential benefits are based on published literature; therefore, empty boxes signify that the indicator was not identified as a key concern or advantage in the available publications.

* The literature highlights both challenges and advantages associated with various aspects of health and safety in the discharge, thermal pre-treatment and pyrometallurgy process steps. Consequently, these boxes indicate the presence of potential risks and potential benefits

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[8] The capacity mapping detailed in Chapter 3 demonstrates that the most common main treatment method is exclusive use of hydrometallurgy (Main Treatment Approach B).

[9] LCAs reported on emissions from recycling NMC batteries, all using their own specified routes.

[10] The environmental assessment does not consider potential technological innovation and solely evaluates the impact of operations in their present state.

in this Chapter is primarily qualitative, with quantitative data obtained from academic LCAs and TEAs integrated to support the insights, where relevant. The objective is not to engage in a direct comparison of LCAs or compile their outcomes, for the reasons outlined in Information Box 4.

CHAPTER 4 KEY TAKEAWAYS

- **Each recycling step has inherent sustainability implications, irrespective of the overall route in which it is incorporated.** Figure 14 summarises the sustainability benefits and risks identified for each operational step. The risks can be mitigated or avoided through the application of industry best practices.
- **The sequencing of steps in each route also gives rise to distinct sustainability considerations.** Decisions regarding which steps to include and in what order result in additional risks and benefits beyond those associated with the individual steps themselves. These primarily concern the point at which materials are extracted within the route and the intermediates which are used as feedstock for subsequent phases.
- **There is no 'one size fits all' assessment of LIB recycling sustainability.** The environmental, social and economic impacts of LIB recycling vary significantly based on the individual recycler's operations, as the treatment steps and recycling routes employed are highly divergent. For instance, water use could have a substantial impact where a recycler employs aqueous discharge treatment and hydrometallurgy; but its significance is relatively minor if the facility applies only the pyrometallurgy refining step. Moreover, water use of hydro processes are of lower concern outside of water scarce regions.
- **Optimising recycling routes for sustainability involves weighing a series of trade-offs.** Given the multiple sustainability dimensions involved, optimising for one indicator may have adverse effects for another. Therefore, recyclers must consciously balance sustainability aspects and make data-driven decisions to improve overall sustainability (see Figure 15 for a summary of trade-offs relating to the features of recycling routes).

Figure 15: Summary of trade-offs related to sequencing of recycling routes

Route Feature A *Exclusion of Dismantling*	**Route Feature B** *Exclusion of Thermal Pretreatment*	**Route Feature C** *Thermal Pretreatment after Mechanical processing*	**Route Feature D** *Pyrometallurgy in combination with hydrometallurgy*	**Route Feature E** *Exclusion of all thermal process steps*
Scalability is improved as slow manual treatment step is avoided, but resource demand and waste production of subsequent processes may increase	Energy usage and operational cost is reduced prior to main treatment, but lower recovery rates may result as the critical metals are not entirely liberated from their supports	Energy usage is lowered for the thermal pretreatment step as a smaller mass requires heating, but recovery rate of critical metals may be lower and discharge benefit of thermal pretreatment is not leveraged	Recovery rate is enhanced when lithium is reclaimed via hydrometallurgy from slag produced in pyrometallurgy, but additional primary resource input is required (e.g., reagents, energy, water)	Recovery rate is boosted and climate impact can be improved as anode material (graphite) is not burnt and can instead be reclaimed, but recovery options can be expensive and resource-intensive

INFORMATION BOX 4: THE ONGOING DISCOURSE ON THE COMPARATIVE ANALYSIS OF LCAS

The LCAs of LIB recycling processes that have been conducted thus far exhibit considerable variability in results due to the diverse methodological choices made by practitioners. Factors that may produce inconsistencies and make direct comparisons difficult include the following:

- **System boundaries:** Variations can occur in the operational phases and in the steps included in the analysed process routes (eg, exclusion of the preparation phase from the assessment). Additionally, system inputs may be at cell/module/pack level and may include pre-consumer and/or post-consumer materials. System outputs can also be a source of discrepancy, as different routes may yield a range of products of varying technical usability and economic value (eg, battery grade versus technical grade).

- **Underlying data:** LCAs conducted by different entities may use a variety of primary and secondary data sources and different functional units.

- **Allocation:** No methodological consensus has been reached on which recycling allocation to use (eg, cut-off/substitution/circular footprint formula), how to allocate multi-functionality or how to account for electricity use.

- **Timeliness of analysis:** LCAs can quickly become outdated as industrial operations are continuously optimised and updated, meaning that the performance of a particular technology may have improved since the analysis was conducted.

Factors such as these make it challenging to meaningfully compare or compile LCA results – an issue that is often cited by academia as a key barrier to understanding the relative impact of different battery recycling operations.[55],[58],[64]

To address this issue, entities such as the EU Joint Research Council (JCR) and the GBA are working to develop emissions accounting standards for battery materials. In 2023, the JCR published a draft of the Harmonised Rules for the Calculation of the Carbon Footprint of Electric Vehicle Batteries. Article 7 of the EU Battery Regulation mandates the calculation and communication of the carbon footprint of EVs. Similarly, the Greenhouse Gas Rulebook developed by the GBA aims to provide a 'globally harmonised approach' to calculating battery carbon footprints for inclusion in a battery passport. A battery passport is an electronic record containing battery model and individual usage data, which will become mandatory under the EU Battery Regulation from 2027 (see Chapter 5 for further details).

4.1 OPERATIONAL STEPS

Each operational step carries its own inherent sustainability considerations, irrespective of the overall recycling route in which it is incorporated. Battery recycling – like many other industrial processes – can consume substantial resources and generate large waste streams, emphasising the need for careful consideration of best practices and a balanced approach to achieve optimal sustainability outcomes.

4.1.1 Preparation phase

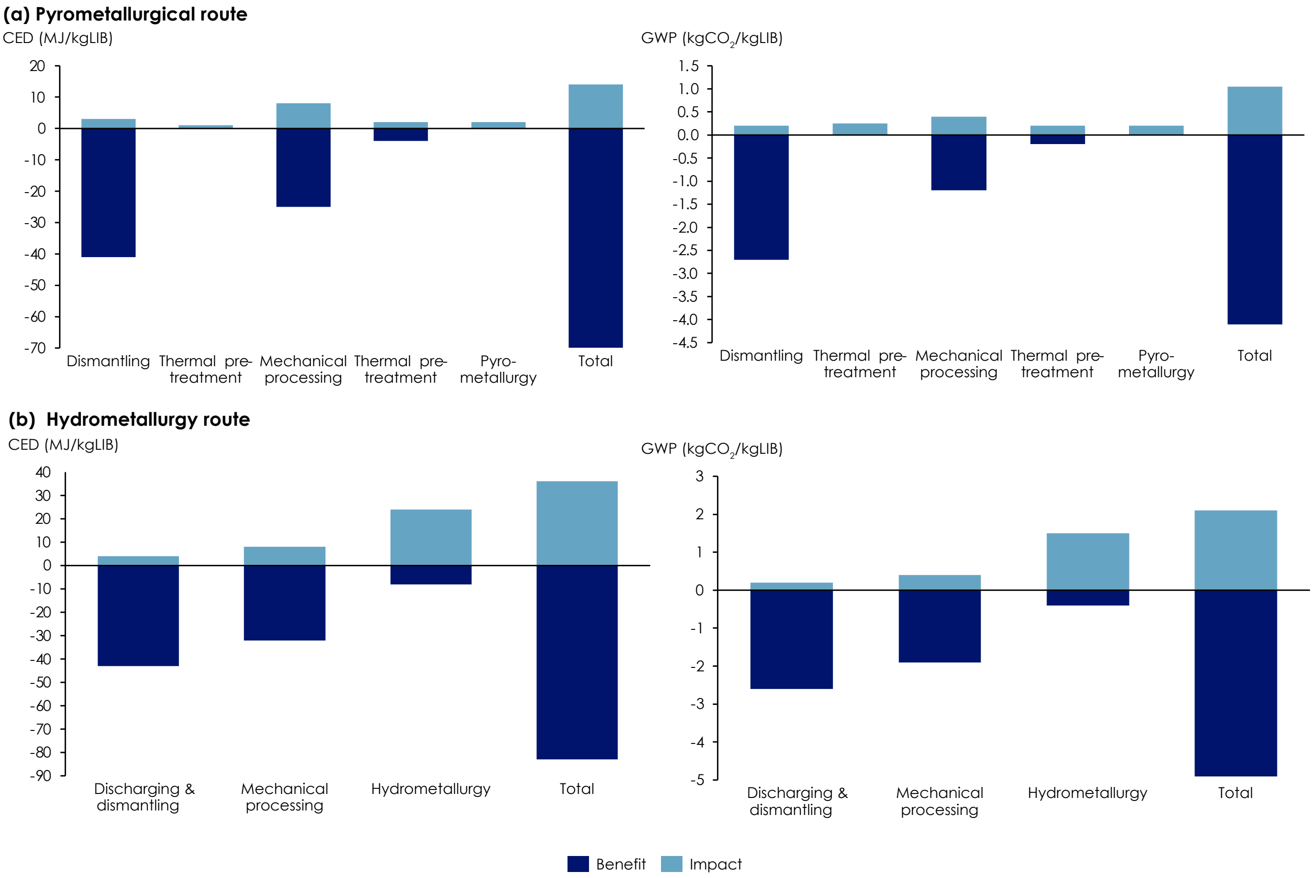
	◆ **Potential benefits**	● **Potential risks**
Discharging	**Health and safety** risks are reduced through mitigation of electrical and thermal hazards (eg, shocks, thermal runaway).[11][16] **Energy usage** is optimised through the recovery of residual stored energy when a discharge device is used.[47] However, this process requires skilled labour, so economic feasibility is contingent on labour cost versus energy cost savings.[53]	**Health and safety** risks arise from harmful gas emissions produced through side reactions (eg, chlorine produced in electrolysis of aqueous salt solution) and from electrical hazards to workers deploying discharge devices.[58] Damaged, Defective, and Recalled (DDR) batteries pose a significant risk to workers and operators. **Water input** and water discharge considerations arise when aqueous solution discharge is used, due to high consumption and the risk of contamination from hazardous electrolyte and electrode materials (eg, carcinogenic nickel and cobalt; hydrogen fluoride (HF) in solution).[53]
Best practices	• Residual energy recovery via discharge devices is preferable to dissipating and wasting residual energy.[68] • Water usage should be minimised. If aqueous discharge is necessary, aim for a closed water loop; if this is not feasible, adhere to high treatment standards. • Analyse battery state-of-health data and analytics (eg, battery passport) to ensure discharge method is safe.[53]	
Dismantling[12]	**Resource recovery** rates are increased by early removal of non-electrode battery elements, which can be recycled or reused. Dismantling helps to maintain the purity of recovered materials, reduce impurities in subsequent treatment and avoid material losses.[55],[56]	**Health and safety** considerations arise due to the hazards associated with the manual handling of batteries and battery materials. There is a risk of chemical exposure, electrical hazards and thermal events if the battery is not properly discharged (eg, electrical shocks from short-circuiting; formation of toxic HF emissions during thermal runaway, which may become trapped and result in an explosion).[51],[53],[56] DDR batteries pose a significant risk to workers and operators.

[11] Thermal runaway is a chain reaction, triggered when a critical temperature is reached in a battery and an exothermic reaction of the electrolyte and electrodes is initiated.

[12] Dismantling refers to the deconstruction of the battery and does not refer to the disassembly of the battery from the host vehicle. Removal of the battery from the vehicle occurs outside the recycling operations system boundaries.

	◆ **Potential benefits**	● **Potential risks**
Dismantling	**Energy usage** and climate impacts of primary material production are avoided when non-active materials are recycled/ reused. One LCA found that the most significant global warming potential benefit of LIB recycling occurs during dismantling, when aluminium, copper and plastics from casings and electronics are recovered, due to their substantial mass and the high environmental impact of their primary production (see Figure 16).[13][58]	**Economic feasibility** is uncertain, primarily due to low throughput and high labour costs. Scalability is limited due to the manual nature of the process and the extensive safety measures required. Cost is highly variable by location due to divergent labour cost: one TEA studying five geographies found that dismantling in China is highly cost effective; whereas in Belgium and the UK, it may not be economically realistic. The depth of disassembly chosen also affects the cost (eg, dismantling to module level or to cell level) (see Figure 17).[56],[69]
Best practices	• Maximise the reuse/recycling of non-active materials separated during dismantling (eg, components such as casings, electrical elements); prioritise component retrieval for reuse over recycling where possible. • Ensure the highest standards of safety for workers who undertake manual dismantling, using appropriate protective equipment and training.	

Figure 16: LCA results for two process flows, (a) including pyrometallurgy and (b) including hydrometallurgy, demonstrating the large potential energy and climate benefit derived from appropriate dismantling preparation. (adapted from[58],[63],[65])[14]



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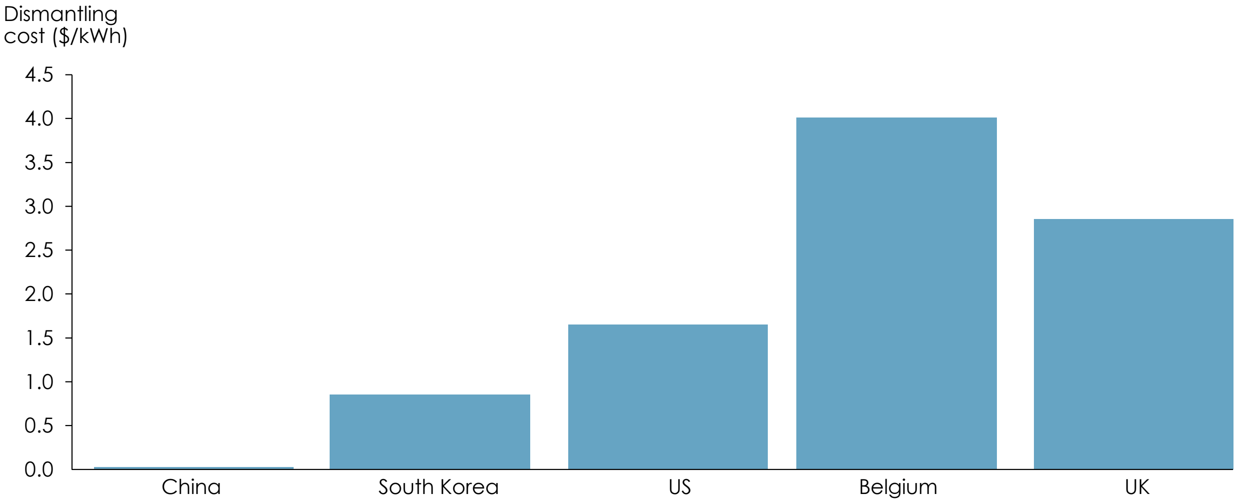
[13] All original LCA figures and clarifications of adaptations made can be found in **Annexes III** to **VIII**.

[14] These LCA results do not offer a direct comparison between recycling routes utilising pyrometallurgy and hydrometallurgy for main treatment. These results have been included solely to illustrate potential benefits derived from dismantling. The pyrometallurgy route would necessitate additional hydrometallurgy processes for the recovery of battery-grade salts.

Figure 17: Dismantling cost, in dollars per kWh, for a Tesla Model S battery pack dismantled in selected countries (adapted from[69])



Summary

Discharge via aqueous solutions offers cost advantages, as it is relatively easy to scale; however, depending on process design the potential for water contamination carries risks. With regard to energy consumption and its implications for climate change, a discharging process that facilitates the recovery (rather than dissipation) of residual energy is preferred. However, energy recovery processes have a higher capital cost and are more labour intensive than solution discharge. Therefore, this process may be economically unfeasible in geographies with high labour costs, such as the EU. Advanced automation may offer a solution to this economic challenge and resolve this barrier to scaling. However, the diversity of battery cell designs renders current automation processes inefficient, highlighting the importance of cell standardisation or machine-readable battery information for effective automation (please see Chapter 5 for further details on information sharing and Chapter 6 for a discussion on battery design for recycling).[68]

Manually dismantling battery packs boosts resource recovery by selectively reclaiming battery elements and maintaining material purity. However, safety concerns for workers and poor process efficiency lead to questions around economic feasibility, particularly in countries with high labour costs. This builds a case for the mandated provision of dismantling guides which would help to speed up operations, increase throughput and improve safety. Additionally, increased automation and the corresponding implementation of recycling-oriented battery design would improve the efficiency and safety of this step.[56]

4.1.2 Pre-treatment phase

<table>
<tr><th></th><th>◆ Potential benefits</th><th>● Potential risks</th></tr>
<tr><td>Mechanical processing[15]</td><td>Resource recovery is accelerated via efficient separation into distinct material fractions (eg, shredded foils, separator parts and black mass).[52] The process is a straightforward and relatively inexpensive way to break down battery waste streams. A diverse range of feedstocks can be accepted (eg, cell/module, pouch cell/cylindrical cell). Fractions that do not contain cathode material can be separated and further recycled, producing a valuable product stream and improving the purity of black mass (eg, copper from electrode foils can be isolated and treated through established recycling processes).[16]</td><td>Health and safety risks arise as the flammable constituents of batteries are exposed to ignition sources created from grinding metals (eg, sparks). Shredding in an environment with moisture in the air can generate toxic HF gas, potentially leading to explosions and the formation of hydrochloric acid (HCl), which can harm both workers (eg, severe burns) and the environment (eg, acid rain). A fine dust containing harmful substances is generated during shredding, posing risks to workers' respiratory health; the extent of this harm is contingent on battery chemistry, as some cathode chemistries are higher risk (eg, nickel and cobalt are carcinogenic).[11],[51],[70]</td></tr>
<tr><td>Best practices</td><td colspan="2">• Maximise recycling of processed materials beyond black mass (eg, shredded foils and casings).
• Mitigate the release of fine dust and HF emissions by applying strict emissions control measures.
• Minimise fire risks by using control measures to suppress oxygen (eg, inert atmosphere, vacuum, submersion).</td></tr>
<tr><td>Thermal pre-treatment</td><td>Resource recovery rates increase as polymeric binder material (eg, PVDF) is broken down, liberating active materials from their supports. Organic contamination and electrode foil impurities in black mass are reduced if the material is subsequently shredded. Volatile organic compounds (VOCs) from the electrolyte can be recovered if condensed and collected in the off-gas treatment.[55]
Health and safety risks from residual charge are eliminated as the electrolyte is completely evaporated.</td><td>Emissions to air may include environmentally harmful gases. Graphite used in the anode may be burned, producing CO_2 and increasing climate impact. VOCs from the electrolyte can contribute to air pollution and smog formation, leading to respiratory issues and environmental degradation. HF generation can result in HCl formation upon exposure to moisture, leading to acid rain and soil contamination.[70]
Energy usage is high as a result of the large amounts of energy needed to heat furnaces to high temperatures (in the range of 400-600˚C). Health and safety risks arise from the consequences of VOCs and HF emissions, as highlighted above.</td></tr>
<tr><td>Best practices</td><td colspan="2">• Enhance the mass balance recovery rate via recovery of the electrolyte.
• Mitigate the release of VOCs and HF emissions by applying strict control measures.</td></tr>
</table>

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[15] The table lists the potential benefits and risks of mechanical processing when no control environment is applied. Specific industrial techniques (eg, inert atmosphere, vacuum and submersion) are examined in Table 2.

Summary

Mechanical processing offers an economical and efficient approach to releasing battery materials for recovery. It enhances the scalability of battery operations by minimising the need for extensive pre-sorting and preparation steps. Additionally, applying separation techniques to the shredded mass allows for different material fractions to be removed and recycled, reducing the impurity levels of the black mass waste stream. However, there is a high risk of fire, due to the exposure of flammable materials to ignition sources in the shredder. Additionally, there is the potential for hazardous gases and substances to be released as the materials are broken down (eg, carcinogenic dust, HF). This necessitates a controlled environment for shredding (eg, an inert atmosphere, vacuum or alkaline solution submersion). Each of these approaches carries its own sustainability considerations, giving rise to trade-offs that must be carefully managed (see Table 2 for summarised considerations for each of the industrial shredding techniques).

Table 2: Sustainability comparison of the different conditions used in industrial mechanical processing[51],[58],[63]

	Additional sustainability benefits	Sustainability risks
Inert atmosphere (eg, nitrogen, CO_2, argon)	**Health and safety:** Suppressed oxygen allows processing without risk of fire. HF formation is prevented due to the absence of moisture in the environment.	**Auxiliary material use:** Large volumes of inert gas are required; inert gas can be reused but the capture process may have limited efficiency, requiring inert gas makeup. **Energy use:** Energy demand for electrolyte drying and inert gas scrubbing is high. **Economic feasibility:** Batch process reduces throughput; the large quantities of inert gas required are expensive; energy-intensive electrolyte evaporation and gas scrubbing involve high costs; discharge is required prior to mechanical processing.
Vacuum	**Resource recovery:** Electrolyte VOCs can be recovered in the evaporation process. **Health and safety:** Suppressed oxygen allows processing without a risk of fire; HF formation is prevented due to the absence of moisture in the environment.	**Energy usage:** Significant energy is needed to form a vacuum. (Note: There is reduced energy use for electrolyte drying, as low pressure lowers the evaporation point.) **Economic feasibility:** Batch process reduces throughput.
Alkaline solution submersion	**Economic feasibility:** Continuous processes increase throughput; no preceding discharge step is required. **Health and safety:** An oxygen-free solution eliminates the risk of fire; no hazardous dust is released; there is no HF risk if electrolyte salt reacts to form stable compounds; there is no risk of fire.	**Resource recovery:** Lithium reacts with water and can be lost if further recovery steps and a closed-loop water system are not applied. **Water use and discharge:** There is a risk of organic wastewater pollution if a closed-loop water system is not used; the effluent requires cleaning.

Thermal pre-treatment proves advantageous for resource recovery by breaking down organic materials and liberating valuable cathode metals. This step also eliminates health and safety risks from residual charges by deactivating batteries (if cells and modules are being treated), as the electrolyte is removed via evaporation. Therefore, some recyclers may choose to omit discharge from the preparation phase, leveraging this dual benefit and reducing the number of treatment steps required. Additionally, it is possible to recover the electrolyte VOCs from the gas phase, thus boosting the mass balance recovery rate. However, environmental and health risks arise from thermal pre-treatment as a result of the emissions that may be released, including VOCs, HF and CO_2.

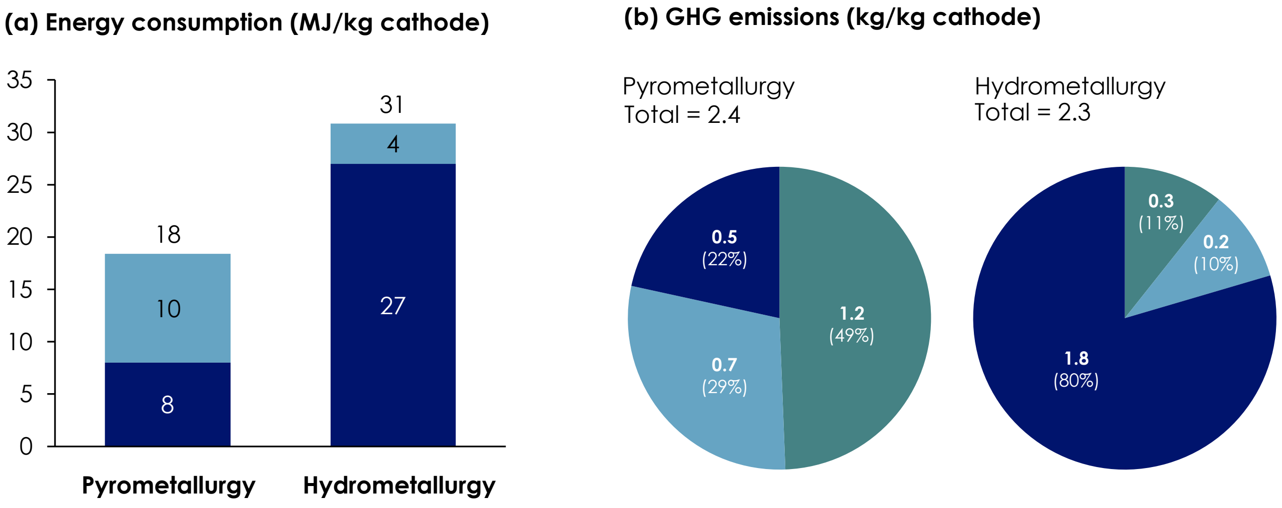
4.1.3 Main treatment phase

	◆ **Potential benefits**	● **Potential risks**
Pyrometallurgy	**Economic feasibility** is enhanced by the flexibility to accommodate diverse feedstocks (eg, different ages, chemistries and pre-processing depths). The rate for critical metals is high (>95% for nickel, cobalt and copper), which boosts operational profitability.[11],[62],[71] **Health and safety** risks are limited as hazards are contained within the furnace, limiting worker exposure.[53]	**Resource recovery** of the overall battery mass suffers due to graphite burning and loss of the electrolyte (these components respectively account for ~20% and ~10% of the total battery mass.[50] Recovered metals (nickel, cobalt and copper) are in the form of metallic alloys, and lithium, aluminium and manganese enter the slag – both of which require further hydrometallurgical treatment to produce battery-grade salts, necessitating significant additional resource input.[16],[17] **Solid waste** (slag) generated may be contaminated, posing environmental and health risks (eg, toxic metals such as nickel and cobalt). Some recyclers may engage in improper disposal methods, such as discarding into waste dumps, if there is limited access to engineered landfills (more common in emerging economies).[70] **Emissions to air** released in exhaust gas can contribute to environmental harm (eg, VOCs/HF – see thermal pre-treatment risks in Chapter 4.1.2 for more detail). Combustion emissions contribute to climate impact: one LCA found that combustion accounted for ~50% of the total GHG emissions of the pyrometallurgy process (see Figure 18 for LCA results).[72] **Energy usage** is high due to the continual heating process – processing energy was found to account for 30% of GHG emissions in the LCA shown in Figure 18.[72] **Health and safety** risks arise from the consequences of VOCs and HF emissions, as highlighted above.

	◆ **Potential benefits**	● **Potential risks**
Best practices	• Proactively explore potential reuse options for slag (eg, road construction).[58] Where reuse is not feasible, ensure proper disposal through appropriately engineered landfill. • Implement emissions control measures for exhaust gas that adhere to the highest environmental and health protection standards. • Minimise the direct release of GHGs from furnaces and utilise carbon capture technology for exhaust emissions. • Ensure that energy used for heating is from biofuels and renewable sources where feasible.[73] • Include a processing step for the recovery of lithium (eg, hydrometallurgical treatment of slag; novel techniques for lithium separation via evaporation applied at an earlier stage of the operations (not yet industrialised)).[55]	
Hydrometallurgy	**Resource recovery** potential is good, as the process can yield high recovery rates for battery-grade materials (metal losses are less than for cobalt, copper and nickel).[50] Facilities can be designed to accommodate black mass produced from many cathode chemistries, increasing versatility.[71],[74]	**Economic feasibility** of recovering battery-grade materials is contingent on input demand (eg, reagents, water and energy) and the value of output. So far, valuable cathode materials such as nickel and cobalt are often restored to battery-grade quality; while other valuable metals such as lithium and manganese may only be processed to battery grade by refiners making use of greater economies of scale (eg, via co-production), as the additional expenses associated with further refinement are not currently offset by the output generated in traditional battery recycling methods. **Auxiliary material** input is high, as significant volumes of acids and bases are required in the leaching process.[62] Reagent production requires high energy usage and generates GHGs, resulting in a large upstream carbon footprint:[58] one LCA found that the input materials contributed ~80% of the emissions from the recycling process studied (see Figure 18).[72] **Water use** and **water discharge** are inherent challenges for aqueous chemical processes due to high consumption and waste:[71] one study found that ~3.76 litres of wastewater are produced per kilogram of battery.[16] Environmental and health risks arise due to the potential contamination of water from acids and high-hazard-class battery materials (eg, nickel and cobalt).[11],[70] **Solid waste** is generated from by-products of the leaching and purification processes (eg, sodium sulphate). These compounds are generally non-toxic, so landfill disposal is an option; but their high solubility and quantity can complicate finding suitable sites. Some recyclers choose ocean disposal, which can harm marine ecosystems by altering water pH levels.[75]

Best practices	
	- Maximise the recovery of outputs for recycling beyond cathode metals (eg, electrolyte). - Select reagent suppliers based on sustainability criteria, prioritising chemicals with a lower carbon footprint. - Reduce reagent use through the design of a circular flowsheet that regenerates acids and bases where possible.[75] - Implement strategies to minimise water consumption in aqueous processes, ideally creating a closed water loop; if that is not feasible, adhere to high treatment standards.

Figure 18: LCA findings for (a) energy consumption and (b) GHG emissions of hydrometallurgical and pyrometallurgical recycling processes (adapted from[72])



Summary

Pyrometallurgy is a well-established refining technique that offers high recovery rates for critical metals such as nickel, cobalt and copper. It has well-defined safety protocols, ensuring relatively low health and safety risks. It also accommodates a wide range of battery chemistries, ages and pre-processing depths (eg, modules, cells and black mass), enhancing scalability. Accommodating heterogeneous feedstocks will become increasingly important as post-consumer content becomes the dominant source of LIB material sent for recycling, rather than the relatively homogeneous pre-consumer material that accounts for the greater share today.[56]

However, there are also challenges associated with material recovery through this treatment. Some materials are burned (eg, graphite), reducing overall mass recovery rates; metals are recovered in the form of alloys, requiring further processing to reach battery grade; and lithium and manganese are lost to the slag output. It is possible to recover lithium and manganese through hydrometallurgical treatment of the slag; however, significant additional resource input and operational expenditure are required to do so, meaning that it may be more advisable to attempt lithium recovery at an earlier stage of the process through novel evaporation techniques.[55]

Slag and exhaust emissions also pose environmental risks, demanding proper treatment and containment. Combustion emissions released in exhaust gas are a particular concern due to their contribution to climate change effects.[72]

The economic feasibility of pyrometallurgy is significantly influenced by battery chemistry: while it is viable for chemistries with high nickel and cobalt content, the growing adoption of LFP batteries reduces its profitability.[76] This, coupled with lithium recovery quotas in the EU, may call into question the continued relevance of this technology for LIB recycling.

Hydrometallurgy can yield high-quality battery materials at excellent recovery rates. However, the grade of the recovered materials must be balanced with higher demand for auxiliary resources and increased operational cost and environmental impact. The demand for reagents significantly contributes to the process carbon footprint, as the production of acids and bases is an emissions-intensive process.[58],[75] Enhancing resource recovery may be decoupled from a larger process carbon footprint through careful chemical supplier selection and circular approaches such as reagent regeneration.[75]

The aqueous nature of this process results in high water demand; and the hazardous battery components and reagents used in the treatment present a risk of wastewater contamination. Reducing water intensity and addressing water discharge concerns require comprehensive treatment strategies, ideally aimed at process water recycling and a closed water loop. However, wastewater treatment can be a complex, energy-intensive and expensive process; so the optimal strategy is to reduce overall water use.[62] This can be done, for example, by optimising the leaching process to increase the solid-to-liquid ratio.[75]

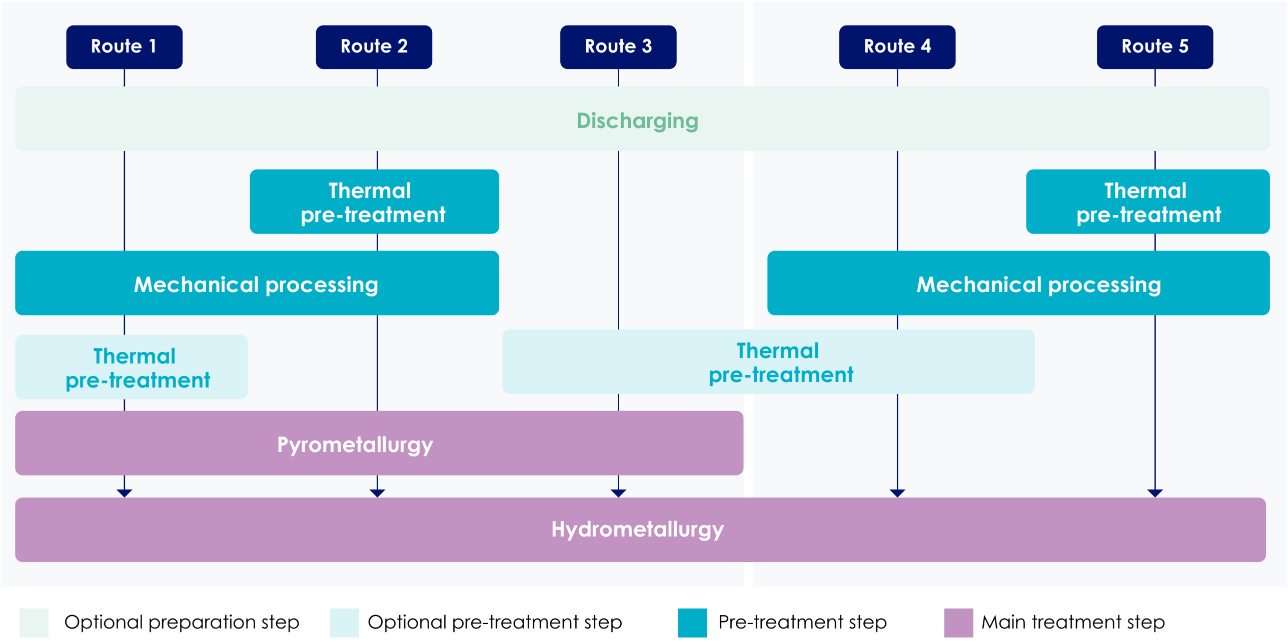
Finally, dealing with large volumes of by-products, such as sulphate compounds, involves weighing disposal and reuse options to minimise environmental impact. Best practice would involve recyclers taking a proactive approach to this waste management issue, selecting reagents that produce by-products with better reuse applications (eg, opting for ammonia-based reagents instead of sodium or calcium-based reagents can yield ammonium sulphate, which holds value in the fertiliser industry).

4.2 RECYCLING ROUTES

Sustainability considerations extend beyond the inherent characteristics of individual operational steps: their sequencing can also introduce unique risks and benefits. Particular 'route features' (referring to specific attributes of a recycling route) can trigger sustainability implications for other phases of the recycling process.

4.2.1 Route Feature A – Exclusion of dismantling

Figure 19: Archetypal industrial battery recycling routes that exhibit Route Feature A



Trade-off: Scalability is improved as the slow manual treatment step is avoided; but resource demand and waste production of subsequent processes may increase.

◆ Potential benefits

Excluding the dismantling process from LIB battery recycling removes the need for manual processing, **improving the health and safety** of workers as exposure to hazardous materials is reduced. Additionally, the potential risks of fire and explosions resulting from human error are mitigated. The elimination of manual dismantling means that a key process bottleneck is avoided, resulting in higher throughput and increased scalability. This factor, combined with the additional benefit of lower labour costs, means that the exclusion of dismantling may contribute to a **more economically streamlined** recycling process.

● Potential risks

Exclusion of the dismantling step can **increase the energy use and cost** of the pre-treatment phase. In the absence of preliminary dismantling, the battery housings and casings must also be processed through mechanical shredding. These components are typically made from robust materials such as aluminium and steel, and so require high energy input for crushing and opening. More powerful shredding equipment may be necessary, entailing greater capital expenditure; and the thermal pre-treatment processes also have a higher energy demand, given the larger mass requiring heating.

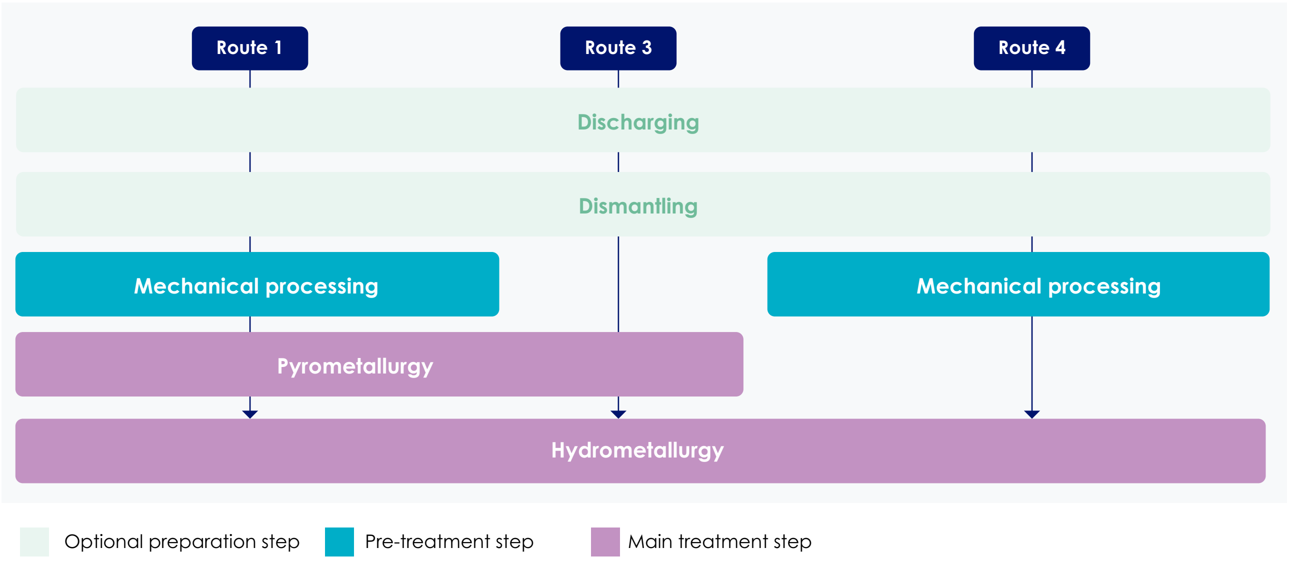
The sustainability of the main treatment phase is also impacted. With fewer non-active materials extracted during the initial phases, recycling routes involving pyrometallurgy yield **increased quantities of solid waste**, as the impurities are sent to the slag. The presence of more impurities increases the processing burden for hydrometallurgical treatment. The greater mass of material that requires separating translates to **higher auxiliary material input** (ie, larger reagent volume) and **greater operational cost**. A TEA of different hydrometallurgical processes revealed that when dismantling is used in hydrometallurgical recycling routes, cost savings (compared with the use of virgin materials) could be in the range of 20%-50%. However, when no dismantling was applied, cost savings were generally <20%. This was primarily a result of recycling routes without dismantling requiring a more expensive hydrometallurgy process. However, these savings do not account for the cost of the dismantling step and therefore may not reflect the true economics of an industrialised process. Therefore, the actual cost advantages of dismantling will rely on the development of cost-effective, semi-automated dismantling techniques. Innovations in automated dismantling also have the potential to decrease reliance on mechanical processing and facilitate a more sustainable approach to separating battery materials, as there is less risk of material loss and the output material streams are purer.[56]

Table 3. Final products, net profits and cost savings of eight hydrometallurgical processes (cost savings are relative to the cost of virgin material use)[56]

Route	Final products (purity, %)	Gross profit	%Cost savings
No dismantling			
I	MnO_2, $Fe_2(SO_4)_3$, $CuSO_4$, $CoSO_4$ (<98), Li_2SO_4	-0.19 - 0.94	-2-9
II	MnO_2 / Mn_2O_3 (99), Li_3PO_4 (99), $FeCl_3$ (98)	0.19 - 1.35	2-13
III	Co (99), Mn)$_2$ (96), Li_2CO_3	1.13 - 1.61	13-16
IV	Li_2CO_3 (100), $MnSO_4$ (100), $CoSO_4$ (100), $NiSO_4$ (100)	0.58 - 1.81	6-18
V	$Cu(OH)_2$, $Al(OH)_3$, $CoCO_3$, Li2CO$_3$, $NaCl_2$, MnO_2/Mn_3O_4	0.94 - 1.87	9-19
Dismantling			
VI	Li_2CO_3 (100), NMC111, $Al(OH)_3$	3.05 - 5.37	31-54
VII	Li_2CO_3 (99.9), NMC111	2.66 - 5.27	27-53
VII	NMC111, mixed hydroxides, Li_2CO_3	2.06 - 3.7	21-37

4.2.2 Route Feature B – Exclusion of thermal pre-treatment

Figure 20: Archetypal industrial battery recycling routes that exhibit Route Feature B



Trade-off: Energy usage and operational cost are reduced prior to main treatment; but lower recovery rates may result, as the critical metals are not entirely liberated from their supports.

◆ Potential benefits

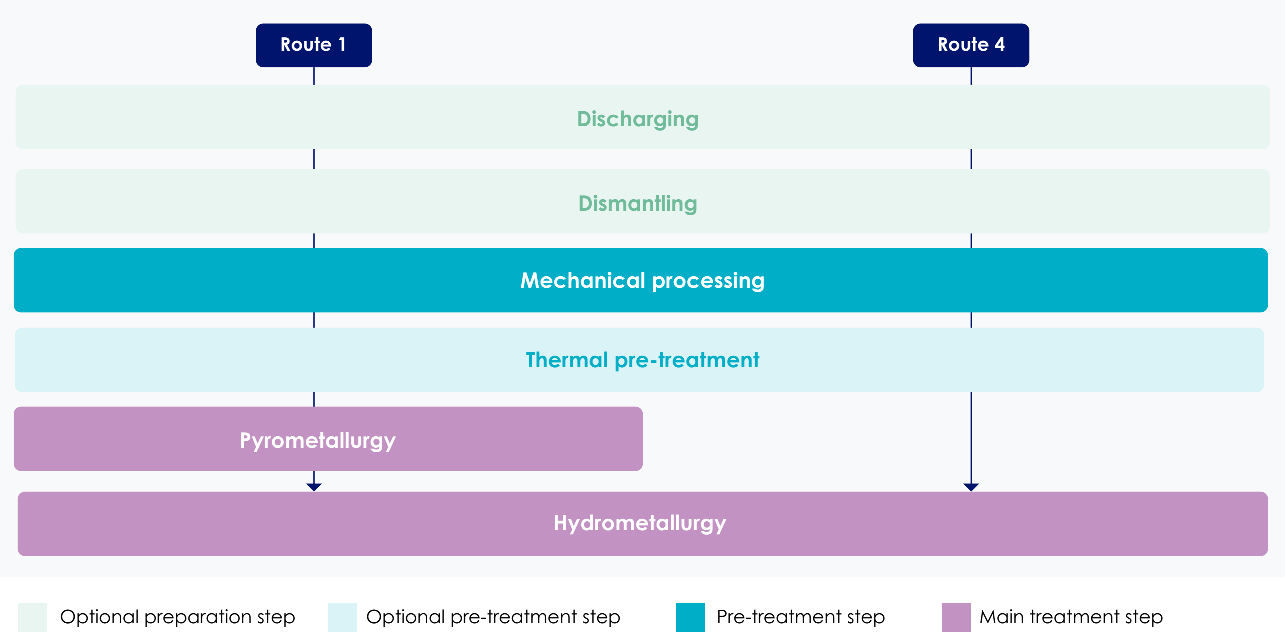
Some recyclers may choose to bypass thermal treatment, avoiding this complex and capital-intensive process, which requires comparatively high throughputs to be economically feasible.[11] Excluding thermal pre-treatment can yield sustainability advantages such as **reduced energy consumption, emissions** and **expenses** compared with high-temperature processes.

● Potential risks

Omitting thermal pre-treatment may **impact the resource recovery rate** of the valuable cathode active materials. The binder (PVDF) which holds the active materials to the carbon conductive agents and fixes them to the foils creates strong bonds that cannot be destroyed through purely mechanical processing.[11] Therefore, some active material is lost to other output fractions in the mechanical separation process and the yield of black mass is reduced – in some cases with a loss of up to 60%.[47] To avoid these losses, the foil material must remain within the black mass fraction and undergo subsequent main treatment procedures. Consequently, the main treatment processes may require specific parameter adjustments to facilitate the extraction of the foil material (eg, copper) and manage contaminants (eg, the binder). Routes employing pyrometallurgy in the main treatment exhibit flexibility in this regard, as copper becomes part of the alloy output; although **energy usage may increase** as a greater mass requires heating. Hydrometallurgy processes may **require additional auxiliary material input** (reagents) to handle lower concentrations of active materials. In this case, end-to-end operations could be beneficial, as the main treatment could then be tailored to the impurity profile generated in the mechanical processing step and be optimised for enhanced resource efficiency and recovery.

4.2.3 Route Feature C – Thermal pre-treatment after mechanical processing

Figure 21: Archetypal industrial battery recycling routes that exhibit Route Feature C



Trade-off: Energy usage is lowered for the thermal pre-treatment step, as a smaller mass requires heating; but the recovery rate of critical metals may be lower and the discharge benefit of thermal pre-treatment is not leveraged.

◆ Potential benefits

When thermal pre-treatment is used after mechanical treatment, the processes can benefit from **reduced energy consumption**. After mechanical treatment, some mass fractions can be separated from the shredded material (eg, aluminium and copper), meaning that less mass requires heating in the thermal pre-treatment of black mass.

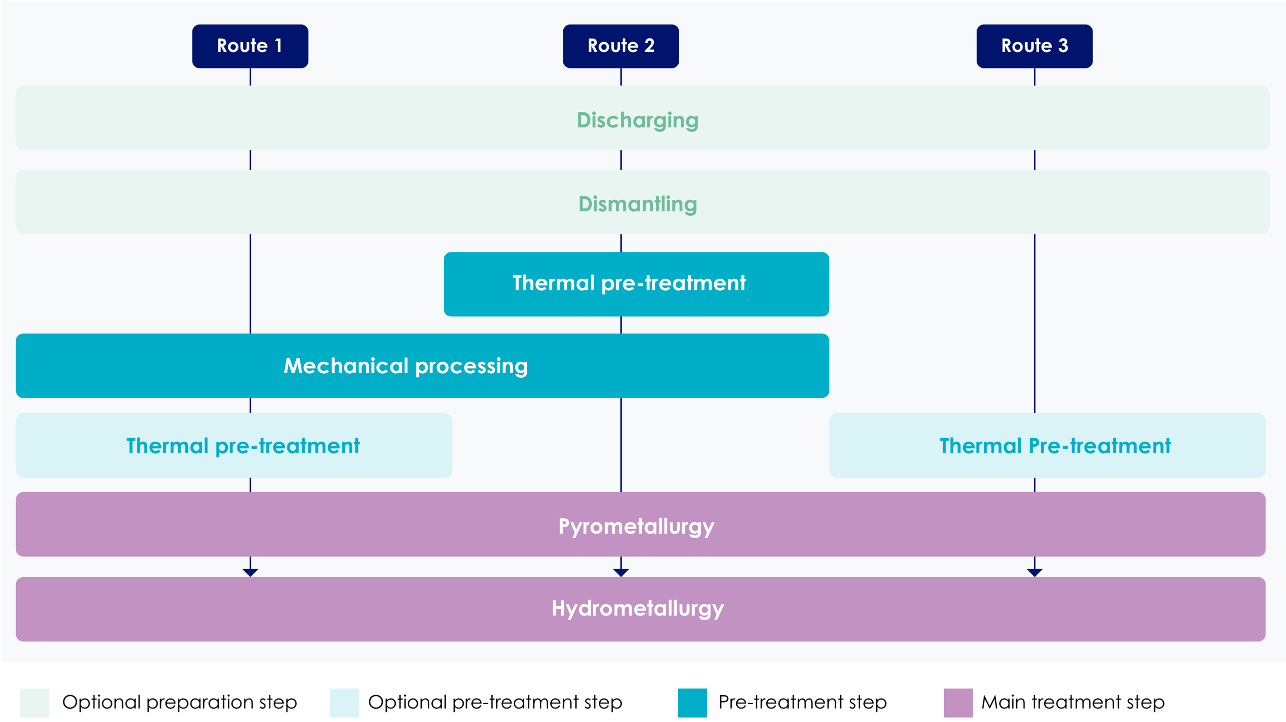
● Potential risks

The drawbacks of using thermal treatment after mechanical treatment are primarily related to the **reduced efficiency of the recycling route**.

Thermal pre-treatment offers the dual benefit of releasing the active material by breaking down binders and deactivating a cell by removing the electrolyte. By not using thermal treatment prior to mechanical processing, this twofold advantage is not leveraged and the battery must be discharged and rendered safe by other means. One option is for the cell to be discharged in a preparation step (eg, through aqueous solution discharge or energy recovery). Alternatively, the mechanical process must allow for in-situ deactivation and apply specific safety measures to prevent explosion and ignition (eg, submerged shredding).[11]

4.2.4 Route Feature D – Use of pyrometallurgy in combination with hydrometallurgy

Figure 22: Archetypal industrial battery recycling routes that exhibit Route Feature D



Trade-off: The recovery rate is enhanced when lithium is reclaimed from slag; but additional primary resource input is required (eg, reagents, energy, water).

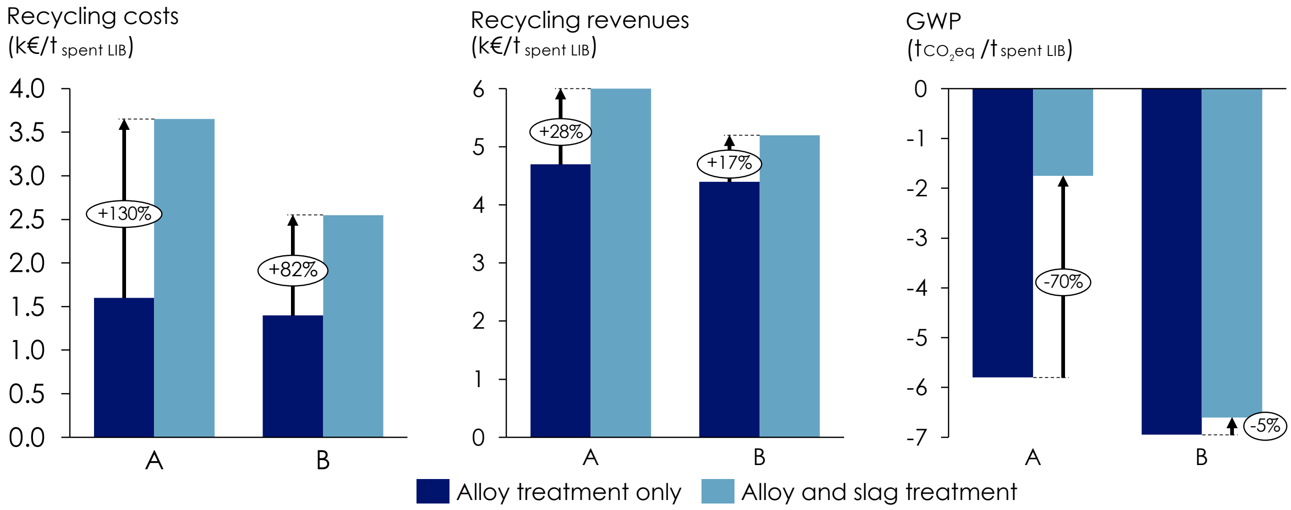
◆ Potential benefits

The use of pyrometallurgy prior to hydrometallurgy treatments can **decrease energy usage** in pre-processing, **reduce auxiliary materials input** in subsequent processing and **improve some aspects of resource recovery**. As pyrometallurgy can accept heterogeneous feedstocks, no pre-processing is required. Therefore, by omitting pre-treatment steps, energy usage prior to main treatment is significantly reduced. Additionally, the production of a homogeneous alloy intermediate reduces reagent usage in the hydrometallurgy refining step, due to limited contaminants and thus a higher concentration intermediate. Finally, losses that occur in the production of black mass via mechanical processing can also be avoided, potentially increasing the overall recovery rate.

● Potential risks

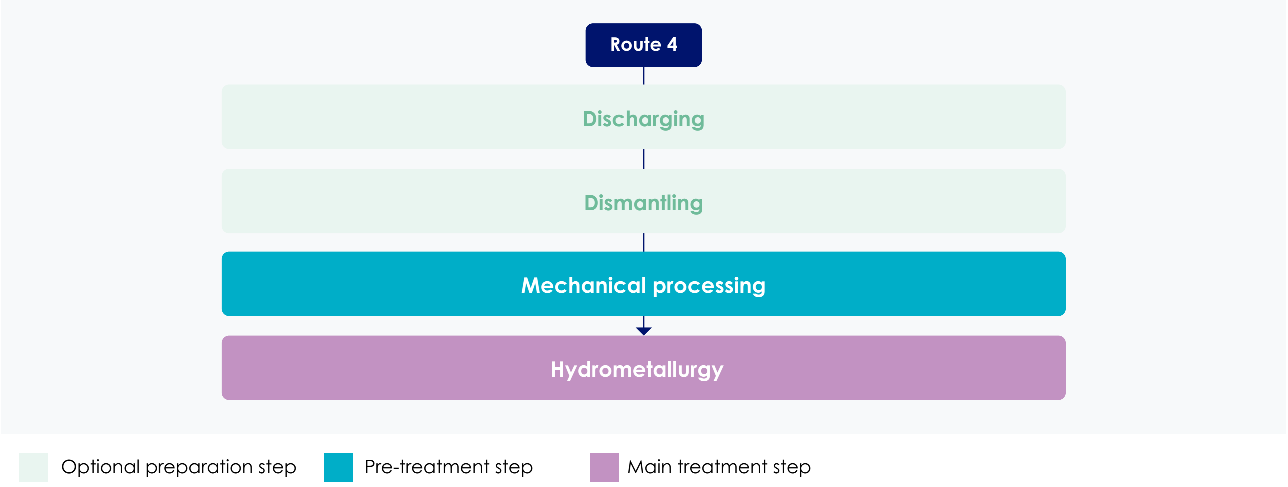
The use of pyrometallurgy can result in a **poor resource recovery rate for cathode active materials**, as lithium and manganese are lost to the slag. If the slag is treated by hydrometallurgy, the recovery rate can be improved; but the **cost increases** as larger material flows require processing, corresponding to **increased demand for infrastructure, operating resources and energy.**[55] One LCA found that the use of hydrometallurgy to treat the slag in addition to the alloy results in higher processing costs and reduces the climate benefit of recycling (see Figure 23). Nevertheless, recycling revenues do increase as a result of the additional value recovered from the materials in the slag. Additionally, the study showed that using pre-treatment prior to pyrometallurgy results in a smaller cost and emissions increase, as non-cathode mass is removed early and the hydrometallurgical burden is reduced.[55]

Figure 23: LCA study results for two routes: A - Discharge > Dismantling > Pyrometallurgy > Hydrometallurgy (Route 3 in Figure 22); B - Discharge > Dismantling > Thermal Pre-treatment > Mechanical processing > Pyrometallurgy > Hydrometallurgy (Route 2 in Figure 22) (adapted from[55])



4.2.5 Route Feature E – Exclusion of all thermal steps

Figure 24: Representative industrial battery recycling routes that exhibit Route Feature E



Trade-off: The recovery rate is boosted and climate impact can be improved, as anode material (graphite) is not burned and can instead be recovered; but recovery options can be expensive and resource intensive.

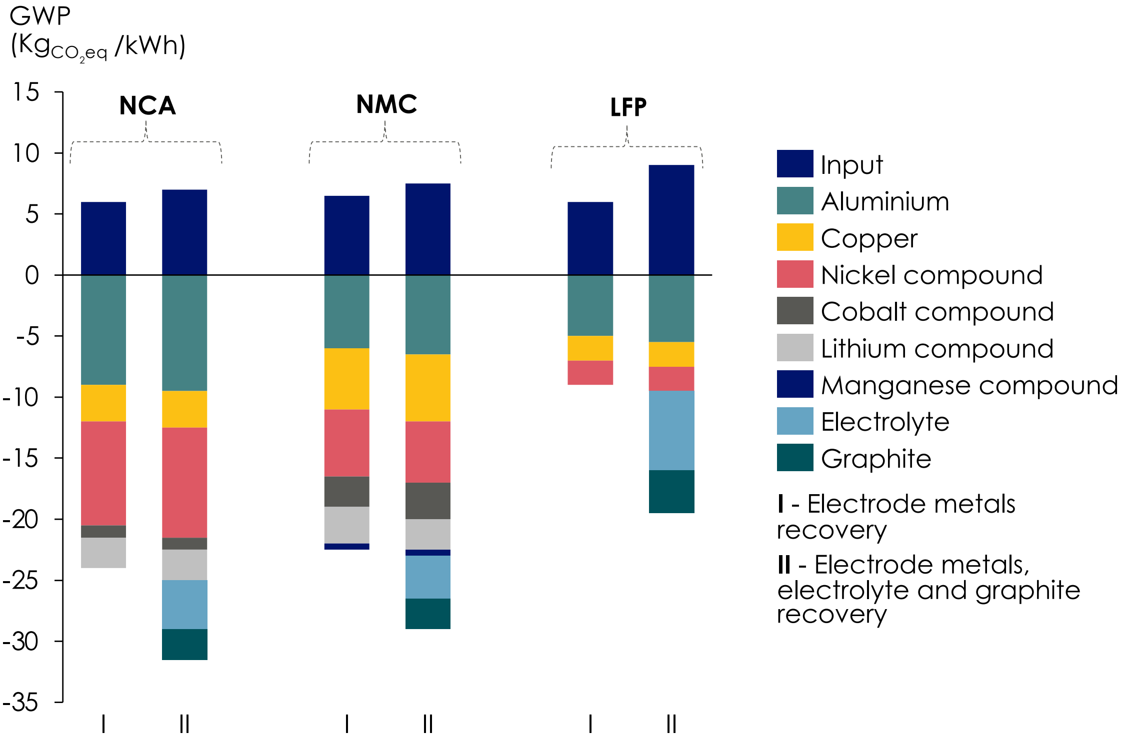
◆ Potential benefits

Recycling routes that do not include thermal pre-treatment or pyrometallurgy can achieve **high recovery rates** (~73% and higher).[50] By avoiding these thermal processing steps, the anode material (graphite) is not burned, allowing for its recovery. Reclaiming graphite not only benefits the circular economy, but also can improve the climate impact of batteries. One LCA study found that when recycling NCA, NMC and LFP LIBs via a route that does not include thermal steps, the additional emissions impact created by graphite (and electrolyte) recovery is outweighed by the benefits (see Figure 25). For LFP chemistries, the net benefit of additional recovery is notably lower than for other LIBs, as the impact avoided is lower when nickel and cobalt are not present.[64]

● Potential risks

While a very high overall mass yield is theoretically achievable, the industrial recovery of graphite is **dependent on economic feasibility.**[50] The lower value of graphite often does not justify the cost of the additional resources required to recover it. Despite this, there are multiple reuse applications for secondary graphite, including returning it to battery-grade graphite; using it in the lubricant industry in the form of graphene; and pelletising it for use as a secondary energy source. Some of the recycling or reuse techniques for these outputs may lead to additional climate impacts, as they are energy intensive. In this case, recyclers should conduct an LCA to ensure that recovery does not lead to negative environmental impacts.

Figure 25: Global warming potential of hydrometallurgy with two recovery processes (I and II) for the treatment of three LIB cathode chemistries.



Note: Negative values indicate net benefits (reduction of impacts due to recovered materials); positive values are environmental impacts (due to inputs for the recycling process)

Summary

Our findings indicate that while a wide range of recycling routes is available, specific attributes within those routes – such as the sequencing of steps or the inclusion/exclusion of particular treatments (‘route features’) – can lead to trade-offs, as optimising one aspect of sustainability may inadvertently have adverse effects on another. For instance, achieving higher product quality and quantity often results in increased primary resource inputs, such as greater energy, water and auxiliary materials usage.

As a guiding principle, recyclers should optimise operational parameters through data-driven analyses such as LCAs. This approach ensures that enhanced material grade does not translate into elevated emissions or negative environmental impacts. Chapter 7 provides an overview of this and other key principles for establishing sustainable practices in industrial battery recycling.

CHAPTER 5

ENABLERS TO IMPLEMENT AND SCALE SUSTAINABLE BATTERY RECYCLING

5. ENABLERS TO IMPLEMENT AND SCALE SUSTAINABLE BATTERY RECYCLING

Key enablers to implement and scale sustainable battery recycling processes include investment and innovation; information access and sharing; recycling-related targets; environmental footprints and recycling standards; and skills and jobs in the recycling industry. This chapter introduces these key enablers. Practical recommendations for policy makers and industry leaders to implement these enablers are presented in detail in **Annexes IX** to **XV.**

CHAPTER 5 KEY TAKEAWAYS

There are six key enablers for sustainable battery recycling operations:

1. **Investments and R&D in battery recycling should adhere to strict sustainability criteria.** As the industry is experiencing rapid growth and innovation, it is crucial to prioritise sustainability now to avoid the need for costly retrofitting later.
2. **Safe, sustainable and efficient battery recycling relies on the availability of comprehensive information at various levels.** Information on (EoL) batteries in circulation, battery characteristics and recycled content can facilitate high collection rates, support safe and efficient sorting and dismantling, and encourage the use of secondary materials.
3. **Recycling targets can help to scale the recycling industry and ensure a high level of material recovery and recovered material quality.** Potential targets include battery collection, recycling, recovery and recycled content targets.
4. **Standards and certifications play an important role in defining and expanding sustainable battery recycling practices.** Areas requiring standards relate to the environmental, health and social impacts of battery recycling; the quality of black mass; recycled content and recycling; and supplier due diligence, including secondary material provenance.
5. **Quantifying sustainability benefits through environmental footprints – such as GHG emissions reductions achieved through the use of recycled materials – encourages recycling, the use of recycled content and the mitigation of recycling impacts.** A consistent framework is needed to calculate recycling footprints.
6. **New jobs and skills are needed to scale sustainable battery recycling.** This is crucial due to the associated health, safety and environmental risks; as well as long-distance transportation to regions with less stringent safety and sustainability practices.

Both the private and public sectors have a role to play in unlocking these enablers and should collaborate to achieve optimum outcomes. In this chapter, we introduce current best practices; present policy and industry examples across different regions and industries; and highlight areas for further improvement.

5.1 INVESTMENT AND INNOVATION

Investment and R&D in battery recycling should adhere to strict sustainability criteria. As the industry is experiencing rapid growth, with significant investments and R&D activities, it is crucial to prioritise sustainability now to avoid the need for costly retrofitting later. By the end of 2023, the value of the LIB recycling market in terms of sales revenues is projected to have increased more than fivefold compared to 2022.[25] In Europe, Strategy& and PEM forecast investments of €2.2 billion by 2030 and an additional ~€7 billion by 2035.[5] Sustainable and efficient scaling can ensure high recovery rates, minimal energy and material usage, a focus on safety and prevention of socially and the environmentally adverse impacts. Therefore, sustainability in the innovation and investment agenda – both public and corporate – should be prioritised.

Recommendations for policy and industry to support investments in sustainable battery recycling are set out in **Annex IX**. As for any investment, the challenges of trade-offs and the speed of technological change must be kept in mind, as outlined for battery recycling in Information Box 5.

INFORMATION BOX 5: CHALLENGES IN IDENTIFYING SUSTAINABLE BATTERY RECYCLING INVESTMENTS

- **Innovation and investments in sustainable battery recycling technology or infrastructure may involve trade-offs.** For instance, innovations to enhance battery energy density and packaging could undermine circular design principles, hindering disassembly and recycling. Innovation should strive to address and mitigate such trade-offs, with support from well-designed policies and financial aid.[15]

- **Battery chemistries evolve** fast due to technological advances, shifting consumer preferences and environmental considerations. NMC and LFP batteries currently predominate and will thus account for most EoL batteries from 2030 onwards. However, it may take five to 10 years before the prevailing chemistry becomes apparent. The battery market offers first-mover advantages but is unpredictable, making returns uncertain. Therefore, when investing in battery recycling technology, consider the current 10-year EoL trajectory and the development of new chemistries to ensure strategic timing and investment decisions. Maintaining a reliable source of EoL batteries is vital to avoid building excessive, unprofitable recycling capacity.[15],[77],[78]

R&D for sustainable battery recycling

Innovation is crucial in building and scaling a sustainable battery recycling system. Key measures to promote sustainable battery recycling are presented in Information Box 6.

Levers and examples for policy makers and industry leaders to accelerate R&D and promote innovation in sustainable battery recycling are outlined in **Annex X**.

INFORMATION BOX 6: KEY MEASURES TO PROMOTE SUSTAINABLE BATTERY RECYCLING INNOVATION

- **Enhancing existing recycling methods** can improve efficiency, quality and closed-loop potential, reducing waste, material use and adverse environmental impacts. Research has investigated economically feasible electrolyte and lithium recovery and anode material longevity through surface modifications.[83],[84] Investment in carbon-neutral recycling equipment investment minimises the GHG footprint, while safe disassembly tools reduce hazards for workers.[6],[15]

- **Novel recycling technologies** with higher recovery rates and quality are crucial, even for lower-value materials. Exploring the potential of direct recycling can enable the recovery of high-value material and make LFP recycling financially and environmentally beneficial. However, this may be constrained if direct recycling remains limited to production scrap.[6],[71],[83]

- **The development of per- and polyfluoroalkyl substance (PFAS)-free LIBs** is essential due to the PFAS restriction proposal issued by the European Chemicals Agency in 2023. Manufacturers should innovate for alternatives to PFAS and emission mitigation during recycling. PFAS are a large class of synthetic chemicals that are categorised as environmental pollutants and may have negative effects on human health.[85]

- **Exploring automation** for disassembly, cell opening, processing and sorting can improve safety, efficiency and material purity when dealing with large volumes of EoL LIBs. This will require enhanced battery design and improved data availability.

5.2 INFORMATION ACCESS AND SHARING

Safe, sustainable and efficient battery recycling relies on the availability of comprehensive information at various levels:

- **Information on battery volumes in circulation can prevent batteries,** especially those at EoL, from escaping the recycling system and enable the clear allocation of EoL responsibilities.

- **Information on battery characteristics can enable safe and sustainable collection and recycling.** To ease battery return, widely available information on collection points is important. Information on static battery characteristics (eg, materials, hazards, repair and dismantling guidance, safety protocols) and dynamic battery characteristics (eg, condition, charge, state of health, usage history) supports safe, efficient and sustainable processes (eg, sorting, transportation, dismantling and recycling). Providing a dismantling guide and hazardous substance information can save time and labour and mitigate safety risks during dismantling. Disclosing the battery composition minimises sampling and sorting costs and streamlines recycling processes by creating homogenous material streams, thus reducing costs and chemicals usage, and enhancing material recovery.

- **Information on battery recycled content** encourages the use of secondary materials over primary materials and aligns with the goals of reducing carbon footprints and adhering to recycling targets, whether mandated or internally set.

Annex X outlines recommendations to enhance the accessibility of important information for sustainable battery recycling and promote information-sharing practices.

5.3 TARGETS, STANDARDS AND FOOTPRINT ASSESSMENTS

Ambitious targets, footprint calculation rules and standards are important drivers for sustainable battery recycling. For instance, recovery targets can boost recycling efficiency; while recycling standards can ensure safe, high-quality recycling processes. As an example, a mandatory carbon footprint can incentivise the use of recycled content and reduce emissions from recycling processes.

Recycling targets

Binding recycling targets can help to scale the recycling industry while ensuring that material recovery and secondary material quality are high, and that secondary materials can be continuously recycled and reused. Before ambitious targets can be established, clear definitions and unambiguous system boundaries are needed. Targets should be developed collaboratively by industry and policy makers to ensure both ambition and feasibility. Effective enforcement mechanisms – such as certifications for recycled content or audits of recycling facilities – are important; as are incentives or penalties (eg, tax relief for compliance or fines for non-compliance).

Alongside recycling targets for EoL batteries, regulations on battery reuse and design for circularity are needed to ensure true circularity of batteries, as outlined in Chapter 6.

Annex XII provides a summary of recommendations for policy makers and examples of three recycling targets.

Standards for battery recycling

Standards play an important role in defining and expanding sustainable battery recycling practices. Typically, third-party supply chain assurances demonstrate (eg, via certifications) that supply chain practices adhere to agreed standards. To be effective, standards must be credible and based on ambitous benchmarks. Draft principles for high-quality supply chain schemes, as outlined by the Battery Pass Consortium,[36] are presented in Information Box 7. Collaborative efforts involving technical experts, industry and governmental bodies are essential to develop appropriate standards. To ensure global consistency and create a level playing field, standards should be applied and enforced worldwide, requiring harmonisation efforts between various regulatory systems and governments.[43]

INFORMATION BOX 7: DRAFT PRINCIPLES FOR SUPPLY CHAIN SCHEMES, AS OUTLINED BY THE BATTERY PASS CONSORTIUM[99]–[102]

- **Stakeholder representation:** Civil society and the Global South should be fairly represented on the decision-making boards of supply chain schemes; and audits should encompass external stakeholders and all rights holders.
- **Verification:** This includes credible (ideally site-specific) third-party verification and assessment processes; certification upon successful verification; transparent and detailed communication of audit results; an independent oversight mechanism; and an issues resolution system.
- **Themes covered:** Standards should cover a broad range of sustainability themes to encompass all impact categories of relevance for battery materials.
- **Common references:** To facilitate equivalence between standards and mutual recognition, common references such as ISO 14001, ISO 45001/OHSAS 19001 should be followed.

To implement these principles, supply chain schemes can participate in, and be approved by, organisations such as the International Social and Environmental Accreditation and Labelling Alliance – a global membership organisation for credible sustainability standards.[103]

To promote and scale sustainable battery recycling, standards and certifications are required in three critical areas:

1. **Sustainable recycling:** Standards addressing the environmental, health and social impacts of battery recycling are essential to reduce risks such as fire hazards, electrical charges or toxic components. Global implementation of these standards is necessary to prevent the externalisation of adverse external impacts, such as the export of EoL batteries to less regulated regions. The mandatory and widespread adoption of sustainable battery recycling standards can create competitive advantages for compliant recyclers. While stringent standards are important, excessive administrative burdens should be avoided.[15],[104],[105]

2. **Black mass, recycled content and recycling quality:** Developing and harmonising global quality standards for black mass composition can enable closed-loop recycling and safe handling. Standards can also help to create reliable markets. Recycling process standards can ensure high recovery rates while creating a level playing field, despite the potential additional costs.[6],[15],[90],[105],[106]

3. **Supplier due diligence, including secondary material provenance:** When procuring EoL batteries or black mass, suppliers should be carefully verified to ensure that the materials have caused no adverse social and environmental impacts. In doing so, established safety and environmental standards should be followed. Certifications are needed to verify the origin of secondary battery materials, preventing the false labelling of primary materials as secondary. This will ensure compliance with recycled content goals and help to prevent the use of materials from conflict-affected areas or uncertified mines.

Detailed recommendations and examples for these standards are provided in **Annex XIII.**

Battery footprint calculation rules and implementation

Quantifying sustainability benefits (eg, GHG emissions reductions) from the use of recycled materials through environmental footprints encourages recycling and the use of recycled content. Communicating these benefits as part of their sustainability reporting can be valuable for companies. The quantification of sustainability benefits can be further incentivised through emissions trading (eg, carbon pricing) or caps (eg, carbon thresholds). Environmental footprint data also facilitates the benchmarking of recycling processes to identify more sustainable practices. At present, however, granular benchmarking is limited by a lack of available data and analysis (eg, in the form of LCAs).[83]

A consistent framework is needed to calculate recycling footprints. While various impact categories exist, the carbon footprint – focused on GHG emissions – has received the most attention. See **Annex XIV** for recommendations, using the carbon footprint as an example.

5.4 SKILLS AND JOBS

In the evolving EV battery recycling sector, new roles and skills are necessary to mitigate the associated health, safety and environmental risks of battery recycling. Technical expertise in transport, disassembly, diagnostics, testing and recycling processes is increasingly required. Knowledge of battery design optimisation, regulatory compliance and education and communication is also important.

The impact of automation and industry changes in the automotive and battery sectors makes future job outcomes uncertain. The World Economic Forum[3] suggests that 10 million global battery-related jobs will be created by 2030; the Boston Consulting Group[110] predicts a net balance of job losses and gains; and the European Association of Automotive Suppliers[110] projects a net loss of auto-industry jobs, mainly between 2030 and 2035. Irrespective of the exact numbers, new types of skills will be needed for safe, efficient and sustainable battery recycling. Recommendations to facilitate skills and job creation are summarised in **Annex XV.**

CHAPTER 6

CIRCULAR ECONOMY PRACTICES FOR A SUSTAINABLE BATTERY SYSTEM

6. CIRCULAR ECONOMY PRACTICES FOR A SUSTAINABLE BATTERY SYSTEM

Battery recycling is just one piece of the puzzle when it comes to achieving battery circularity. Other strategies such as battery reduction, reuse and design for circularity should be applied first, based on the circular economy hierarchy. In addition, alongside the recycling process itself, transportation and collection and the use of recycled content should be optimised for sustainability. This chapter explores the value chain activities that contribute to sustainable battery recycling and levers outside the recycling system which can minimise the impact of batteries and battery recycling.

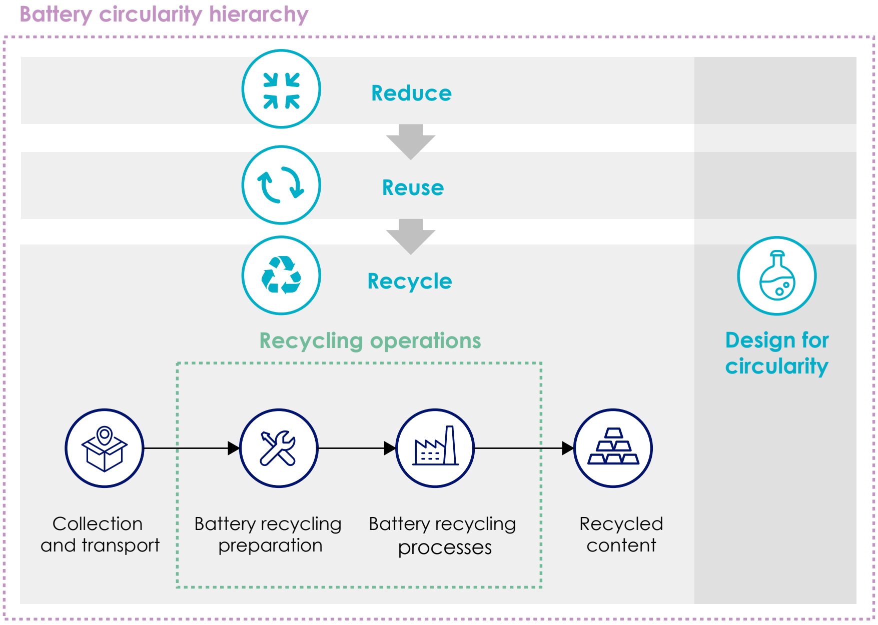
While battery recycling is an important element in achieving battery circularity, it is just one of several aspects, as outlined in the EU Waste Framework Directive and depicted in the battery circularity hierarchy in Figure 26:

1. **Reduce:** Decrease demand for batteries and battery materials.
2. **Reuse:** Extend the battery lifespans (eg, by repurposing in other applications).
3. **Recycle:** Enable sustainable battery recycling, including collection and transportation, and the recovery of high-purity recycled materials.

For all levers within this framework, **design for circularity** is key to ensure that batteries are durable, repairable, reusable and recyclable.

Within the recycling system, besides recycling operations themselves (see Chapters 3 and 4), safe and efficient **battery collection and transportation** are important to scale sustainable battery recycling and achieve high recovery rates. Further, the recycled content resulting from recycling operations should be of high purity, to facilitate repeated reuse and recycling.

Figure 26: Battery circularity hierarchy and recycling (methodological framework)



CHAPTER 6 KEY TAKEAWAYS

Besides optimising recycling processes, building a sustainable recycling system and optimising upstream and downstream value chain conditions will help to maximise the sustainability potential of batteries and their recycling:

- **Reduce:** Before optimising recycling for sustainability, battery demand should be reduced through measures such as improved public transportation, active mobility options and mobility-as-a-service (MaaS) models.

- **Reuse:** As many EV batteries retain sufficient capacity for non-EV applications after their first life, their lifespan before recycling can be extended. Information on and assessment of EoL batteries, reuse targets and clear classification, liability and safety standards are needed to scale battery reuse.

- **Redesign:** Standardised and simple (eg, easy to disassemble) battery designs would promote circularity. This could be achieved through standardised battery design guidelines, voluntary industry participation or mandatory principles. As the industry matures, a degree of consolidation of battery designs is to be expected. In addition, smaller vehicles and more efficient batteries can minimise material consumption per battery and hence the impacts during recycling.

- **Recycle – transport and collection:** Ensuring safe, sustainable and efficient battery transport and collection is important for achieving high material recovery rates and scaling sustainable battery recycling. Clear definitions and transport requirements for EoL EV batteries, along with improved information sharing, are needed. Careful planning of a battery collection, sorting and deactivation network can enhance efficiency and scalability. Responsible EoL treatment, supported by extended producer responsibility (EPR) schemes, international recycling standards and clear instructions and incentives for battery takeback, can prevent batteries from escaping the recycling system or being recycled irresponsibly.

- **Recycle – recycling processes:** From a circular economy perspective, battery recycling is crucial for addressing waste streams, avoiding environmental impacts tied to primary material extraction and mitigating potential future resource constraints. See chapter 4 for details on the recycling process.

- **Recycle – secondary battery materials:** Recycling of high-purity materials should be prioritised to facilitate repeated reuse and recycling. However, each material has its own optimal recovery rate, considering overall material yields and energy consumption. To achieve high-purity recycling, disassembly processes should be optimised, innovative recycling technologies explored and minimum levels of recycled content mandated.

6.1 REDUCING DEMAND FOR BATTERIES

Reducing demand for batteries is the first step in the circular economy hierarchy to increase the sustainability of the battery system. This can minimise material and energy usage as well as potential adverse social and environmental impacts during:

- battery material mining and battery manufacturing;
- battery (EoL) transportation; and
- battery EoL management, including recycling.

Key levers to enable battery reduction are presented in Information Box 8.

INFORMATION BOX 8: KEY LEVERS FOR BATTERY REDUCTION

- **Reduced travel:** Both the use of private cars and travel distances can be minimised through hybrid work models and increased remote working. However, these changes have social, economic and environmental implications (eg, increased personal energy usage at home) that must be considered.
- **Public and active transport:** A shift towards public transport and pedestrian and cyclist-friendly urban planning can reduce reliance on private cars and thus EV batteries.[120],[121] However, today, many areas (eg, in North America) lack well-connected electric public transport and safe cycling and pedestrian infrastructure.[120] Policies should actively support the development of public and active transport infrastructure through investments, incentives for public transit use and private vehicle parking regulations. To be effective, public transport should be appealing, prioritise cyclists and pedestrians, embrace smart technology, ensure inclusivity and provide last-mile connectivity. Once public transportation infrastructure is built, the transition and utilisation will require a change in behaviour.
- **MaaS:** MaaS is a business model that enables on-demand transportation services for individuals and companies. It is hypothesised to reduce the need for vehicle ownership and improve capacity utilisation and passenger kilometres per vehicle. This encompasses options such as car-sharing, ride-hailing and demand-responsive transport. Research[120] suggests that each shared car could potentially replace six to 23 private cars in North America and four to 10 private cars in Europe. To promote MaaS, funding and improved regulatory conditions – such as preferential lane access and parking fees for MaaS or road pricing favouring MaaS – are vital; these measures have already been implemented in several cities. To be effective, MaaS platforms should be user friendly, offer fair pricing structures and integrate seamlessly with other transportation solutions. However, thus far, consumers have been slow to embrace MaaS models. Challenges include consumer preferences for private transport and insufficient policy support.[43],[51],[90],[122],[123]

- **Battery-as-a-service (BaaS):** BaaS models allow customers to lease batteries as a separate component, saving on the upfront costs of an EV. These models can help to match battery size with specific needs (eg, smaller batteries for local distances and larger ones for longer distances), reduce the overall number of batteries needed and minimise downtime for fleet vehicles.[124] To promote BaaS, consumers should be offered financial incentives and assured access to charging infrastructure or renewable energy sources. Governments might mandate OEMs to offer BaaS as one option or provide grants to facilitate BaaS schemes. Promoting battery design standardisation would ensure interoperability between vehicle models and various BaaS providers. Adequate technological infrastructure, especially convenient battery banks for swapping, is crucial.[124]

6.2 REUSE TO EXTEND BATTERY LIFESPAN

Once LIBs have been used in EVs for approximately eight years, they will likely no longer meet the range and high-power demands expected of EVs. However, they will still retain roughly 70%-80% of their initial capacity, making them suitable for non-EV applications for a further decade.[21],[95] Today, the prevailing practice is to recycle most batteries once they reach their initial end of life (EoL1), even though about 70% of them could potentially be reused before reaching final end of life (EoLf).[26] According to research and expert interviews, only a small percentage of batteries – roughly 10% – are repurposed and just around 1% are remanufactured after EoL1. While the market for second-life battery applications is still in its infancy, today, second-life batteries offer a cost advantage of roughly 30%-70%.[120] If efficiency and automation of logistics and repurposing techniques improve further, this cost advantage will be sustained, even as the prices of new batteries fall. However, widespread second-life battery use will delay access to secondary battery materials and will result in older (potentially high-capacity cobalt content) batteries being used in less demanding second-life applications.[83],[95] Additionally, there are uncertainties around the liability of second-life batteries and the efficiency of collecting EV batteries at EoLf.[95]

Three strategies can extend the useful life of a battery:

1. **Direct reuse:** The battery is used again for the same purpose without any modifications.
2. **Reuse with modifications in the same application:** The battery is used again for the same purpose but may require repairs to restore functionality, reconditioning to replace components or remanufacturing to restore it to a new condition (including warranties and extended life).
3. **Reuse in other applications (repurposing):** Batteries can be repurposed for different applications from those for which they were initially designed – for example, lower-power vehicles, fast-charging stations or energy storage systems.

Key levers to enable battery reuse are presented in Information Box 9 (more detailed considerations for battery reduction can be found in **Annex XVI**).

INFORMATION BOX 9: KEY LEVERS FOR BATTERY REUSE

- **Information availability and accessibility:** A standardised approach for measuring and reporting the residual value of a battery can guide the complex decision-making on the most appropriate treatment of a battery post-EoL1. Mandatory testing processes, supervised by independent service organisations, could facilitate this standardisation. Battery diagnostic systems can allow for the rapid assessment of a battery's state of health and capacity trajectory prediction. These can be complemented by smart BMSs, enhanced in-vehicle diagnostics tools, robotic testing and battery passports. Battery trading marketplaces can determine residual values based on market demand and battery characteristics and matching with suitable use cases.[3],[83],[120],[125].

- **Reuse-tailored regulation:** To promote the reuse of batteries suitable for a second life, regulations can establish minimum quotas for battery reuse. This is important since existing regulations tend to prioritise recycling. In addition, regulatory changes should establish clear classifications distinguishing waste from non-waste batteries based on individual battery conditions. This way, transport conditions and costs can be adjusted to the individual risk level, which can improve the economic viability of returning batteries for a second life.[36],[95] Similarly, terms such as 'reuse', 'repurpose', 'second life' and 'recycling' should be defined in a globally harmonised way to facilitate consistent handling and reduce complexity in laws and practice.[36],[120],[126],[127]

- **Ownership and liability:** Definitions of ownership and liability for second-life batteries should be established. The EPR framework introduced in the EU Battery Regulation assigns EoL responsibility for second-life batteries to the economic operator that places the reused battery on the market. However, the impact on ownership and liability should be outlined more explicitly, as the liability in case of damage caused by a reused battery is unclear.

- **Standardisation:** To enable a second life, batteries should be designed for repair and durability. A request for the standardisation of battery design to facilitate second-life use has been made from the European Commission to the European Standarsiation Organisations CEN and CENELEC.[95] Additionally, standardised BMSs enable easier and more consistent testing, reducing processing costs.[120] Furthermore, safety standards for the battery repurposing process are needed. Initiatives such as the UL 1974 Standards for Evaluation for Repurposing Batteries in North America serve as examples. Similarly, sales of second-life batteries should adhere to requirements relating to durability, safety and location restrictions.

6.3 BATTERY DESIGN FOR CIRCULARITY

Designing batteries with circularity in mind is a prerequisite not only for promoting recycling, but also for ensuring that batteries are durable and can be repaired and reused before being recycled. This also helps to streamline the recycling process – for example, by allowing easy access to components and boosting the economic and technical feasibility of material recovery.[123]

Battery design for circularity

Designing EV batteries for circularity is a significant challenge.[120] On the one hand, battery designs lack standardisation and are fast evolving. [8],[70] The batteries of different manufacturers vary significantly in terms of pack configurations, sizes, shapes, chemistries and connection methods, making standardisation challenging. To maintain competitiveness, companies protect proprietary design details such as formulations, manufacturing techniques and internal structures.[99] Even the new EU Battery Regulation does not specify standardised design, manufacturing or BMSs.[95] The diversity in battery design and chemistries complicates battery pack disassembly, making it complex, time-consuming, expensive and hazardous. Manual disassembly often excludes bulk processing, can damage cells during removal and can increase process steps, energy usage and material requirements.[36],[95] Additionally, recycling processes vary widely (see Chapter 3); and not all chemistries can be recycled through the same recycling routes.[8],[95]

On the other hand, battery design often clashes with circularity due to divergent sustainability, technical, economic and safety interests. For instance, batteries are designed with the aim of enhancing material efficiency, energy density and weight reduction to increase range and capacity. Structural batteries – which combine lightweight properties with improved energy density – reduce energy consumption during use but complicate recycling due to the difficulties of dismantling them.[95] In China, for example, battery taxes are weight based, encouraging weight reduction.[95] As another example, flame retardants are added to batteries to prevent battery fires, but this increases cell complexity and affects recycling efficiency.[96] Below, four drivers to enable circular battery design are introduced.

Driver 1: Battery design guidelines for circularity

Guidelines for circularity should be introduced and regularly updated to reflect fast-changing battery design and chemistry developments. Standardising battery component design – such as using identical or compatible sizes and types of screws, fasteners and connectors – can facilitate the scale-up of recycling efforts. This standardisation would allow for the use of (semi-)automated disassembly processes, making recycling safer and more economically advantageous.[3],[8],[52],[96] Additionally, battery construction and assembly design can play a significant role in promoting circularity. By designing batteries for swift dismantling and standardised tooling, the costs associated with collection, transportation and handling for recycling could be cut by up to 50%.[3] Design considerations should include ensuring that screws, joints and cells are readily accessible and separable. Examples include module-less packs with easy-to-open, separatable cells; integrated attachment points to facilitate battery lifting; and solid, fixed busbars instead of flexible cables.[3],[36],[96] Material choice is another critical design consideration.

To make it easier to remove battery components and enable safe battery recycling, materials such as rubber seals and screws should be preferred over non-removable adhesive seals and glues. Special attention should be paid to electrode design, with the aim of reducing the use of binders between the current collector and the active material.[36],[83],[96]

To ensure the implementation of circular design guidance, the industry could voluntarily commit to these guidelines. To incentivise adherence, a circularity score based on design indicators could be introduced, measuring the removability, replaceability and recyclability of batteries.[36] Circular battery design could be further incentivised through an eco-modulated EPR fee based on dismantling and recycling costs, which would also cover additional dismantling expenses.

Mandatory principles can be implemented through laws requiring design approaches that facilitate the maintenance, repair and repurposing of batteries. While the new EU Battery Regulation does not specify standardised design or manufacturing, it does require that EV batteries – including joining, fastening and sealing elements – be removable and replaceable by independent professionals.[36] In addition, Recital 26c of the EU Battery Regulation tasks the European Commission with 'encourag[ing] the development of standards for design and assembly techniques that facilitate the maintenance, repair and repurpose of batteries and battery packs'.[36]

These battery design guidelines can align with the product parameters for recyclability proposed in the EU Ecodesign for Sustainable Product Regulation, proposed in March 2022. These product parameters address durability, repairability, reusability and recyclability. The parameters addressing recyclability are presented in Information Box 10.

INFORMATION BOX 10: PROPOSAL ON EU ECODESIGN FOR SUSTAINABLE PRODUCT REGULATION – RECYCLABILITY PRODUCT PARAMETERS

- **Annex I(d):** '[E]ase and quality of recycling: use of easily recyclable materials, safe, easy and non-destructive access to recyclable components and materials or components and materials containing hazardous substances, material composition and homogeneity, possibility for high-purity sorting, number of materials and components used, use of standard components, use of component and material coding standards for the identification of components and materials, number and complexity of processes and tools needed, ease of non-destructive disassembly and re-assembly, conditions for access to product data, conditions for access to or use of hardware and software needed.'

- **Annex I(e):** '[A]voidance of technical solutions detrimental to re-use, upgrading, repair, maintenance, refurbishment, remanufacturing and recycling of products and components.'

Driver 2: R&D and innovation

R&D and innovation play a pivotal role in circular battery design. Ongoing efforts by battery manufacturers to improve battery components, design and chemistries are essential. Governments can support these initiatives through tax incentives, grants, subsidies and research funding. Public-private partnerships can also accelerate R&D in this area.

Industry partnerships are another driving force for circular battery design. Automotive manufacturers can form alliances or share platforms to distribute R&D costs associated with battery development. Such collaborations can lead to some degree of battery design convergence.[83],[95] For instance, VW is jointly developing EVs for China with the Chinese OEM Xpeng; and Audi is doing likewise with SAIC Motor.[128]

Information sharing within the industry, especially at the EoL stage, can assist battery recyclers. Tools such as battery passports (see Chapter 5.3) and open-access research platforms or databases on circular battery design can facilitate knowledge sharing and collaboration.

In addition to optimising batteries for circularity, efficiency needs to be considered when designing batteries. As the number of EVs continues to increase, so does their size. In Germany, over the past decade, smaller car stocks increased by just 3%, while stocks of vans, SUVs and similar vehicles surged by 80%.[121] Larger cars require bigger batteries, which consume more energy and materials during recycling. Cars with fewer seats can also increase material usage per passenger. Consumer preferences and psychological factors can hinder the adoption of smaller vehicles; while in some cases, smaller cars may not offer enough space.

Driver 3: Efficiency improvements

Improving material efficiency (ie, using less material for the same functionality) can reduce the size of batteries. This can be achieved through optimised design and chemistries.[123]

Driver 4: Smaller vehicles

Smaller vehicles require less battery capacity. Moreover, battery size should match EV usage – for example, a commuter car may need less range than an EV used for long-distance travel. Standardising battery sizes and formats across vehicle models and manufacturers will ensure that batteries are only as large as necessary. Government mandates for emissions standards and efficiency targets should incentivise the production of smaller vehicles and batteries. Congestion pricing, parking incentives for smaller cars in cities and taxation based on vehicle weight can further promote smaller cars with reduced battery sizes.[15]

6.4 SAFE, SUSTAINABLE AND EFFICIENT BATTERY COLLECTION AND TRANSPORTATION

Efficient and effective return and collection systems are needed to achieve high recycling and material recovery rates and to effectively scale recycling.[43] At present, just half of all EoL batteries globally are available for recycling; the remainder are stored, hoarded or disposed of but not recycled. However, some of these EoL batteries are initially reused in other applications and only become available for recycling later.[125] To scale up safe, sustainable and effective battery collection and transportation, three key dynamics must be addressed:

1. the safety and classification of EoL batteries;
2. the maturity of battery collection and dismantling networks; and
3. the global trade in EoL batteries.

Battery transport safety and classification

Incorrect EoL battery management can lead to leakage, outgassing and even hazardous incidents such as thermal runaway, fires or explosions. This risk is aggravated by the reality that some automotive recyclers lack expertise in safe EoL battery handling and struggle to assess battery health.[8],[71],[95]

Due to the risks associated with transporting batteries, regulations are complex, stringent and costly, encompassing a diverse range of equipment, labelling, documentation, licences, approvals and specialised drivers. Currently, EoL batteries are classified as ‘waste’, which subjects them to strict safety standards during transportation. Specific transport regulations for EV batteries and EoL EVs have yet to be established; and inconsistent classification of black mass across regions further complicates transportation logistics.[31],[46],[71],[96],[120]

Driver 1: Clear classification of EoL batteries and black mass

Definitions and transportation requirements for EV batteries intended for recycling and reuse should be clarified and harmonised across jurisdictions. For instance, instead of automatically classifying batteries as ‘waste’ at EoL1, they should arguably be classified as ‘products’ if they are intended for a second life or if they present no significant safety risks during transportation. To allow for a safety assessment of EoL batteries and avoid incidents such as the occasional LIB fires that are currently reported, well-defined criteria are needed which consider the battery’s condition and potential reuse or recycling arrangements.[6],[126] Based on these criteria, appropriately stringent safety requirements for transportation should be imposed. The EU Battery Regulation aims to provide definitions and clarifications around EoL batteries.[43],[71],[120]

Similarly, a clear and consistent classification system for black mass from EoL batteries should be established, ideally at a global level. Some suggest that black mass should be classified as hazardous waste and treated as an intermediate stream rather than as a product. This would ensure that high sustainability and safety standards were adhered to, create a level playing field within the EU and prevent the export of black mass to non-OECD countries.[31],[105] However, others caution that this could impose excessively burdensome requirements on the handling and transportation of black mass, and thus limit the efficient allocation of black mass to recycling operations globally (see also Chapter 7.2).

Driver 2: Enhanced information sharing, standardisation and training

Battery diagnostics, BMS data and information on battery chemistry and health hazards can facilitate the precise classification of batteries, which in turn can inform appropriate safety measures during transport. Information can be made accessible through tools such as battery passports. Battery analytics can assess battery health in terms of voltage, current and temperature.

Standardised battery sizes, designs and chemistries can further streamline battery collection and transport.

Moreover, the professionals handling EoL EVs should be well trained and observe defined safety protocols.[71] Inter-industry partnerships can facilitate knowledge transfer within the EV value chain; and appropriate tools and protective equipment (eg, high-voltage gloves) are essential.[95]

Driver 3: Carefully planned battery collection, sorting and deactivation

Establishing recycling plants in proximity to the source of EoL batteries can reduce transport risks and costs.[71],[78] Well-organised sorting – ideally before transport – minimises safety risks and avoids contamination in recycling.[71],[129] Deactivating the battery before removal can also reduce risks during disassembly. However, a full effective discharge requires overriding the BMS. The energy from the battery can be recovered through a vehicle-to-grid connection.

Battery collection and dismantling network

Today, there is a lack of well-established and consistent pathways for battery collection and transport. Recyclers are often small, family-owned businesses and lack scale; and long distances between collection points, recycling facilities and battery manufacturing plants result in substantial transport emissions. This dispersal is hindering the development of a scalable and efficient recycling industry.[100] Another challenge arises from the insufficient volume of EoL batteries that is currently available, which often results in underutilised truck capacity, as some regulations prohibit the transportation of EoL batteries alongside other products. As a consequence, the costs and emissions for each transported EoL battery are high.

Driver 1: An efficient, hub-and-spoke-based EoL battery network

The development of efficient, sufficiently dimensioned dismantling networks on a geographical basis is crucial. These networks would assess battery health and dismantle batteries for recycling. Network design should minimise transportation distances and consider factors such as timing, locations, dimensions and facility specifications. However, in Europe, the limited volume of EoL batteries currently available provides little incentive for dismantlers to make the necessary investments.[43],[99] Once the number of EoL batteries begins to increase, this should improve.

A battery recycling, preparation and pre-treatment network based on a hub-and-spoke model can reduce lifecycle impacts and transportation distances and enhance the economics of recycling. This model involves centralised hubs for major treatment processes and decentralised spokes for further processing or initial distribution.[130] Spokes should be located closer to battery sources; while centralised recycling hubs, requiring substantial capital, should ideally be situated near battery manufacturing facilities. According to a study by Strategy& and PEM (2023), a 1:10 hub-to-spoke ratio – with spokes handling approximately 10kt of EoL batteries per year and hubs processing around 40 kt of black mass per year – is considered ideal and would lead to significant cost reductions. Regional forecasts for battery recycling are essential for optimal network planning.[5],[78],[96] Companies such as Li-Cycle have adopted a hub-and-spoke model: spokes handle mechanical processing for battery discharge and black mass reduction, while hubs purify black mass into battery-grade material. Battery manufacturers can adopt similar models by pre-treating battery scrap in production facilities before sending it to central recycling hubs.

Driver 2: Decarbonised transportation

The transportation of EoL batteries, black mass and recycled content should be decarbonised to mitigate emissions. [71] Recyclers should extend these effort beyond their own transportation systems, including to direct and, if possible, indirect suppliers.

Global trade in EoL batteries

Many jurisdictions lack effective mechanisms for tracking and collecting EoL batteries. The absence of clear definitions of EoL responsibility, along with immature and inconsistent takeback schemes, is hindering the recovery of batteries at EoL. As a result, valuable battery materials are lost, exacerbating material and carbon inefficiency and potentially leading to adverse social and environmental impacts such as contamination if batteries end up in landfill.[71],[120] In particular, safe disposal of reused batteries at EoL can be challenging if responsibility is not clearly transferred and enforced. In the EU, for instance, many batteries are first sent to Eastern European member states for a second life.[43]. Moreover, when recyclers lack direct connections to the battery material market, this can hinder closed-loop battery recycling. The export of batteries can also involve long transportation distances.

Meanwhile, variations in battery recycling standards and local energy sources across different geographies lead to differences in carbon emissions, social and health risks and recycling quality. For instance, in China, a substantial portion of energy production still relies on coal and oil sources.[131] Additionally, while officially approved recyclers in China adhere to defined standards, there are also numerous unauthorised companies operating outside of official channels, making it difficult to ensure compliance. This notwithstanding, regions that offer a lower cost base in terms of labour and energy present an economic opportunity for recycling lower-value cell chemistries. Given the surge in lithium prices and China's favourable cost structure, the nation is currently best positioned to profitably recycle LFP batteries. At the same time, China is the largest battery manufacturer in the world. Consequently, global trade will be crucial in maximising the utilisation of recycled materials in the production of new EV batteries.[6]

Driver 1: Clear responsibility for EoL treatment

Registering and tracking batteries across their lifecycle can ensure that assigned responsibilities are maintained throughout. Initiatives such as the mandatory battery passport in Europe and China's traceability management platform can help to achieve this goal. Digital tracking and tracing solutions can reduce transaction costs and boost collection rates.[3],[71]

Clearly defining responsibility for the collection and treatment of EoL batteries can prevent them from escaping the recycling system or being disposed of irresponsibly.[71] EPR schemes – an environmental policy approach that extends producer responsibility to the post-consumer stage of a product's lifecycle – have been implemented in various regions for EoL vehicles and batteries. For EPR schemes to be effective, strong enforcement mechanisms are essential. Reporting to enforcement agencies and product declarations can help to prevent informal treatment and illegal exports.[132] These schemes should cover all EV batteries placed on the market – including second-life batteries, by transferring responsibility. An eco-modulated EPR fee based on dismantling and recycling costs can incentivise circular battery design (see Chapter 6.1) and cover additional dismantling expenses. However, success depends on harmonised criteria and implementation of eco-modulation at the EU level.[132] Information Box 11 presents examples of how responsibility for EoL batteries is allocated in different jurisdictions.

INFORMATION BOX 11: RESPONSIBILITY FOR EOL BATTERIES IN THE EU AND OTHER JURISDICTIONS

- **EU:** The EU End-of-Life Vehicle Directive (2000/53/EC) governs the collection of EoL LIBs from EVs; while the new EU Battery Regulation has introduced an EPR scheme that requires producers to finance the collection, treatment and recycling of batteries to ensure high environmental and health protection standards, recycling efficiencies and material recovery. Both producers themselves and producer responsibility organisations can assume this responsibility. The EPR scheme also extends to economic operators marketing second-life batteries. The Regulation stipulates that the export of waste batteries outside the EU contributes to meeting its obligations, efficiencies and targets only if documented proof – approved by the competent authority in the destination country – demonstrates compliance with EU environmental and health protection requirements.
- **China:** In China, responsibility for EoL batteries rests with EV and battery manufacturers and importers.
- **UK:** In the UK, battery producers are obliged to accept and treat EV batteries free of charge.[65]
- **Other jurisdictions:** Several jurisdictions – including California and Quebec – are considering introducing similar EPR regulations.[100] In the United States, there are no universally applicable requirements for the return of LIBs; however, voluntary alliances such as the ELV Solutions consortium exist.[16]

Driver 2: International recycling standards

To prevent the externalisation of adverse environmental impacts and ensure high global material recovery rates, the adoption of international standards for sustainable battery recycling is imperative (see also Chapter 5.2). Only then will regions that currently lag behind in the electrified transport transition be able to securely, sustainably and efficiently recycle EoL batteries (potentially after a second life).

Driver 3: Information and incentives for takeback

Clear, user-friendly guidelines must be provided to consumers, car repair establishments and scrappers for the proper return of EoL batteries. For example, the EU Battery Regulation mandates instructions for the separate disposal of waste batteries and the provision of information on takeback and collection points through labelling and via the battery passport.[36] The return of EV batteries should be free – as also stipulated in the EU Battery Directive of 2006.

Offering financial incentives to consumers when returning batteries could be an even more effective approach. OEMs could purchase batteries from car owners directly or as part of new car purchase incentive programmes. Alternatively, a deposit system could be implemented.

The Traction Batteries Working Group of the Circular Economy Initiative Germany (CEID) has recommended a deposit return system (DRS) with a deposit that slightly exceeds the battery's scrap or recycling value. Such a system should be designed to ensure high take-up and user-friendliness.[43] The European Commission has been tasked with reporting on the feasibility and potential advantages of a DRS for batteries by the end of 2027. In addition, fiscal policies can be employed to discourage improper disposal or non-recycling of batteries – for example, by imposing landfill or disposal fees.[15] Moreover, MaaS models, under which battery ownership is retained by OEMs, simplify the tracking and return of batteries for recycling purposes.

Driver 4: Mandatory collection targets

Mandatory collection targets can be set to force OEMs to step up their battery collection efforts. Notably, the EU Battery Regulation has introduced higher collection targets solely for portable and light means of transport batteries, with no specific mention of EV batteries.

Driver 5: Sufficient local and regional recycling capacity

Another driver to reduce EoL battery exports is sufficient local recycling capacity, which is anticipated in Europe by around 2030.[5],[133]

6.5 RECYCLED MATERIALS: IDENTIFYING THE OPTIMAL RECYCLING SET-UP

Recycling processes can be optimised to enhance the quality of output materials, but only at a cost. Depending on the potential subsequent uses of secondary materials, this leads to a debate around optimal battery recovery rates and output quality, and whether open-loop or closed-loop recycling is preferable. The CEID's[43] position on open-loop recycling is outlined below. However, there are ongoing questions regarding the desirable quality and use of recycled materials that require further consideration.

Quality of recycled materials

Battery recycling processes can be designed to result in high-purity materials (functional recycling, which prioritises the retention of material functionality) or lower-quality materials (non-functional recycling or downcycling). Only functional recycling ultimately enables true 're-cycling' by facilitating the repeated reuse of materials and thus long-term resource decoupling. However, this typically comes at the cost of higher economic and energy efforts and can also result in lower yields by mass. In practice, different materials have different optimal recovery rates. While most battery materials can be efficiently recycled to high purity, for some (eg, graphite, gypsum and the electrolyte) this is challenging. Near 100% recovery of all battery materials at the highest purity is likely impossible, or at least environmentally and economically undesirable. To determine the optimal recovery rates, comprehensive evaluations comparing recycled and newly mined materials across various sustainability aspects are needed. [8],[43],[120]

However, optimal recovery rates can be hindered by the wide variety of battery types and components, potentially leading to impurities and quality issues in recycled batteries. In addition, quality requirements for recycled batteries are currently falling short. Although the EU Battery Regulation sets recycling content goals and emphasises high-quality recycling, it lacks specific guidelines on the recycling process. Likewise, recycling procedures and input material standards still need to be developed.[36],[43]

Application of recycled materials

Recycled materials can either return to the same applications (closed-loop recycling) or find new uses (open-loop recycling). The preferred option for battery materials remains the subject of debate. On the one hand, keeping battery materials within the battery sector supports their reuse, driven by EPR schemes and the high value of batteries. On the other hand, extending material applications beyond batteries (open-loop recycling) could enhance the recycling industry's scale and efficiency, reducing costs and impacts. However, since the key materials (lithium, nickel, cobalt, graphite) are predominantly used in batteries,[15] no similarly large alternative markets exist that could incentivise a truly open-loop recycling system. Meanwhile, closed-loop battery systems can be hampered by long geographical distances between recycling facilities and recycled content.

The CEID and various experts consulted for this study emphasise that open-loop recycling for high-quality products should demonstrate an overall positive or at least neutral effect on system efficiency and maintain appropriate quality.[43]

Downcycling may be acceptable where lower-quality materials are intended and sufficient for other applications and would otherwise stem from primary sources; and where recycling them to a higher quality would be environmentally undesirable. For example, this could apply to steel: Until the Chinese housing crisis in 2023, demand for lower-grade steel in the global construction sector afforded ample use of downcycled steel from the automotive sector.

Driver 1: R&D and battery design for high-quality recycling

To achieve high-quality recycled content and minimise impurities, disassembly processes and R&D for innovative recycling technologies should be optimised (see Chapter 4). For example, recycling rates for graphite are low as the associated costs are high compared to those for virgin graphite; cost-effective recycling methods are thus needed. As recycling technologies advance and more batteries reach EoL in future, economies of scale should bridge the cost gap between recycled and newly mined materials, thus promoting closed-loop recycling.

Standardised battery design optimised for dismantling and recycling can further facilitate high-quality recycling (see Chapter 5.2).

Moreover, standards and certifications for recycled battery material quality and recycling facilities can promote continued battery material recycling. For battery materials employed in open-loop applications, certifications should demonstrate that alternative high-quality applications with a positive or neutral impact on system efficiency have been selected. The clear assignment of responsibility for meeting recycling quality requirements is also necessary (eg, through EPR schemes). A battery passport can help to track batteries to ensure that this responsibility is being met (see also Chapter 5.3).

Driver 2: Partnerships to secure supply and offtake

Collaboration and long-term contracts between recycling firms and battery manufacturers can secure supply for manufacturers and provide offtake options for recyclers. For example, Umicore is partnering with LG Chem and Audi. Alternatively, OEMs can establish closed-loop battery systems that encompass takeback, recycling and integration into manufacturing processes, similar to Tesla's approach.[21] Public procurement and offtake agreements for large-scale production of next-generation batteries can stimulate demand for closed-loop recycled materials.[15]

Additionally, the creation of a market for secondary battery materials and black mass trade will enhance security and ease of trade (eg, S&P Global Commodity Insights has established a black mass market).[134]

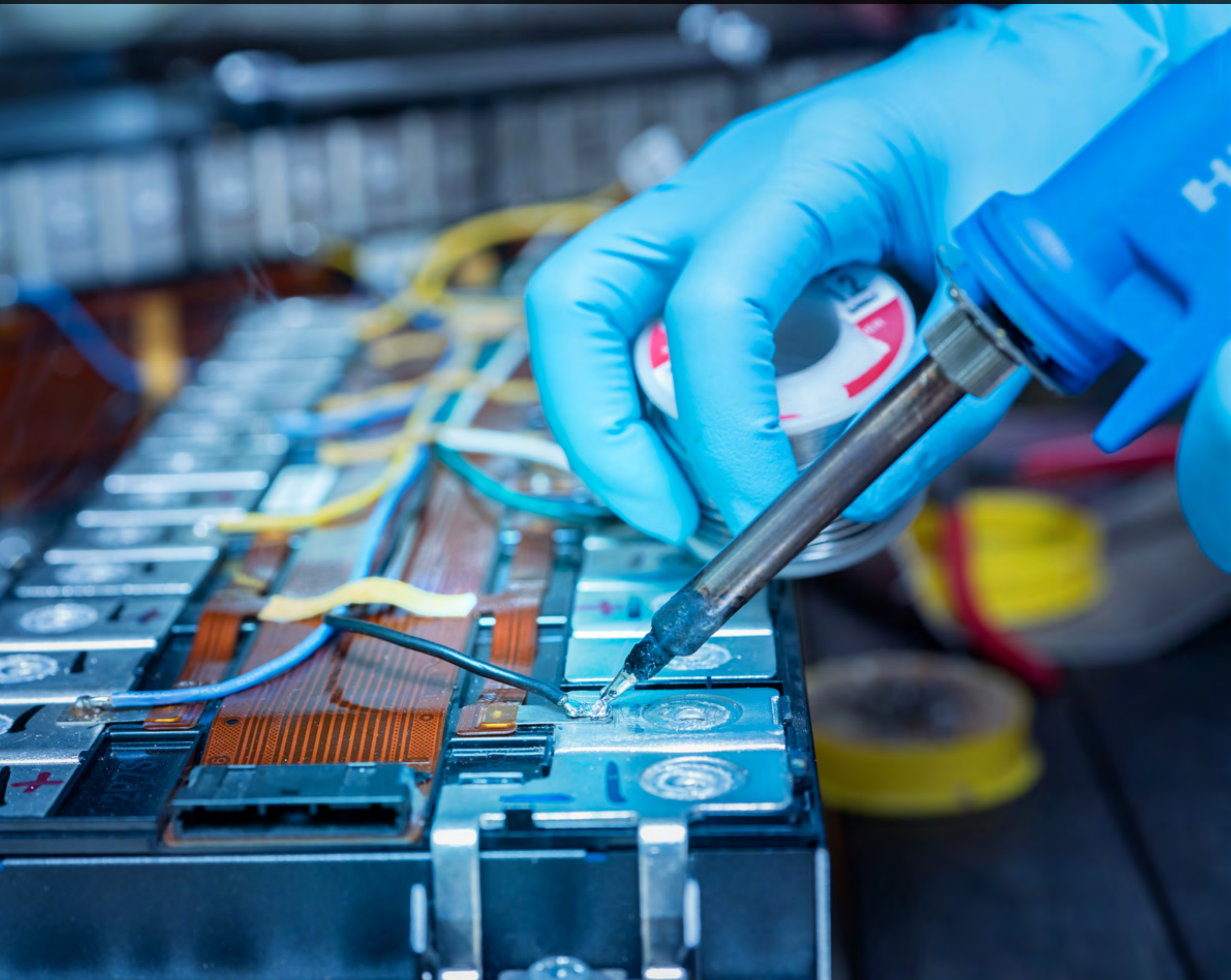
Driver 3: Minimum levels of battery recycled content

Mandating minimum levels of recycled content in batteries indirectly promotes closed-loop recycling to further secure the supply of recycled content. The EU Battery Regulation sets recycled content targets for various materials, with corresponding recycling efficiency and material recovery targets. However, the requisite quality of recovered materials is not specifically defined.

CHAPTER 7

NEXT STEPS FOR THE BATTERY RECYCLING INDUSTRY

Implementing and scaling sustainable battery recycling will require active public sector engagement, as elaborated in Chapters 5 and 6. At the same time, LIB recycling is technically complex: it involves a multi-step approach and battery recyclers have different technology options at each step, as well as choices on how to sequence the various steps within an end-to-end battery recycling route. Diverse battery recycling technologies and routes are being adopted worldwide, giving rise to distinct sustainability considerations. But despite this divergence, universal sustainability principles can be applied across the entire battery recycling industry.



7.1 INDUSTRY PRINCIPLES FOR SUSTAINABLE BATTERY RECYCLING

The 10 principles outlined below provide practical recommendations for the recycling industry, in order of value chain steps. Industry participants should actively encourage their partners to adhere to these principles to ensure sustainable battery recycling across their value chain.

RECYCLING OPERATIONS

1 **Safe operations:** Prioritise stringent health and safety standards in recycling operations

Commit to the highest health and safety standards, ensuring that workers are appropriately trained and provided with high-quality protective equipment. For example, adhere to ISO 45001 – an international standard for health and safety at work – or relevant ILO standards and guidance on occupational health and safety in industrial operations. Ensure fair working conditions through regulated and licensed economic activity along the entire recycling value chain to rule out exploitative practices. This should take priority above all.

2 **Technology selection and process design:** Incorporate sustainability impact assessments into the selection of battery recycling technologies and processes

Recycling processes differ according to local situations, inputs and desired outputs; and no one process has a clear sustainability advantage in all dimensions. To make informed decisions, conduct in-depth data driven analyses of recycling routes, considering the advantages, disadvantages and trade-offs of the recycling flowsheet from a cradle-to-gate perspective and considering all inputs.

3 **High-ambition recycling:** Maximise material recovery and carbon efficiency, and prioritise recycling to high-grade materials

Optimise recycling operations for maximum recovery of key materials and minimum carbon footprint. This includes recovering energy during discharge and reclaiming non-active materials during disassembly and mechanical processing. Aim for high-purity secondary materials which allow for repeated reuse and recycling. Recovery of active and critical materials should take precedence. However, each material has its own optimal recovery rate, considering overall material yields and energy consumption. To determine the optimal material recovery rates, comprehensive evaluations comparing recycled and newly mined materials across various sustainability aspects are needed. To facilitate high-purity recycling, optimise disassembly and pre-processing steps and explore innovative recycling technologies.

4 **Water management:** Adopt best practices for water reduction and wastewater management

Aim to implement a closed water loop within recycling facilities – that is, a system that consumes no more water than is lost through evaporation or oxidation, and that recycles and purifies water processes. If this is not feasible, establish treatment systems to ensure that the quality of water entering the facility matches that of the water leaving it and minimise overall water consumption.

5 **Minimal waste:** Design and operate recycling processes to minimise waste streams and ensure that all waste is treated and disposed of in accordance with international standards

Minimise solid waste generation by exploring reuse options wherever possible – for example, repurposing hydrometallurgy sulphate by-products for the detergent industry or using slag produced in pyrometallurgy for road construction. Where this is not feasible, ensure that responsible disposal practices are in place, adhering to the highest environmental and safety standards – for example, ISO 14001 on environmental management systems, including waste management procedures; and ISO 24161 on waste collection and transportation management.

6 **Energy usage and GHG emissions:** Decarbonise recycling operations

Reduce the overall energy intensity of operations to the minimum. Ensure that the electricity used is sourced from renewable sources. Consider investing in renewable energy generation infrastructure such as photovoltaic systems or wind turbines. If complete electrification is not feasible for certain operations, transition to low-carbon fuel alternatives. For any unavoidable air emissions, employ reduction and control measures that align with the strictest carbon, environmental and health standards. Where feasible, minimise the direct release of GHGs – for example, by implementing effective capture methods.

RECYCLING VALUE CHAIN

7 **Auxiliary materials:** Minimise consumption and GHG emissions of used chemicals, gases and other input materials

Reduce the auxiliary materials consumption of recycling processes. If possible, recycle or regenerate the inputs – for example, recover used acids via regenerative chemistry or scrub and reuse inert gas used in shredding. Procure auxiliary materials such as chemicals with low environmental footprints – including considerations such as climate (eg, carbon footprint), freshwater and land impacts – in alignment with the planetary boundaries.

8 **Supplier engagement:** Apply sustainability assessment criteria and robust controls to ensure that suppliers of auxiliary materials adhere to internationally accepted environmental, social and labour standards

When procuring end-of-life batteries, black mass or auxiliary materials, conduct rigorous due diligence on suppliers to ensure that their materials have not caused adverse social and environmental impacts. Adhere to established international safety and environmental standards, follow due diligence regulations and refer to guidance such as the OECD's Due Diligence Guidance for Responsible Business Conduct. Verify supplier provenance to prevent materials from uncertified or problematic sources – ideally through established certification schemes.

BROADER VALUE CHAIN

9 **Transport:** Optimise transport routes and electrify modes of transportation

Prioritise the decarbonisation of all transportation relating to recycling operations, extending this effort beyond primary suppliers whenever feasible. Optimise transport routes to minimise distances and enhance the efficiency and scalability of dismantling and recycling networks. Invest in comprehensive training and equip personnel to uphold strict transport protocols, ensuring safety and environmental responsibility. When outsourcing transportation services, hold partners to these same high standards, including by requesting relevant certifications.

10 **Data availability:** Implement digital tools and enhanced traceability in line with the digital ecosystem along the value chain

Deploy digital tools such as battery passports, battery analytics and intelligence software to access information about battery history and composition. This will also enhance the recovery rates of valuable materials and facilitate sustainable recycling processes.

7.2 MOVING FORWARD – OPEN QUESTIONS

Industry alignment is needed on some open questions relating to sustainable battery recycling, outlined below. These debates have emerged due to discrepancies in definitions, regulations and practices, resulting in divergent perspectives among stakeholders. These issues bear significance for the design and operation of sustainable battery recycling processes. The need to resolve these debates through clear standards, regulations and guidelines was highlighted earlier in this report. **Ideally, these questions should be addressed through pre-competitive collaboration between battery recyclers, alongside wider multi-stakeholder engagement.**

1. **Classification of black mass:** The appropriate classification of black mass is under debate. It is crucial to consider the underlying motivations and weigh the trade-offs, including local protectionism, recycling capacity, sustainability and a global just transition. One perspective suggests treating black mass as hazardous waste rather than as a product, which would ensure that strict safety and sustainability standards apply during transportation. This approach would also prevent the export of black mass to non-OECD countries, creating a level playing field within the EU.[5],[31] However, the classification of black mass as hazardous waste could hinder efficient allocation to recycling facilities and limit access to secondary materials for non-OECD countries, potentially impeding the development of their recycling industries.

2. **Trade of EoL batteries and black mass:** Different countries have varying perspectives and interests in the trade of EoL batteries and black mass. Legal instruments such as the US Inflation Reduction Act aim to support local recycling industries, which can boost the economy and ensure ready access to valuable raw materials. However, this approach may hinder the development of a global recycling market and access to second-life batteries and secondary materials in the Global South. Global trade of EoL batteries and black mass could also make the recycling of less valuable battery chemistries (eg, LFP) economically viable in regions with lower costs and ensure that existing recycling capacity is utilised.

3. **Circular battery design:** Battery design has significant implications for recyclability and is a vital consideration for recyclers. It is essential that manufacturers and recyclers come together to discuss their respective design requirements and concerns. Standardisation and regulations will be instrumental in finding solutions. Battery manufacturers often safeguard proprietary design details to remain competitive and may prioritise material efficiency, energy density and weight reduction over circularity. On the other hand, for battery dismantlers and recyclers, standardised battery designs can simplify disassembly and dismantling processes, enhance worker safety and automate EoL battery processing.

4. **Access to materials and second-life applications:** Views differ on whether EV batteries should be recycled directly after their initial use or be repurposed for second-life applications. Multiple factors should be considered, including battery types (lower-density batteries may be preferred for reuse) and potential second-life applications (energy storage systems with fewer battery cycles could be ideal). Additionally, forecasts on battery production and EoL batteries can help to inform perspectives. Some suggest that the widespread use of second-

life batteries could delay access to critical materials and slow the development of the battery recycling industry. Recycling older, high-capacity battery chemistries would enable materials and emissions to be shared with newer, more efficient batteries. However, as EV batteries often retain sufficient capacity for non-EV applications, a second life can improve their carbon and resource efficiency.

5 **Co-production of primary and secondary materials:** When considering whether processing primary and secondary materials together should be defined as ‘recycling’, concerns around transparency and meeting mandatory targets should be discussed. On one hand, viewing co-production as a form of battery recycling can make the processing of secondary materials more economically viable: it allows recyclers to achieve favourable energy and mass balances and optimises plant utilisation, while increasing the availability of spent LIB materials. On the other hand, blending new and recycled materials could create confusion in labelling and certification, making it difficult for consumers to distinguish between genuinely recycled batteries and those made from virgin materials. Additionally, co-production operations using pyrometallurgy cannot meet mandated lithium recovery rates, as lithium can only be efficiently recovered through dedicated processes designed to achieve the necessary lithium concentration in the slag.[11]

6 **End-to-end recycling versus a multi-stakeholder recycling value chain:** When weighing up the benefits of end-to-end operations versus the division of the value chain between multiple recyclers, several factors – such as transportation, process efficiency and cost – must be considered. On one hand, end-to-end recycling reduces environmental impact by minimising material losses and transport emissions during transitions between stages. Comprehensive control can also lead to more streamlined operations, improving efficiency, maximising material recovery and providing greater assurance that the materials will be returned to battery production. On the other hand, a multi-stakeholder recycling value chain offers flexibility and cost efficiency, making recycling operations more economically attractive. Specialisation in one aspect of the recycling value chain allows facilities to enhance process efficiency and adapt to changing market demands and technologies.

7 **Closed-loop versus open-loop recycling:** Views differ both on the quality of the materials (technical versus battery grade) and on the applications (closed-loop battery versus open-loop recycling), so further discussion is warranted. The CEID suggests that open-loop recycling is acceptable as long as secondary products maintain high quality and contribute positively or neutrally to system efficiency.[43] This approach aims to ensure that recycling remains environmentally and economically beneficial, and proposes optimal recovery targets for different materials. However, some argue that focusing on battery-grade materials is the only way to facilitate sustainable closed-loop recycling, which prevents materials from leaving the system; while others contend that the industry does not necessarily require quality criteria for recycled content due to sufficient existing market incentives.

8 **Evolving battery chemistries and recycling technologies:** Battery technologies are evolving fast. The growing market share of low-cost technologies such as LFP creates uncertainty around the economic feasibility of recycling. Na-ion or solid-state batteries may require different methods for sustainable recycling. Research is needed to understand how these batteries can be cost-effectively recycled without compromising sustainability. Regulations must adapt to ensure that all battery chemistries can be recycled sustainably. Recycling technologies are constantly evolving in response, introducing new solutions and potential risks. While this report does not extensively cover these emerging aspects, they should be addressed in future discussions.

GLOSSARY

Active material: Battery materials directly linked to electrochemical performance, including the cathode, anode, electrolyte and separator.

Auxiliary material input: Additional material resources required for battery recycling treatments (eg, acids and reducing agents).

Battery-grade materials: Materials of sufficient quality to use in the manufacture of new batteries.

Black mass: A fine powder containing valuable cathode and anode materials. After battery discharge and dismantling, the residual electrolyte is removed and black mass is produced through a thermomechanical process.

By-products: Outputswith an economic value above zero, for which demand at the specific production site is available and evidence can be given that the byproduct is used as intended.

Closed-loop recycling: The reuse of recyclates in the same application as the input materials (ie, they are used to produce new batteries).

Co-production: The refinement of pre-processed waste materials alongside primary materials. An example of co-production is the processing of black mass together with primary metal ores in a nickel/cobalt refinery process.

Direct recycling: The recovery of cathode and anode active materials without breaking down their crystalline structure.

Discharge: The controlled release of residual stored energy contained within a battery.

Dismantling: The disassembly of the outer components of the battery to reach the module or cell level, following its removal from the host and collection/transportation.

Functional recycling: A process that prioritises the retention of material functionality, allowing secondary material to displace the same primary material.

Hydrometallurgical treatment: The use of chemical solutions to leach and extract target metals from battery waste through a three-step process: leaching; purification; and precipitation (manganese, lithium), crystallisation (cobalt, nickel) or electrowinning in some cases.

Intermediates: Materials and substances produced that require further recycling processing before they can become products.

Mechanical processing: The physical breakdown of battery packs, modules and/or cells through a shredding process.

Non-active materials: Battery materials not directly linked to electrochemical performance, including the casing and electrical components.

Open-loop recycling: The use of recyclates in different applications (eg, repurposing nickel from batteries in the production of steel alloys).

Post-consumer materials: Batteries removed from the host vehicle, potentially after multiple reuse lives and ideally having reached the end of their serviceable lifespan.

Pre-consumer materials: Manufacturing scrap generated during the production of cells/modules/packs as a result of process start-up, trimmings and off-spec components.

Preparation for recycling: The treatment of waste batteries prior to any recycling process, including the storage, handling and dismantling of battery packs and the separation of fractions that are not part of the battery itself (EU Battery Regulation, Article 3, 1).

Products: Outputs that the (recycling) process is operated for and optimised to produce.

Pyrometallurgical processes: The extraction of metal by heating the battery/module/cell scrap, producing a metallic alloy, slag and gases. Pyrometallurgy includes high-temperature processes such as roasting and smelting.

Recyclates: Secondary raw materials recovered through recycling (in particular, purified active material or metals and substances contained therein – for example, as metallic salts or in elemental form) of a quality comparable to that of primary raw materials. Can be used as input for the manufacture of new products.

Recycled content: The volume of secondary material(s) in the overall material(s)/product.

Recycling: Any recovery operation by which waste materials are reprocessed into products, materials or substances, whether for the original purpose or for other purposes. It includes the reprocessing of organic material, but does not include energy recovery and reprocessing into materials that are to be used as fuels or for backfilling operations. (Waste Directive, Article 3, referenced in the EU Battery Regulation, Article 3, 2(a).)

Recycling process: Any reprocessing operation, as referred to in Article 3(8) of the EU Battery Directive, which is carried out on waste batteries and accumulators and which results in the production of output fractions. The recycling process does not include sorting and/or preparation for recycling/disposal and may be carried out in a single facility or in several facilities.

Technical-grade materials: Materials that may have use in other industries and that are of insufficiently high quality for the battery industry. For instance, technical-grade lithium carbonate is cheaper than battery-grade material, has a higher iron concentration and can be used in applications such as glass or ceramics.

Thermal pre-treatment: Controlled deactivation, discharge and decomposition to remove carbon and organic components.

Waste: An output with zero or negative economic value that requires disposal.

LIST OF ABBREVIATIONS

Abbreviation	**Meaning**
BaaS	Battery-as-a-service
BMS	Battery management system
CEID	Circular Economy Initiative Germany
CLEPA	European Association of Automotive Suppliers
CRMA	Critical Raw Materials Act
DDR	Damaged, defective, and recalled
DRS	Deposit return scheme
EOL	End-of-life
EOLf	Final end-of-life
EOL1	Initial end-of-life
EPR	Extended producer responsibility
ESPR	Ecodesign for Sustainable Product Regulation
ETC	Energy Transition Commission
EU	European Union
EV	Electric vehicle
GBA	Global Battery Alliance
GHG	Greenhouse gas
GWh	Gigawatt-hour
HF	Hydrogen fluoride
ICE	Internal combustion engine
IDIS	International Dismantling Information System
IDSA	International Data Spaces Association
IMDS	International Material Data System
ILO	International Labour Organization
IRA	Inflation Reduction Act
ISO	International Organization for Standardisation
ISRI	Institute of Scrap Recycling Industries
JRC	Joint Research Centre
LCA	Lifecycle assessment
LCO	Lithium cobalt oxide
LMO	Lithium manganese oxide
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
MaaS	Mobility-as-a-service

Abbreviation	**Meaning**
NCA	Lithium nickel cobalt aluminium oxide
NMC	Nickel manganese cobalt oxide
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
PFAS	Per- and polyfluorinated substance
PRO	Producer responsibility organisation
PVDF	Polyvinylidene fluoride
R&D	Research and development
SME	Small or medium-sized enterprise
SoH	State of health
TEA	Techno-economic assessment
TRL	Technology readiness level
Twh	Terawatt-hour
UNEA	United Nations Environment Assembly
UNEP	United Nations Environment Programme
UNFCCC COP	United Nations Framework Convention on Climate Change Conference of the Parties
VOC	Volatile organic compound
WEEE	Waste electrical and electronic equipment
WEF	World Economic Forum

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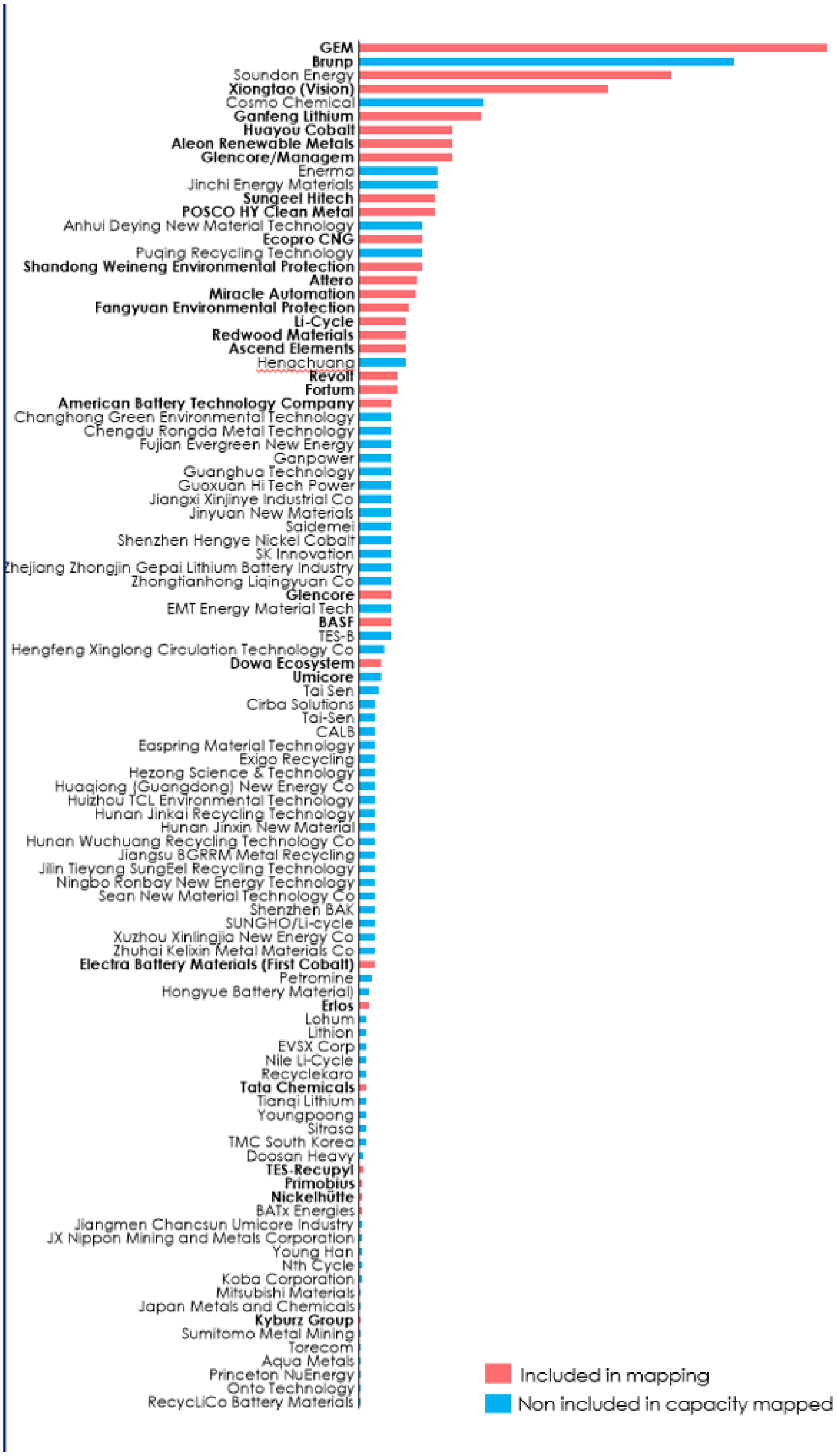
ANNEXES

I. Overview of main regulation mandates

Regulation	**Key focus**
EU	
EU Green Deal (2019)	A package of green transition policy initiatives aimed at reaching climate neutrality by 2050.
Strategic Action Plan for Batteries (2019)	Aimed at reducing dependency on non-EU countries and ensuring safe and clean recycling.
EU Battery Regulation (2023)	Aimed at reducing the environmental and societal impacts across all lifecycle phases, advancing the circular economy and enhancing the operational efficiency of the domestic market.
Critical Raw Materials Act (2023)	Aimed at securing access to a domestic, diversified, affordable and sustainable supply of critical raw materials.
EU Taxonomy (2020)	A classification system for sustainable economic activities, one of the principles being the transition to a circular economy.
EU Battery Directive (2006)	Sets targets for maximum quantities of materials in batteries, that are of insufficiently high waste battery collection rates, as well as financial liability for waste collection and management.
Net Zero Industry Act (2023)	A framework of measures to strengthen Europe's manufacturing ecosystem for net-zero technologies. States that 90% of battery demand within the EU should be met by EU manufacturers, covering at least 550 GWh by 2030.
USA	
Inflation Reduction Act (2022)	Aimed at achieving climate goals while strengthening the domestic market. Among other things, it aims to strengthen local recycling efforts relating to EV supply chains, ensuring the availability of materials. Tax advantages such as the clean vehicle credit and other subsidies encourage localisation of supply chains and EV adoption. The advanced manufacturing production credit incentivises domestic battery manufacturing.
Federal Bipartisan Infrastructure Law (2021)	Provides $3 billion for a programme focused on the processing of battery materials, and an additional $3 billion for the support of domestic battery manufacturing and recycling.
China	
Interim Measures for the Management of Recycling and Utilisation of New Energy Power Vehicle (2018)	Places responsibility for battery recycling on auto manufacturers.

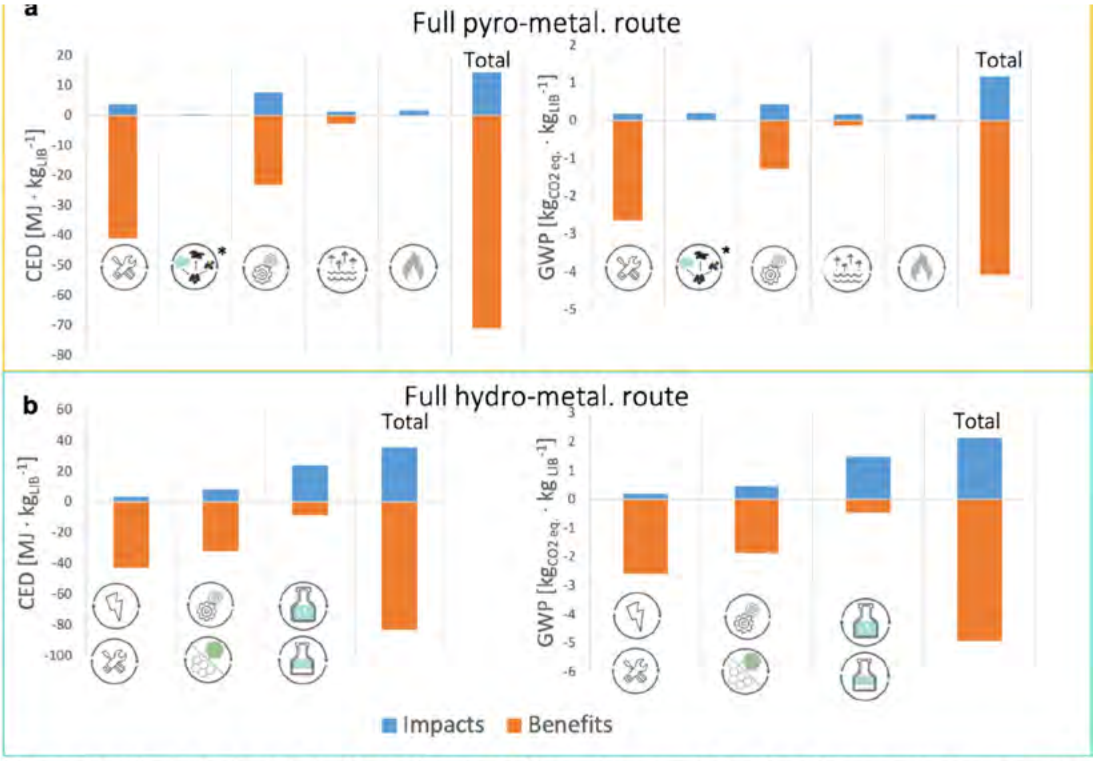
Interim Provisions on the Management of Traceability of Recycling and Utilisation of New Energy Vehicles Power (2018)	Mandates information on battery recycling for manufacturers, automakers and recyclers to evaluate recycling effectiveness.
Guidelines on Construction and Operation of Power Battery Recycling Service Network for New Energy Vehicles (2019)	Narrows the definitions for lithium-ion battery recycling facilities.
Measures for the Administration of Echelon Utilisation of Power Batteries in New Energy Vehicles (2021)	Standardises the quality and recycling of second-life, repurposed and remanufactured batteries.
Code for Recycling and Dismantling of Vehicle Power Batteries (GB/T33598-2017)	Governs safety measures, procedures, storage and management of vehicle batteries.
Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution (2020)	Introduces a credit record system for managing solid waste, including LIBs.

II: Global capacity of LIB recycling according to battery circularity advisory firm Circular Energy



Storage

III: Wagner-Wenz et al figure depicting the results of Oko Institut LCAs[58]



* The publication by Buchert et al. refers to this step as "thermal treatment", but from the process management it can be assumed that pyrolysis is carried out.

Figure 6. (a) The impacts, benefits, and recovered materials presented for each process step in the system boundaries of the full pyro-metallurgical and (b) hydro-metallurgical route.[121, 122]

Adaptations made for visuals in Chapter 4:

- Operational steps are labelled to align with the language employed throughout the report.

IV: Lander et al disassembly TEA findings[69]

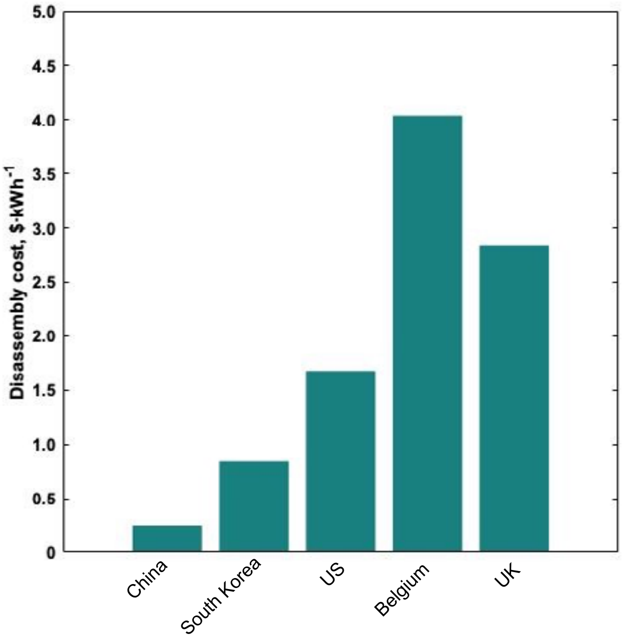
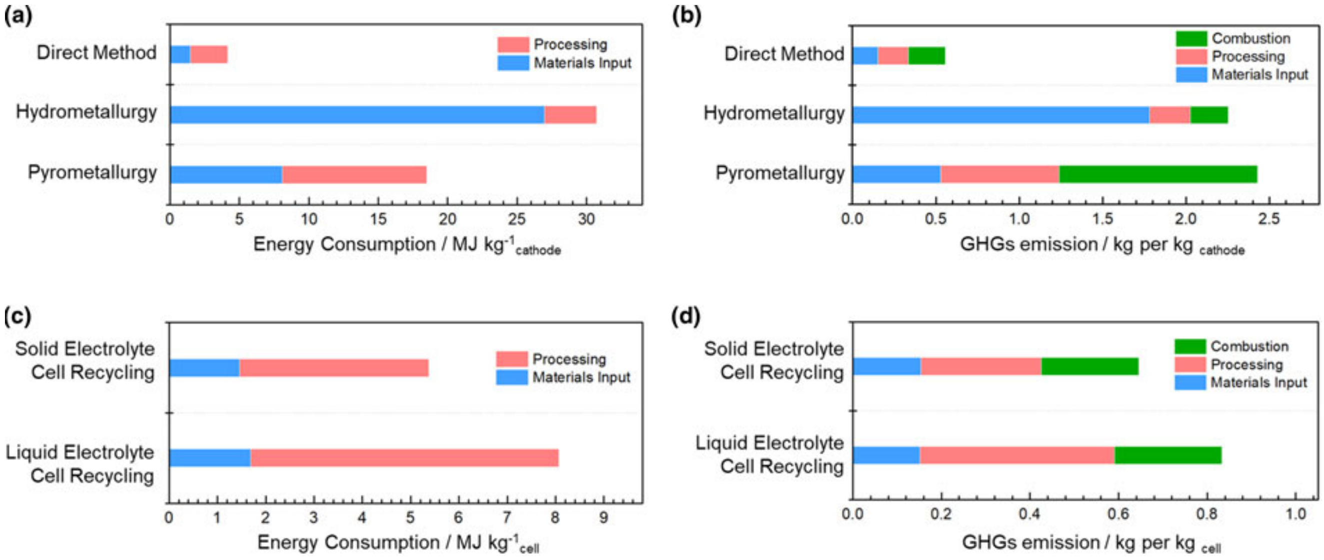


Figure S5. Disassembly cost, related to STAR Methods.
Disassembly cost, given in $·kWh^{-1} for a Tesla Model S battery pack dismantled in the selected countries.

Adaptations made for visuals in Chapter 4:

- Language changed to align with definitions employed throughout the report.

V: Tan et al LCA findings[72]



Adaptations made for visuals in Chapter 4:

- Data regarding solid electrolyte batteries and direct recycling was omitted, as these topics are out of scope.
- GHG emissions graph was converted into a pie chart.

VI: Thompson et al TEA findings comparing processes that include and omit dismantling[96]

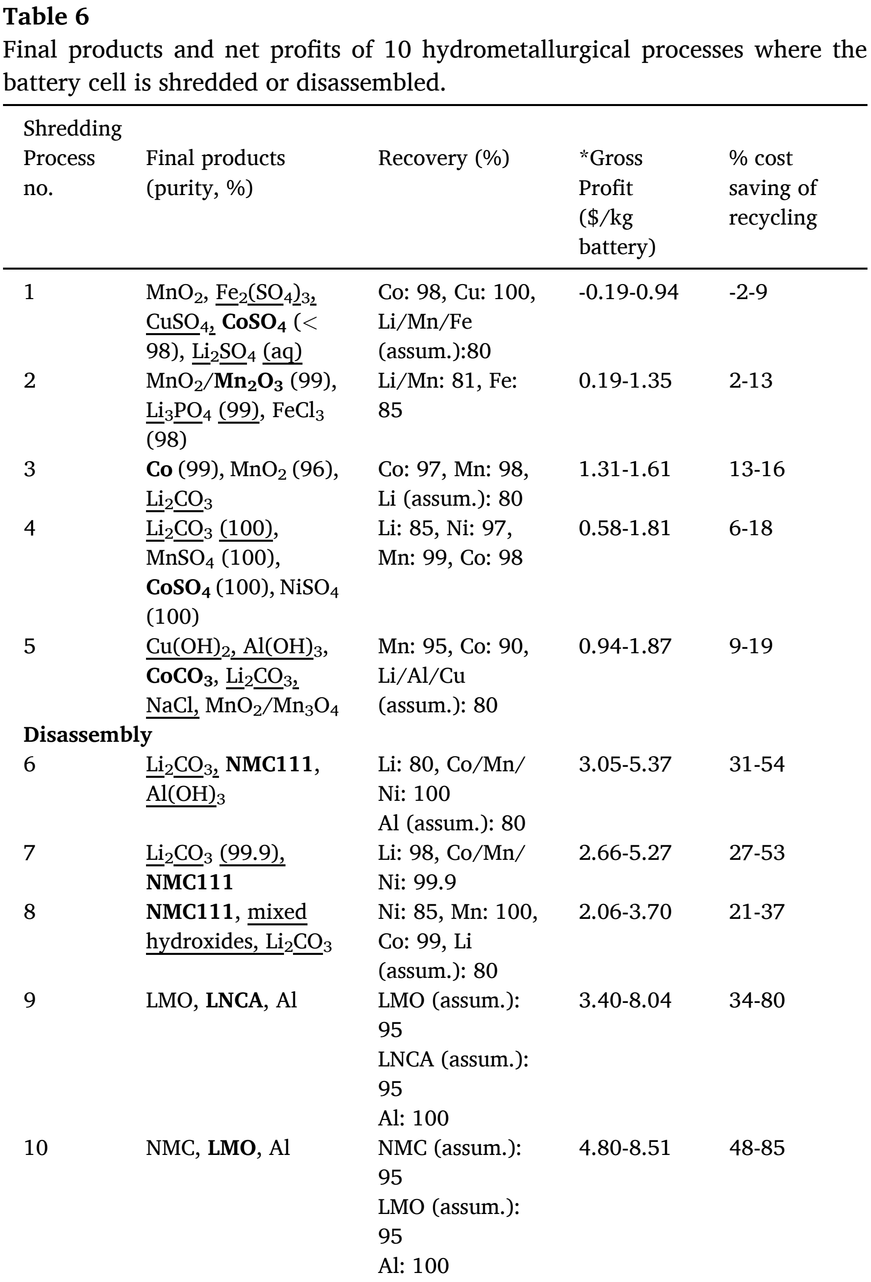


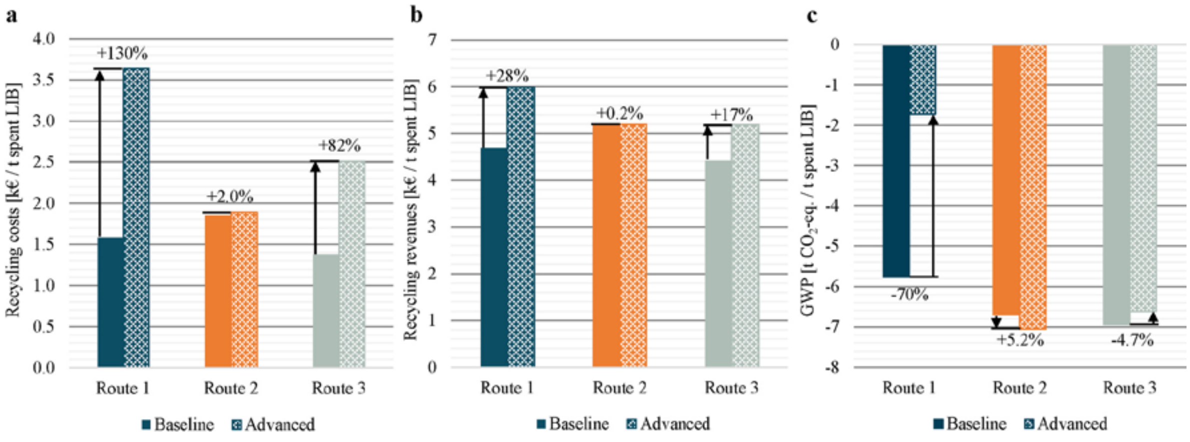
Table 6
Final products and net profits of 10 hydrometallurgical processes where the battery cell is shredded or disassembled.

Shredding Process no.	Final products (purity, %)	Recovery (%)	*Gross Profit ($/kg battery)	% cost saving of recycling
1	MnO_2, $Fe_2(SO_4)_3$, $CuSO_4$, **$CoSO_4$** (< 98), Li_2SO_4 (aq)	Co: 98, Cu: 100, Li/Mn/Fe (assum.):80	-0.19-0.94	-2-9
2	MnO_2/**Mn_2O_3** (99), Li_3PO_4 (99), $FeCl_3$ (98)	Li/Mn: 81, Fe: 85	0.19-1.35	2-13
3	**Co** (99), MnO_2 (96), Li_2CO_3	Co: 97, Mn: 98, Li (assum.): 80	1.31-1.61	13-16
4	Li_2CO_3 (100), $MnSO_4$ (100), **$CoSO_4$** (100), $NiSO_4$ (100)	Li: 85, Ni: 97, Mn: 99, Co: 98	0.58-1.81	6-18
5	$Cu(OH)_2$, $Al(OH)_3$, **$CoCO_3$**, Li_2CO_3, NaCl, MnO_2/Mn_3O_4	Mn: 95, Co: 90, Li/Al/Cu (assum.): 80	0.94-1.87	9-19
Disassembly				
6	Li_2CO_3, **NMC111**, $Al(OH)_3$	Li: 80, Co/Mn/ Ni: 100 Al (assum.): 80	3.05-5.37	31-54
7	Li_2CO_3 (99.9), **NMC111**	Li: 98, Co/Mn/ Ni: 99.9	2.66-5.27	27-53
8	**NMC111**, mixed hydroxides, Li_2CO_3	Ni: 85, Mn: 100, Co: 99, Li (assum.): 80	2.06-3.70	21-37
9	LMO, **LNCA**, Al	LMO (assum.): 95 LNCA (assum.): 95 Al: 100	3.40-8.04	34-80
10	NMC, **LMO**, Al	NMC (assum.): 95 LMO (assum.): 95 Al: 100	4.80-8.51	48-85

Adaptations made for visuals in Chapter 4:

- Routes specifying direct recycling techniques only (9 and 10) were omitted, as this recycling approach was out of scope.

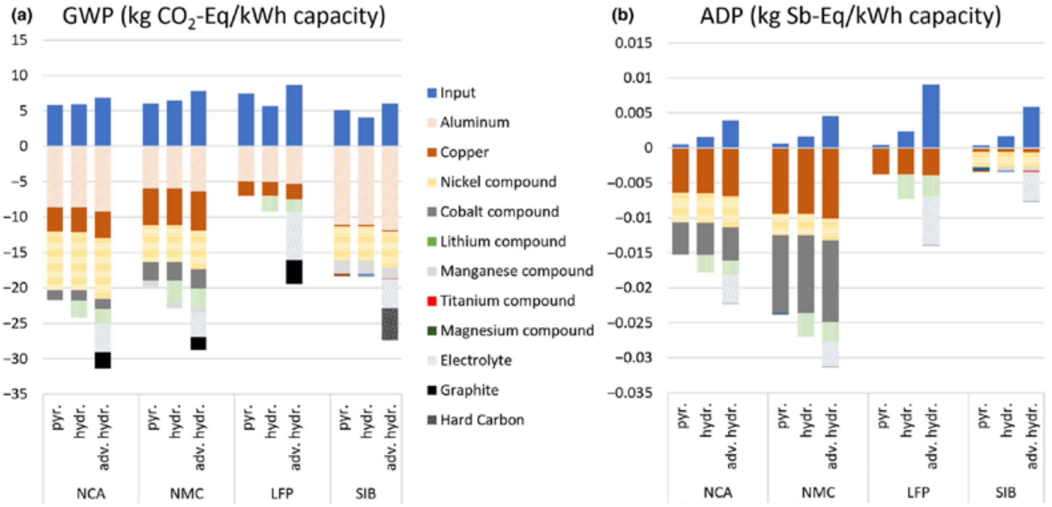
VII: Blomeke et al LCA and TEA findings[55]



Adaptations made for visuals in Chapter 4:

- Route 2 shown in the figure above was removed, as the process does not use pyrometallurgy in combination with hydrometallurgy and therefore was not relevant to Route Feature #4.

VIII: Mohr et al LCA findings[64]



Adaptations made for visuals in Chapter 4:

- ‘Pyr’ data omitted, as this treatment does not exclude thermal processing and therefore does not apply to Route Feature #5.
- Na-ion data removed, as this battery chemistry was out of scope.

IX: Recommendations for policy makers and industry to support investments in sustainable battery recycling

Recommendations for policy makers

Lever	Recommendations	Examples
Link grants to strict sustainability criteria	**Grants should require adherence to strict sustainability (environmental, social, safety) criteria. Grants may address:** • **battery recycling processes** that are not currently cost effective but meet defined sustainability criteria (eg, investment grants to establish facilities for innovative, low-emission or high-yield technologies); and • **older recycling facilities** (eg, upgrade grants to meet evolving sustainability standards). **Sustainability requirements should not complicate application or permitting processes.** Rather, processes should be simplified to reduce timeframes and streamline procedures.	• Recycling is classified a sustainable economic activity under the **EU Taxonomy Regulation** and should follow the latest best available techniques, achieve specific efficiencies and meet the requirements for industry emissions. However, clear criteria, third-party auditing and actionable definitions are needed to implement these requirements effectively.[79] • **The EU Critical Raw Materials Act** supports sustainable raw material projects after their sustainability assessment, emphasising compliance with relevant EU legislation, international standards and certification schemes. It aims to simplify permitting procedures for critical raw materials projects in the EU, while maintaining strong social and environmental protections. Strategic projects benefit from shorter permitting timeframes, single national authority interactions, streamlined environmental assessments and the use of the Single Digital Gateway. InvestEU partners will collaborate with the European Commission to provide financial support, enhancing synergies with existing funding programmes. • Regulations in **China** and the **US** aim to incentivise the scale-up of the recycling industry. In China, local governments are incentivising local battery recycling;[71] while the US Federal Bipartisan Infrastructure Law has allocated $3 billion for battery material processing and $3 billion for domestic battery manufacturing and recycling. However, this should not come at the cost of sustainability; therefore strict requirements will be needed.

Recommendations for policy makers (continued)

Lever	Recommendations	Examples
Introduce tax reductions for sustainable recycling projects	**Tax reductions may address:** - projects investing in sustainable (eg, low-emissions) recycling **machinery**; and - projects aimed at building recycling facilities with the most **sustainable technology and processes** available.	- Regulations that focus on localisation can help to scale the recycling industry. However, to be eligible for tax reductions, companies and projects should adhere to sustainability criteria. For instance, the US **Inflation Reduction Act** offers tax credits of up to 30% for eligible recycling projects, emphasising domestic sourcing. It encourages the use of recycled materials through tax credits – although these can also be secured by using virgin minerals from selected markets.[71]
Implement fiscal policy instruments incentivising recycling or recycled content	**Instruments include sustainability targeted pricing and taxing – for example:** - **carbon pricing** to incentivise the use of recycled materials with lower environmental impacts;[15] and - **material-specific taxation**, which should be carefully designed to avoid increased supply constraints or perverse economic incentives.[15]	- **The California Cap-and-Trade Program** currently addresses approximately 75% of the state's GHG emissions across sectors including transportation, buildings, industry and power. - **South Korea** covers 70% of its emissions by implementing carbon pricing in sectors such as power, industry, aviation, buildings and waste management. - **Carbon pricing within the private sector** can incentivise suppliers and partners to reduce emissions. For example, BP raised its internal carbon price as a foundation for risk assessments and profitability forecasts; while Microsoft introduced an internal self-imposing tax for its emissions.[80]

Recommendations for industry leaders

Lever	Recommendations	Examples
Prioritise sustainability when investing in battery recycling	**When investing, companies should follow stringent sustainability criteria. Such investments can:** - cut costs; - boost efficiency; and - be supported by grants or tax reductions. These investments can be made through strategic partnerships and may cover the entire recycling system to increase effectiveness.	- Partnerships can facilitate the development of a (local) recycling ecosystem. For example, **Brunp** in China (a CATL affiliate) entered into a partnership with **BMW Brilliance** to dismantle and recycle its battery packs. **BASF SE** and **CATL** have also entered into a strategic partnership on battery recycling and cathode active materials. Its objectives include establishing a localised battery recycling network and securing a raw material supply chain in Europe.[81] Importantly, however, such partnerships would need to establish sustainability as a clear criterion
Ensure that sustainable battery recycling scales globally	**Companies can establish global partnerships to ensure safe, high-quality recycling operations, including in markets where second-life batteries are sold:** - Global South companies can share knowledge of local ecosystems; and - Global North companies can share recycling technology expertise.	- For waste electrical and electronic equipment (WEEE), the **Hinckley Recycling** e-waste facility in Nigeria partners with **Innovate UK KTN** and hosts two open innovation challenges to identify solutions for EoL treatment of LIBs. The aim is to build a foundation for more UK-Nigerian partnerships.[82].

X: Recommendations for policy makers and industry to accelerate R&D in sustainable battery recycling

Recommendations for policy makers

Lever	Recommendations	Examples
Provide funding for sustainable battery recycling R&D	• **Provide financial support for sustainable battery recycling research to universities, research** funders and philanthropists, including grants for international research exchanges and public-private research groups.[15] • **Establish central funding coordination centres,** focused on sustainable research, at the country or regional level to assist organisations in identifying and selecting appropriate funding opportunities.[86]	• **The EU Horizon research programme** with the BATT4EU Partnership has a dedicated budget of €925 million for battery recycling R&D.[87] • In **Europe**, up to 10 recycling firms are working with private and academic partners to enhance recycling processes (eg, ReLieVe and the MERCATOR project focus on optimised or battery-grade material recovery).[88] • **US legislation** enacted in 2021 made available $60 million to the Department of Energy ReCell R&D Center, with the aim of increasing purity from recycling.[71] • The **Japan Green Innovation Fund** has allocated ~$16 billion for R&D on carbon neutrality. • The **UK Automotive Transformation Fund** and the National Interdisciplinary Circular Economy Research Programme provide funding for R&D for the scale-up of the UK battery recycling industry.[71]

Recommendations for industry leaders

Lever	Recommendations	Examples
Enhance existing and develop novel recycling methods	**Recycling methods should:** • improve efficiency, quality and yield; • reduce inputs needed; • minimise waste, energy and pollution; • mitigate health and safety risks; and • streamline processes (eg, through automatisation).	• **CATL, Samsung** and **LG** lead the industry on R&D spend (LG spent €610 million in 2022; CATL has spent more than €450 million in recent years; and Samsung spent over €670 million in 2022).[89] Only car manufacturers have larger R&D budgets.[77]

XI: Recommendations for policy makers and industry for information access and sharing for sustainable battery recycling

Recommendations for policy makers

Lever	Recommendations	Examples
Establish and operate (battery) databases	**Publicly operated databases can enable gap analysis of recycling and battery materials, and tracking to prevent illegal exports.[90]** **Databases should:** • be standardised, digital and global; • facilitate the collection, reporting and sharing of data across companies and countries; • make certain data publicly available and provide customisable, in-depth data to recycling stakeholders; • include data on batteries in the system, predictive EoL timelines, waste streams (including exports), available recyclable materials and recycling capacity; and • adhere to competition and confidentiality regulations while safeguarding intellectual property through data governance frameworks (eg, standardised interfaces and transparent protocols). To be effective, these databases would need to be **enforced by supranational entities**. However, gathering data globally will be difficult. Today, companies mostly rely on private, tailored data sets. These **private-sector solutions** can complement public databases.[15],[43]	• **International forums** such as the UN Framework Convention on Climate Change Conference of the Parties and UNEP gatherings can serve as opportunities to establish a global data governance framework.[15] • In accordance with the requirements of the **EU Critical Raw Materials Act**, member states should develop a database of relevant information to promote recovery, including critical raw materials in waste facilities. Information collection should be prioritised, focusing on the largest facilities. Compliance with EU competition rules will need to be ensured. • Under the **EU Battery Regulation**, producers and waste management operators must report battery (waste) related data to competent authorities. Some of this information is relayed by member states to the European Commission via an electronic system.[36] • The **California Advanced Clean Cars II Regulations** mandate manufacturers to disclose battery information through an online data repository accessible via digital identifiers.[71] • Guiding principles for databases can be drawn from initiatives such as the International Data Spaces Association, which aims to promote a global, secure data-sharing system; and **Gaia-X**, which seeks to establish a secure data infrastructure for Europe.

Recommendations for policy makers (continued)

Lever	Recommendations	Examples
Mandate and standardise information sharing (eg, via a battery passport)	**A battery passport is an electronic record containing battery model and individual usage data. As a tool to ensure traceability, it can:** • impact the future management of EoL LIB waste streams;[21] • streamline recyclers' operations; • reduce costs and enhance yield via improved process control;[91] and • if persisting post-recycling, serve as credible proof of origin of recycled content.[36] **To globally expand battery passports,** policy makers can: • standardise reporting criteria and technical frameworks; • integrate existing systems and initiatives; and • provide support to SMEs to develop these passports.[86],[91]	• Under the **EU Battery Regulation**, a battery passport will be required from 2027. Required information relevant to recycling includes battery details such as materials, performance and durability, and dismantling instructions. • In 2018, **China** initiated a high-voltage battery tracing system for EoL tracking and recycling. Aligning with the EU Battery Regulation, China is working on a digital battery passport to facilitate trade.[91] • The **Battery Pass Consortium** brings together different stakeholders to develop guidance to accelerate the adoption of battery passports.

Recommendations for industry leaders

Lever	Recommendations	Examples
Deploy traceability systems for batteries	**A traceability system for batteries can be used to:[36]** • record and trace battery or material journeys upstream and potentially downstream; • enhance the credibility of a battery's carbon footprint, including the recycled content; • follow a unique identifier assigned to secondary materials to validate their origin or certify sustainable recycling; and • if utilised downstream, prevent batteries from escaping the system.	• **Many examples of traceability** solutions exist: Circulor uses AI and blockchain for supply chain traceability; Everledger enhances global supply chain transparency through technology solutions; Circularise offers a blockchain platform for digital product passports and secure data exchange; and Minespider employs blockchain for collecting and communicating supply chain data.

Recommendations for industry leaders (continued)

Lever	Recommendations	Examples
Establish or join information-sharing systems or networks	**Information sharing on battery composition, hazards, structure and disassembly can:** • facilitate safe, sustainable recycling; and • save time and energy costs. Alongside cross-industry solutions such as the battery passport, **industry-led information systems can further improve data sharing. These should:** • be tailored towards information needs at battery EoL; • encompass information from, and be accessible to, the automotive, logistics, waste and recycling sectors; and • ensure that access rights are based on individual data requirements, respecting confidentiality and IP considerations.	• The **International Material Data System (IMDS)** is a widely adopted global data system in the automotive industry. It breaks down automotive structures into components, semi-components, materials and substances. Extending access to this information to battery EoL could streamline recycling processes.[92] • The **International Dismantling Information System (IDIS)** serves as the automotive industry's central repository for EoL vehicle treatment data, providing dismantling and safety information – including on batteries – provided by 26 vehicle manufacturers.[93] • **Catena-X** is an open data ecosystem fostering collaboration in the automotive industry, with the goal of standardising global data exchange.[94]
Deploy battery analytics and intelligence tools at battery EoL	**Battery analytics or intelligence software should be:** • extended and effectively employed by dismantlers, recyclers and OEMs, among others, for efficient battery fleet management. **To succeed, BMSs are required which:** • are accessible by sorters and recyclers; and • integrate more advanced diagnostic capabilities in future.[95]	• The **EU Battery Regulation** requires the reporting of dynamic battery data such as remaining capacity, state of charge and remaining power via the battery passport; and which specifies which groups can access this information.[36] • **Examples of battery analytics companies:** TWAICE provides predictive battery analytics software; and Voltaiq offers an Enterprise Battery Intelligence platform to enhance battery performance optimisation.

XII: Recommendations to policy makers and industry on recycling targets to promote sustainable battery recycling

Recommendations for policy makers

Lever	Recommendations	Examples
Set ambitious battery collection and recycling targets to enhance recovery and reduce losses	• Recycling targets can **enhance collection and recycling efforts.** • As between ~ 30% and 40% of a battery is comprised of substances which are challenging to recover in high quality or at a reasonable cost (eg, the electrolyte, plastics and graphite), **recycling targets for the entire battery should be flexible or focused at the cell level.**[43],[96] • Only recovered materials replacing primary ones should be counted in '**EOL** recycling rates'.[90]	• The **South Korean** government sets an annual recycling target for electronic waste and EoL vehicles.[97] • In the **EU**, 65% of LIBs should be recycled by 2025 and 70% by 2030.
Set ambitious material recovery targets	• Ambitious material recovery targets will help to **phase out inefficient recycling processes.** • Recovery targets should **evolve in line with industry advancements**, such as the best available technology approach, and should be assessed regularly.[43] They should **cover the entire value chain to ensure high-quality output** that supports continued cycling.[90] • For **lower-value materials**, mandatory recovery targets can help to promote LFP battery recycling, among other things.[71] • However, strict electrolyte, plastics or graphite recovery rates should **not compromise the recovery of high-quality battery materials** or worsen the overall energy balance.[43] • Appropriate **waste management** of materials such as gypsum or graphite should be ensured.	• **China** sets voluntary recovery targets for lithium (85%), cobalt (98%), nickel (98%) and manganese (98%), which must be met to qualify for voluntary certification.[71] • The **EU Battery Regulation** sets mandatory recovery targets for 2027/2031 for lithium (50/80%) and for cobalt, copper, lead and nickel (90/95%). • The **CEID** Traction Batteries Working Group recommends specific ambitious recovery rates, as depicted in Information Box 12.

Recommendations for policy makers (continued)

Lever	Recommendations	Examples
Set material-specific minimum recycled content targets to support closed-loop recycling	• Minimum recycled content targets can ensure **high purity of recycled materials** and encourage closed-loop recycling.[71] • However, very high recycled content targets in certain regions might lead to **premiums for secondary materials.** • Only post-consumer recycled content (ie, EoL batteries) should count towards recycled content targets. For pre-consumer waste, clear guidelines are needed on what should and should not count for such purposes. **All materials from mining and refining activities should be excluded,** to prevent uncertified mined material from being claimed as recycled content. • The Battery Pass Consortium suggests **that pre and post-consumer recycled content should be calculated separately** to identify issues at EoL, enhance data transparency and improve forecast comparisons.[36]	• The **EU Critical Raw Materials Act** aims to ensure that recycled material meets 15% of demand for critical metals by 2030. • The **EU Battery Regulation** sets recycled content targets for cobalt (16/26%), lithium (6/12%) and nickel (6/15%) by 2031/2036. Recycled material is expected to meet demand for lithium and nickel by the early 2030s, although a potential cobalt shortage is predicted, according to forecasts by Strategy& and PEM.[5] The regulation includes post-consumer and manufacturing waste, excluding manufacturing scrap ('run-around scrap'). 'Battery manufacturing waste' is defined in the Regulation as 'materials or objects rejected during the battery manufacturing process, which cannot be re-used as an integral part in the same process and need to be recycled'. • **South Korea** mandates recycled content targets for minerals such as nickel, cobalt and copper. • **India** is seeking to ensure that 5% of new batteries use recycled material by 2027, increasing to 20% by 2030.

INFORMATION BOX 12: CEID TRACTION BATTERIES WORKING GROUP RECOMMENDATIONS ON RECOVERY TARGETS[43]

Material	**Recommended recovery rates**	
	2025 Binding	**2030 to be aspired to**
Total battery	60%	70%
Lithium	50%	85%
Colbalt	85%	90%
Nickel	85%	90%
Copper	85%	90%
Steel	90%	95%
Aluminium (without Al foil)	90%	95%

The recommended recovery targets are based on shared technical expertise which can be implemented in practice and which takes into account the results of the entire recycling process. The recommended values should be understood within the context of the system limits, definitions and further explanations set out in the report entitled *Resource-Efficient Battery Life Cycles*, produced by the CEID and informed by expertise from academia and industry.

XIII: Recommendations for policy makers and industry on the development and implementation of standards for sustainable battery recycling

Recommendations for policy makers

Lever	Recommendations	Examples
Establish and enforce sustainable battery recycling requirements	**Establish sustainable battery recycling regulations by aligning with:** • industry best practices; and • ambitious third-party standards and guidelines issued by global policy forums and intergovernmental organisations. **Enforce sustainability requirements through measures such as:** • audits (eg, leveraging experience from audits under the EU Conflict Minerals Regulation); • penalties for non-compliance; and • third-party verification, including officially recognised certification schemes, to prove compliance with legal requirements.	• The **EU Battery Regulation** mandates battery due diligence, including for secondary raw materials. Economic operators that place batteries on the market must establish and report their management systems and risk management plans. Internationally recognised standards and tools – for example, issued by the UN or the OECD (eg, guided by the *OECD Handbook on Environmental Due Diligence in Mineral Supply Chains*) – should be utilised. Due diligence schemes that can demonstrate compliance with the regulation will be recognised and the equivalence approach is under development. Due diligence schemes should include and validate best practices on sustainable battery recycling; otherwise, schemes focused specifically on recycling are needed. • **Due diligence regulations** such as the EU draft Corporate Sustainability Due Diligence Directive and the German Supply Chain Act require companies – including recyclers – to establish due diligence procedures to verify suppliers. • **China** maintains a 'whitelist' of officially approved recyclers that adhere to specific recycling standards relating to technology, efficiency and environmental protection. Meanwhile, Regulation GB22128 sets standards for sites, personnel, facilities, equipment and safety protection during the dismantling process.[107] • Common **health and safety standards** include ISO 45001 and standards of the International Labour Organization (ILO), which has adopted more than 40 standards on occupational health and safety. • In **South Korea,** EoL vehicle recycling facilities must register with relevant authorities to confirm compliance with the necessary standards and guidelines.[97]

Recommendations for industry leaders

Lever	Recommendations	Examples
Follow a sectoral approach to define sustainability best practices	**Industry should align on sustainability best practices by:** • following a sectoral approach, with the participation of and thought exchange between industry and different associations; • consulting with academia and civil society (eg, on defining red lines); and • building on existing guidelines. **Third-party assurances for sustainable battery recycling (eg, certifications) can be developed,** which should be recognised under relevant regulations.	• **Sustainable Electronics Recycling International's R2 Standard** aims to promote responsible practices for used electronics, and certifies facilities by auditing them against criteria relating to responsible reuse and recycling practices.[108] • Certification schemes for (battery) **material sourcing and processing** have been established by the industry – for example, through collaborations between mining companies. Examples include the Initiative for Responsible Mining Assurance and CERA 4in1. Such schemes should be established and implemented across the battery recycling industry.
Develop sustainable battery recycling standards with standardisation organisations	**Develop sustainable battery recycling standards by:** • working with standardisation organisations (eg, the International Organization for Standards, the European Committee for Standardization and the European Committee for Electrotechnical Standardization (CENELEC), the American National Standards Institute, the Standardisation Administration of China and the German Institute for Standardisation); and • ensuring industry-wide standardisation by following a multi-stakeholder process.	• The **EU CENELEC EN 50625 standard for WEEE** sets requirements for monitoring the treatment and collection process, determining recovery rates and monitoring the de-pollution of chemical substances. A similar standard is needed for LIBs. • **China** has adopted the YS-T 1460-2021 standard on battery precursor materials, which is important for the international trade of waste materials and allows imports to China.[109]

XIV: Recommendations for policy makers and industry for increased transparency in battery environmental footprints

Recommendations for policy makers

Lever	Recommendations	Examples
Define battery environmental footprint calculation and reporting rules, including in relation to recycling and recycled content	**Clear and harmonised environmental footprint rules are needed.** The environmental footprint for recycling and recycled content will be influenced by, among other things, rules on: • the EoL and recycling impact of batteries (allocation method); • the functional unit; • system boundaries; and • electricity modelling.	• The **EU Battery Regulation** establishes essential elements for carbon footprint calculation, with a detailed methodology to be specified in secondary legislation, aligned with the product environmental footprint method and category rules. The allocation of recycling processes is considered.[36] • The **JRC** of the European Commission has published guidelines for calculating the carbon footprint of EVs, with other categories to follow.
Mandate reporting on, and potentially cap, selected battery footprint(s)	**Mandatory battery environmental footprints and caps can:** • encourage producers to reduce emissions by increasing recycled content and reducing recycling emissions; • shift away from high-emission recycling processes; and • drive consumer awareness of recycling. In addition to GHGs, **other environmental footprint impact categories** should be carefully selected by assessing the severity of the risk, the availability of an established calculation method and perceived stakeholder importance.[36]	• From 2025, the **EU Battery Regulation** will require that the carbon footprint of a battery over its expected service life be declared, including through the battery passport. The Circular Footprint Formula seeks to balance accounting for both recycled content and EoL recycling.[36] • From 2026, the **EU Battery Regulation** will require reporting on the carbon footprint performance class of relevant battery models per manufacturing plant.[36] • From 2028, **manufacturers in the EU market** will have to demonstrate compliance with maximum threshold levels for lifecycle carbon footprints, with specific thresholds to be determined through delegated acts.

Recommendations for industry leaders

Lever	Recommendations	Examples
Help to shape the rules on battery environmental footprints	**Industry should help to shape the rules on battery environmental footprints to ensure that:** • sufficient details and guidance to meet the requirements in practice are included; and • the entire battery value chain is considered.	• The **Battery Pass Consortium** and the **GBA** – a collaboration between industry and academia – have developed the GBA GHG Rulebook and the Battery Pass Carbon Footprint Rules to establish a basis for measuring and optimising carbon footprints. The documents build on existing standards in compliance with regulatory requirements.[36]
Calculate and report on the battery environmental footprints	**Recyclers should calculate their environmental footprints to optimise their processes for sustainability by:** • using company-specific data or, if unavailable, industry average data; and • collecting data through upstream data exchange along the value chain.	• **Carbon footprint calculations** involve mapping input and output materials and energy for each process step, multiplied by conversion factors to determine the overall impact measured in kgCO2e. This requires consideration of bills of materials, energy usage and auxiliary materials for specific models produced at a particular plant.[36]

XV: Recommendations for policy makers and industry to support skills and job creation for sustainable battery recycling

Recommendations for policy makers

Lever	Recommendations	Examples
Develop training and upskilling programmes for sustainable battery handling and recycling	**Sustainable battery recycling training and upskilling programmes should focus on:** • staff with vocational educations (eg, technical personnel for machine operation); • preparatory training for onboarding in the recycling plants of the future;[111] • alliances for upskilling workers; • safe battery disassembly, diagnostics, testing and transport, battery chemistries, recycling processes, plants and machines; and • international knowledge transfer, including to countries of the Global South.[43] **Educational programmes can be:** • offered as joint programmes in higher education institutions to address more skills and more trainees; • offered as open online courses in addition to in-person training; and • based on ambitious and uniform EU standards for the qualification of workers, which should be defined.[104]	• The **European Battery Academy, initiated by the European Commission**, provides high-quality training programmes for the battery sector. It aims to train around 800,000 workers in the European battery industry by 2025.[112] • The **GEKONAWI Transfer** project has been funded by the German Ministry for Education and Research. This continuing education programme on sustainable business practices provides executives and educators with methods and skills for designing more sustainable work processes.[113]
Offer higher education with a focus on the circular economy	**Higher education should focus on:** • battery recycling and circular economy modules in subjects such as chemistry, material science, engineering and economics; • programmes on the circular economy, batteries, recycling and sustainable mobility, potentially offered as collaborations between universities; and • the current needs of industries, which should be regularly reviewed.[111]	• The **Technical University of Munich** offers a circular economy module which includes dismantling and recycling exercises in its Circular Economy Lab.[114] • Universities in Germany's North Rhine-Westphalia region have proposed a collaborative **circular economy master's** programme.[86] • The **Erasmus Mundus materials for energy conservation and storage joint master's degree** combines a programme on materials science and electrochemistry and a programme on energy storage.[111]

Recommendations for industry leaders

Lever	Recommendations	Examples
Establish partnerships for global knowledge transfer	**The international transfer of knowledge is important to:** - globally promote safe and sustainable battery recycling practices; and - ensure the dissemination of novel technology with reduced emissions and increased recovery rates.	- **ACE Green Recycling** has partnered with African firm **Tabono Investments** to establish a South African joint venture dedicated to LIB recycling – the continent's first such plant.[115]
Offer in-house upskilling and training on sustainable battery recycling	**The biggest challenges are reskilling and upskilling personnel and developing tailored qualifications for sustainable battery recycling. Large companies can variously offer:** - in-house training; - education on the job; - online courses to establish a basic level of knowledge on battery recycling; and - specialised paid training opportunities (eg, on battery disassembly).[104],[111]	- The **Institute of Scrap Recycling Industries** offers an online course titled 'High Voltage Electric Vehicle Technology Training for Recycling Professionals', which is publicly available online. Such training should be complemented by hands-on training and sustainability teaching.[116] - The **European Battery Business Club** offers vocational training for managers and experts along the battery value chain. This is provided online by the Fraunhofer Academy through a subscription model. Live online workshops and expert discussions are included.[117] Battery circularity should be part of such training.
Mobilise the future workforce for sustainable battery recycling	**The future workforce for safe and sustainable battery recycling can be mobilised through:** - awareness campaigns at universities and high schools; - application-oriented apprenticeships; and - lectures and trainings at universities and higher education institutions to cultivate the practical expertise needed.	- **Company education** in Germany aimed at raising interest in MINT degrees (ie, maths, computer science, natural sciences and technology) is covering sustainable batter recycling (eg, BASF's *Gläsernes Labor* programme.[118] - **Formula Student** invited student teams from more than 100 universities in the UK to submit plans for self-designed vehicles. Lithium Battery Recycling Solutions supported this event to raise awareness about battery recycling.[119] Sustainability should be at the core of such programmes.

XVI: Barriers and drivers towards battery reuse

Chapter 6.2 introduces battery reuse as a key circular economy approach to extend the lifespan of batteries and thus improve their carbon and resource efficiency. The reuse levers – information availability and accessibility; reuse-tailored regulation; and standardisation – are detailed out below.

Information availability and accessibility:

- **Developing a standardised approach for measuring and reporting the residual value of a battery is crucial, as decisions on the optimal treatment of a battery after EoL1 can be challenging.** Information such as accurate battery life models, standardised state-of-health (SoH) assessments and battery composition details are often lacking. Furthermore, accessing data is complicated, as OEMs often protect their BMS data. These factors lead to assumptions being made, lengthy testing and increased costs, potentially discouraging second-life applications and promoting blanket recycling of batteries. Furthermore, matching EoL LIBs with the requirements of reused batteries is complex. Supply is uncertain and heterogeneous, and return rates fluctuate, making predictions challenging. [43],[71],[83],[95],[120] A standardised approach for measuring and reporting the residual value of a battery should account for various battery designs and applications. Standardisation could be enforced through mandatory testing processes, supervised by independent service organisations. Ongoing standardisation efforts, such as the European Commission's Mandate M/579, focus on performance, safety and sustainability requirements for batteries. [36],[71],[83],[135]

- Regulations can mandate assessments for battery second-life viability to promote the identification of batteries suitable for a second life.

- **Rapid assessment of a battery's SoH and capacity trajectory prediction can be achieved through battery diagnostic systems.** They can be complemented by smart BMSs, enhanced in-vehicle diagnostics tools, robotic testing, battery passports and other techniques such as X-ray computer tomography or laminography. Emerging battery trading marketplaces can support the battery reuse industry by helping to determine residual values based on market demand and battery characteristics and matching batteries with suitable use cases. [3],[120],[122],[125] To make informed decisions, four types of information should be considered, as highlighted in Information Box 13. Further research, including LCAs and economic modelling, is needed to optimise the treatment of LIBs after EoL1.[95]

Reuse-tailored regulation

- To promote the actual reuse of batteries suitable for a second life, regulations can establish minimum quotas for battery reuse. This is important since existing regulations tend to prioritise recycling, with requirements for recycled content, recycling efficiency goals or incentives such as tax credits for domestically recycled materials. Alongside regulations, (BaaS) business models can promote second-life applications as manufacturers retain ownership of the battery, enabling them to monitor and reclaim batteries that still hold value for a second life.[71],[135]

- Regulatory changes should establish clear classifications distinguishing waste from non-waste batteries based on individual battery conditions. This is important since in the EU, EV LIBs are classified as waste after their first use, impacting transportation conditions and costs and thus the economic viability of returning batteries for a second life.[95],[125] Furthermore, globally harmonised definitions of terms such as ‘reuse’, ‘repurpose’, ‘second life’ and ‘recycling’ would facilitate consistent handling and reduce complexity in laws and practice. South Korea, for instance, has relaxed its rules on the collection and disposal of used batteries, classifying them as recyclable resources rather than waste materials. The EU Battery Regulation is another initiative that aims to clarify battery treatment options. [36],[120],[127]

Ownership and liability

- **Clear definitions of ownership and liability for second-life batteries should be established.** The EPR framework introduced by the EU Battery Regulation assigns EoL responsibility for second-life batteries to the economic operator that places the reused battery on the market. However, the impact on ownership and liability should be outlined more explicitly, as to date liability where a reused battery causes damage is unclear. Consequently, OEMs are hesitant to permit battery usage in grid storage unless they retain ownership, affording them the option to recycle the battery later. This lack of defined liability also deters insurance companies from engaging in EV LIB repair following accidents. Additionally, OEMs are concerned about potentially exposing their battery intellectual property through reuse, which may incline them towards recycling.

Standardisation

- **Batteries should be designed for durability and longevity to extend EoL1 and enable a second life.** Similarly, they should be designed for repair and reuse. For instance, improved battery design can decrease dismantling costs when repairing or repurposing a battery. A request for the standardisation of battery design to facilitate second-life use has been made to the EU.[95] Additionally, standardised battery management systems would enable easier and more consistent testing, thus reducing processing costs.[120]

- **To ensure a safe battery second life, safety standards for the battery repurposing process are needed. Initiatives such as the UL 1974 Standards for Evaluation for Repurposing Batteries in the US and Canada serve as examples.** Similarly, sales of second-life batteries should adhere to requirements relating to durability, safety and location restrictions. This is important as there is a lack of regulatory guarantees for the quality and performance of second-life batteries; only a few industry standards are in place; and damaged or ageing batteries might be more prone to failures and explosions.[21],[95] Standards can establish a certified test-cycle range for reused EV batteries for specific periods or distances driven. This approach – adopted in California and by the UN Economic Commission for Europe, and considered in the EU proposal for Euro 7 standards – can enhance safety.[71] In addition, the implementation of technical advancements for second-life batteries is key to ensure their safe reuse. This includes developing control strategies to stabilise power output, equalisation strategies to reduce variations in the electrochemical behaviour of individual cells or modules, and advanced fault diagnosis algorithms.[71]

INFORMATION BOX 13: INFORMATION FACTORS FOR BATTERY AFTER-USE TREATMENT OPTIONS

- **Product information:** Initial technical characteristics (eg, chemical composition), degradation level, remaining capacity (eg, SoH).
- **Process information:** Available recycling and reuse technology (capacity, utilisation, maturity), input requirements, expected outcomes (eg, recovery rates, battery capacity), and impacts (eg, emissions, safety, toxicity).
- **Market information:** Current market conditions, prices, material supply distribution and demand for materials and second-life batteries.
- **Regulatory requirements:** Quotas, goals, responsibility, liability (eg, EPR, particularly for second-life batteries) and other incentives.[43]

SYSTEMIQ

ADVANCING SUSTAINABLE BATTERY RECYCLING: TOWARDS A CIRCULAR BATTERY SYSTEM