JRC-IEA-EGRD Workshop on Clean energy supply chains

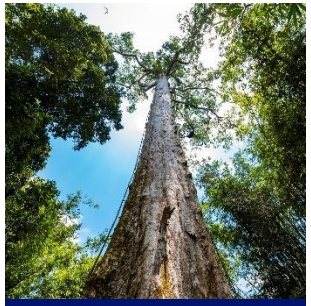
ADVANCING SUSTAINABLE BATTERY RECYCLING: TOWARDS A CIRCULAR BATTERY SYSTEM

SYSTEMIQ

SYSTEMIQ – WHO ARE WE?

Systemiq is the world's only 'pure play' climate and systems change company. Our mission is to accelerate the transition to a net-zero, nature-positive and more inclusive economy

We do this by building ambitious multi-stakeholder coalitions; advising leading companies, financial and public institutions; and investing into disruptive businesses that will scale new solutions across the energy, nature and materials systems.


NATURE


ENERGY


MATERIALS


FINANCE


CITIES

INSIGHTS AND ANALYTICS | IMPACT COALITIONS | ADVISORY

PEOPLE & PROJECTS

- ~400 employees, 18 partners
- Diverse backgrounds from
  - Consulting and finance
  - Industry
  - Public & non-profit
  - Academia
- 300+ projects since inception in 2016
- 7 major coalitions

LOCATIONS

- Headquartered in UK (London)
- Offices in
  - Brazil (São Paulo)
  - France (Paris)
  - Germany (Munich, Berlin)
  - Indonesia (Jakarta and others)
  - Netherlands (Amsterdam)

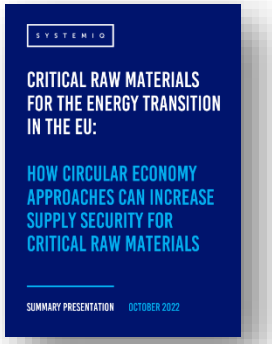
Energy Transitions Commission

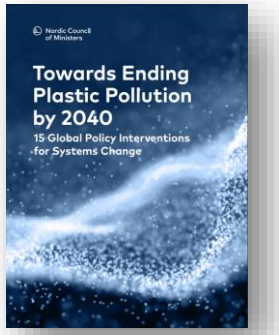
Battery Pass

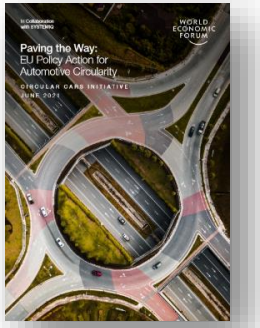
MISSION POSSIBLE PARTNERSHIP

Circular Economy Initiative Deutschland

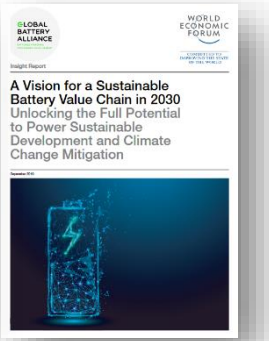


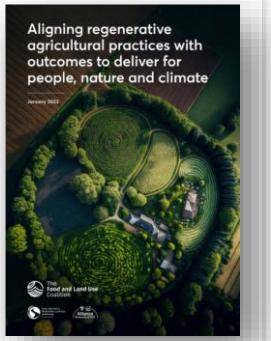












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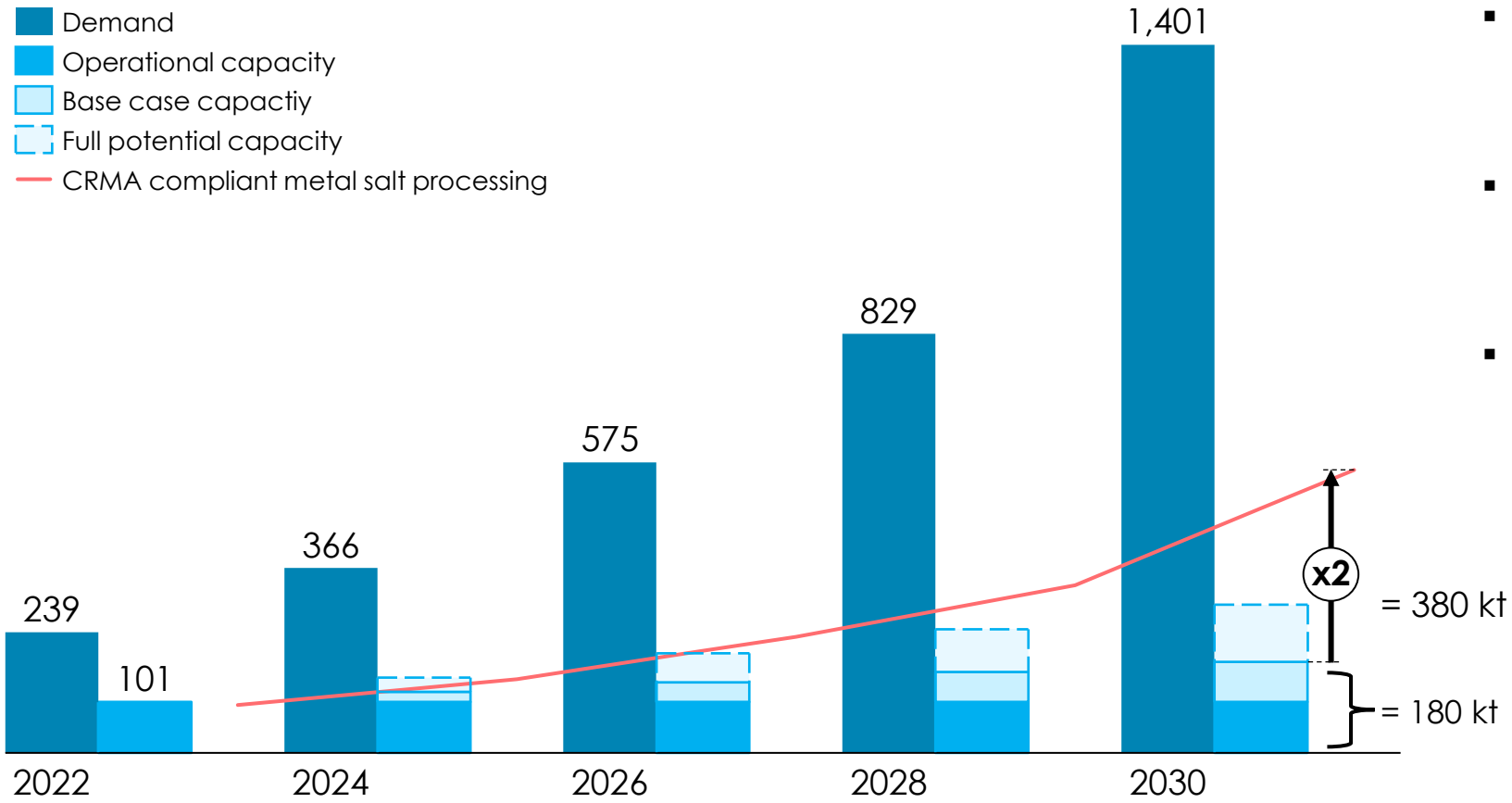
REPORT CONTEXT

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IN ORDER TO MEET THE CRMA BENCHMARK, IT IS EVIDENT THAT THE PROJECTED EU REFINING AND PROCESSING CAPACITY FALLS SHORT, NECESSITATING RESHORING

EU battery material processing supply and demand forecast [kt p.a.]



Insights

- Assuming the **base case** capacity scenario is achieved, then the EU is forecast to have **180 kt of material refining capacity by 2030.**
- This would mean **380 kt of battery material refining and processing** would require reshoring to meet the CRMA 40% benchmark.
- Even when the **full potential** of the current pipeline is forecast, the 2030 capacity **falls short of the 40% target by ~260 kt.**[1]

Note: Demand and supply is for **battery application only**, does not reflect total EU refining capacity. CRMs include lithium, nickel, manganese, cobalt and graphite. Utilisation rate of facilities not accounted for in capacity forecast. Capacity to meet CRMA benchmark calculated to meet 40% of total battery demand. [1]**CRMA must provide additional clarity** to establish if benchmark needs to be met at end-product level or per intermediaries across the value chain.
Sources: Systemiq analysis; Transport and Environment, *A European Response to the US Inflation Reduction Act* (2023); BNEF, *Equipment Manufacturers Data Hub* (2023); KU Leven, *Metals for Clean Energy: Pathways to solving Europe's raw materials challenge* (2022); SCRREEN, *CRMS 2023 factsheets* (2023)

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WE HAVE ASSESSED ENVIRONMENTAL IMPACTS OF ACHIEVING CRMA TARGETS IN REFINING

Unmitigated environmental impact of midstream production per unit of battery material

Highest impact — Lowest impact

N.B Impact factors are global averages

		Lithium	Nickel	Cobalt	Manganese	Natural graphite
Operational input	Water use			*		
	Land use[2]					
Operational output	Freshwater Eutrophication	1				
	Marine Eutrophication					
	Acidification		*		4	
	Human Toxicity - Cancerous			3		
	Human Toxicity - Non-cancerous					
	Particulate Matter Formation		2			
	Freshwater Ecotoxicity					
	Marine Ecotoxicity					5
	Terrestrial Ecotoxicity					

Insights

1 Lithium – eutrophication

- The primary contributors to eutrophication potential is the **leaching step in the upstream production** of sodium carbonate, with sodium hydroxide

2 Nickel – Particulate formation and ecotoxicity

- Smelting of sulphide concentrates generates **sulphur dioxide gas** which can result in **acid rain formation**.
- Potential **heavy metal exposure**[1] and acid rain would have harmful impact on ecosystems.

3 Cobalt – human toxicity

- Potential **heavy metal**[1] emissions; Inhalation of cobalt dust or fumes can lead to **respiratory and cardiovascular** problems such as condition known as "hard metal lung disease" or "cobalt lung."

4 Manganese – acidification

- Acidification impacts from manganese are primarily due to **nitrogen oxides and phosphates accumulation** in water environments.

5 Natural graphite – marine ecotoxicity

- Anode graphite refining wastes up to 70% of the initial graphite leading to **large quantities of waste effluent**.
- Process chemicals and effluents could have negative impacts on aquatic biodiversity through the **contamination of water resources**.

Note: (1) Heavy metals - a group of metallic elements that can be toxic at relatively low concentrations due to their ability to accumulate in living organisms and interfere with normal biological functions; (2) Land use is not analysed in depth as literature reviewed does not discuss this impact category in detail and the LCAs indicated land use is largely associated with upstream production; *see Annex A for other key environmental insights (i.e. dark cells not highlighted in insights. Sources: Systemiq analysis; Ecoinvent – cut-off approach

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FOR ALL ENVIRONMENTAL IMPACT CATEGORIES, WE FIND THAT POTENTIAL RISKS EXISTS BUT NOT ONLY ARE SMALL COMPARED TO THE CURRENT FOSSIL SYSTEM, BUT CAN ALSO BE SUCCESSFULLY MITIGATED

Key regulation mitigating environmental impact

- The following legislative instruments aid in the objective of establishing a **toxic-free environment**, as outlined in the European Green Deal (please see Appendix A for full list of relevant legislation).
- These regulations also contribute to the pursuit of the 2030 targets associated within the framework of the **zero-pollution action plan.**
- The 1st and 3rd points of the action plan state that the EU should:
  - **reduce premature deaths of air pollution by >55%;**
  - **reduce ecosystems where air pollution threatens biodiversity by 25%.**
- Policies have been developed or updated in the past 20 years. However, guidelines must be reviewed to ensure they address all impacts of the evolving industry, as well as ensuring they are equally enforced across member states.

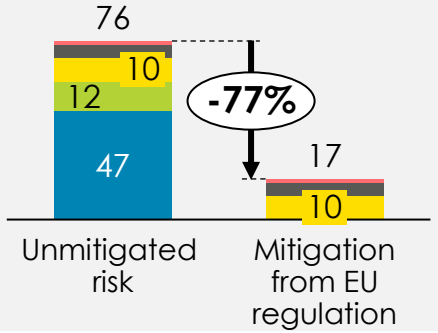
Legislative instruments	Description
National Emission reduction Commitments Directive(NECD) (2016/2284/EU)	Sets national emission reduction commitments for Member States and the EU for five key air pollutants[1].
Industrial Emissions EU Directive (2010)	Main EU instrument regulating pollutant emissions from industrial installations.
Occupational Exposure EU Directive (2017)	Lists indicative occupational exposure limit values for chemical agents.
Carcinogens, mutagens or reprotoxic (CMR) substances at work EU Directive (2004/37/EC)	Minimum requirements for protecting workers against risks to their health and safety from CMR substances.

Examples of reduced impact in the EU

Non-Exhaustive

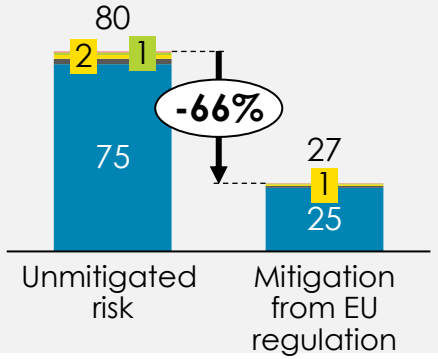
Lithium Cobalt Nickel Manganese Graphite

2030 Cancerous human toxicity [cancer cases]



- The EU carcinogens and mutagens Directive sets a **limit to occupational exposure to nickel compounds** and the commission is set to propose an occupational **exposure limit to cobalt** by the end of 2024.
- This regulation alone could **prevent up to 77% of potential cancer cases** in 2030.

2030 Particulate matter [Million kg PM2.5]



- Commitments set by EU member states in NECDs are predicted to **reduce premature deaths from fine particulate matter (PM2.5) by 66%** by 2030 from 2005 levels, overshooting the 55% target.
- Assuming unmitigated PM2.5 emissions reflect 2005 levels, by 2030 the refining fine particulate emissions would be **reduced from 80 million to 27 million kg**[2].

Sources: EU commission; SCRREEN (EU Horizon project), *Critical Raw Material factsheets* (2023)
Notes: [1]Five key air pollutants included in NECD - nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), sulphur dioxide (SO2), ammonia (NH3) and fine particulate matter (PM2.5); [2]Assumes deaths caused and PM2.5 emissions volume have a direct correlation.

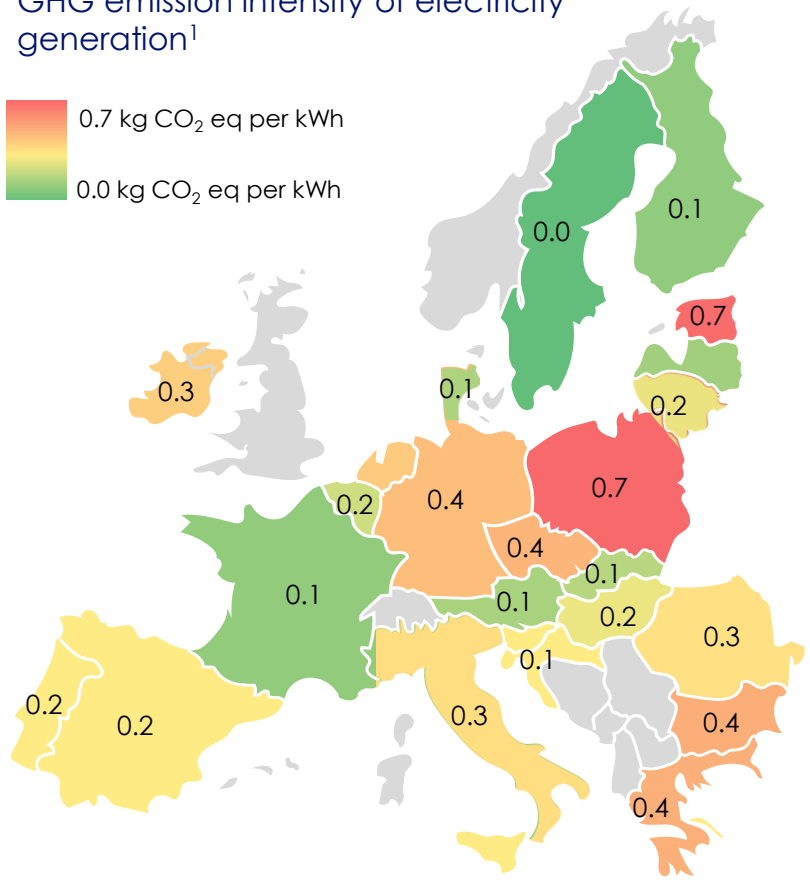
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HAVING ANALYSED CO2 FOOTPRINTS OF BATTERY MANUFACTURING, WE FIND THAT DIFFERENCES BETWEEN CHEMISTRIES ARE NOT SIGNIFICANT AND THE SECTOR'S CO2 EMISSIONS WILL BECOME SIGNIFICANT BY 2030 (BUT WOULD HAPPEN ANYWAY)

Share of GHG emissions from manufacturing energy (electricity and heat) in battery cell production [%] **and impacts from emissivity of energy input** [kg CO2 eq per kWh]

GHG emission intensity of electricity generation[1]



Type	% of GHG emissions from energy[2]	GHG emissions for battery manufacturing (kg CO2 eq per kWh) EU average vs Sweden
NMC	40%-45%	83 → 48 (-43%)
NCA	35%-40%	81 → 51 (-36%)
LFP	45%-50%	91 → 46 (-49%)
SIB	30%-35%	73 → 51 (-31%)

Insights

- The **cell manufacturing energy** (electricity and heat) represents the **largest portion of the production GHG emissions** for each cell chemistry
- **Share of manufacturing energy is the highest in LFP** batteries. This is because lower energy densities require higher volume of materials and size

Sources: Systemiq analysis; European Environment Agency – Published Oct 202; Mohr M et al. (2020)

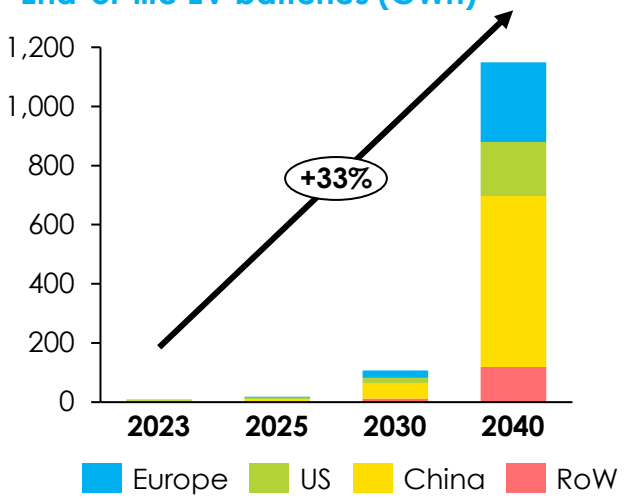
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A WHOLE NEW INDUSTRY AROUND EV BATTERY RECYCLING IS DEVELOPING, DRIVEN BY THE INCREASE IN EV BATTERIES AND THE STRATEGIC AND REGULATORY IMPORTANCE OF SECONDARY MATERIALS

1. Increasing number of EOL batteries

- Passenger electric vehicles (EVs) are close to a tipping point, and will grow exponentially
- End-of-Life batteries volumes expected to increase rapidly

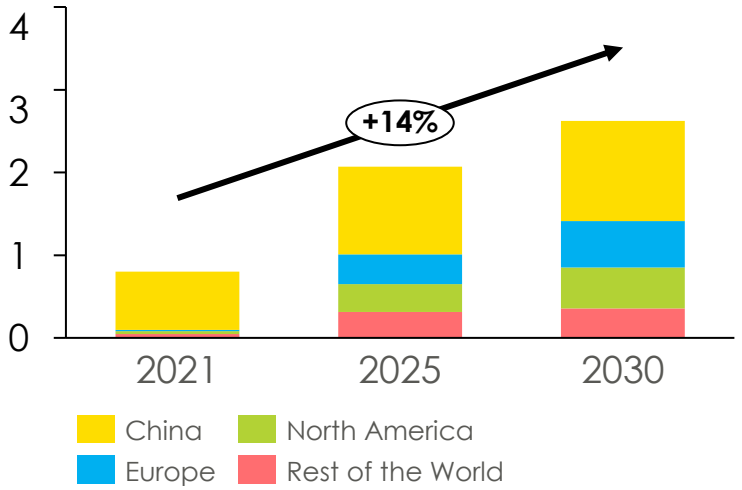
End-of-life EV batteries (GWh)



2. Supply chain resilience

- OEMs are looking to reduce dependency on mining and build resilience against supply chain disruptions
- LIB recovery capacity being developed globally as the result

LIB recovery capacity, mmt (input)



3. Regulatory development

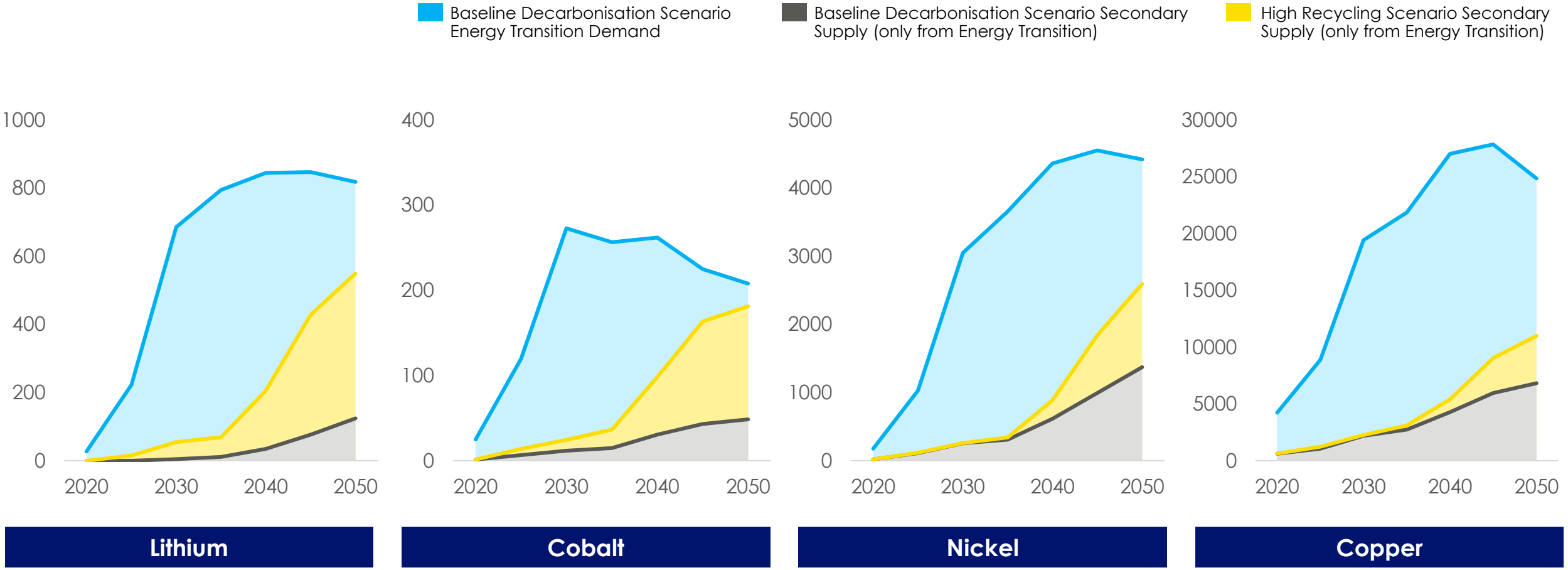
- Strict recovery & recycling targets (new EU battery regulation)
- Planned digital battery passport to enhance tracing system live since 2018
- Regionalisation through IRA

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AFTER 2035, END OF LIFE BATTERIES RECYCLING WILL CONTRIBUTE TO MATERIAL DEMAND - BUT WILL NOT SUFFICE TO COVER DEMAND

Annual energy transition demand and secondary supply

Thousand metric tons

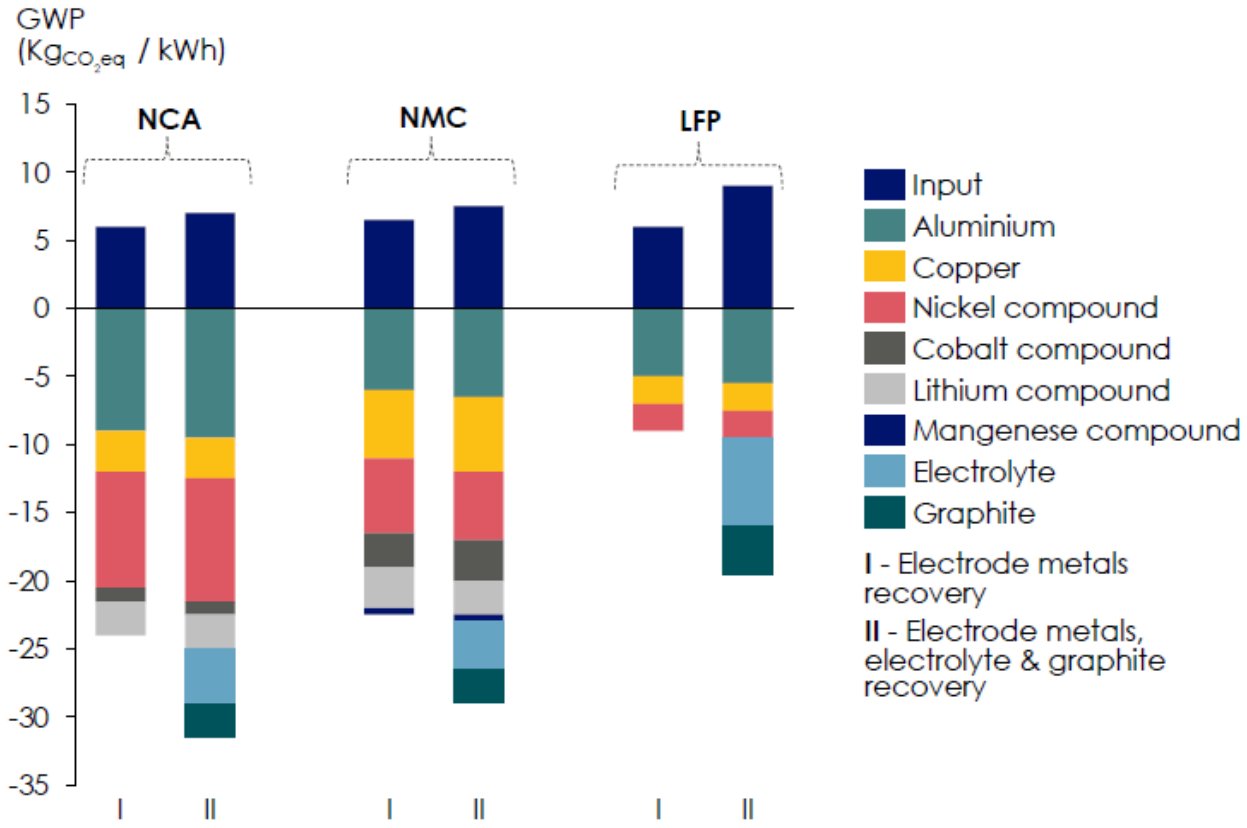


Source: Systemiq for Energy Transitions Commission (2023)

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EV BATTERY RECYCLING CAN REDUCE ENVIRONMENTAL IMPACT OF BATTERIES THROUGH REDUCED PRIMARY MATERIAL PRODUCTION – BUT IT COULD ALSO GENERATE ITS OWN RISKS AND IMPACTS

Global warming potential of hydrometallurgy with two recovery processes



*Negative values indicate net benefits (reduction of impacts due to recovered materials; Positive values are environmental impacts due to the recycling process

- **Scaling up battery recycling** is a **critical** task for the next decade to accelerate **clean transition in transport & energy**
- Battery recycling has **environmental and social advantages over virgin mining**
- There is an **opportunity to further optimise the sustainability** impact of battery recycling

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TO PRE-EMPT LICENSE TO OPERATE CHALLENGES FOR BATTERY RECYCLING IN EUROPE AND SUSTAINABILITY RISKS IN OTHER MARKETS, WE SET OUT TO FILL KNOWLEDGE GAPS AND PROPOSE ACTIONS



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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 saf
trained and provided with high-qualit
45001 – an international standard for
and guidance on occupational healt
working conditions through regulatec
recycling value chain to rule out expl

2 **Technology selection and process** assessments into the selection of b

Recycling processes differ according
and no one process has a clear susta
make informed decisions, conduct in
routes, considering the advantages,
flowsheet from a cradle-to-gate pers

3 **High-ambition recycling:** Maximize and prioritise recycling to high-gr

Optimise recycling operations for ma
recovering energy during discharge
disassembly and mechanical process
allow for repeated reuse and recyclin
take precedence. However, each mc
overall material yields and energy co
rates, comprehensive evaluations cor
various sustainability aspects are nee
disassembly and pre-processing step

4 **Water management:** Adopt best p wastewater management

Aim to implement a closed water loo
that consumes no more water than is
and that recycles and purifies water
treatment systems to ensure that the
that of the water leaving it and minir

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 **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.

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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-

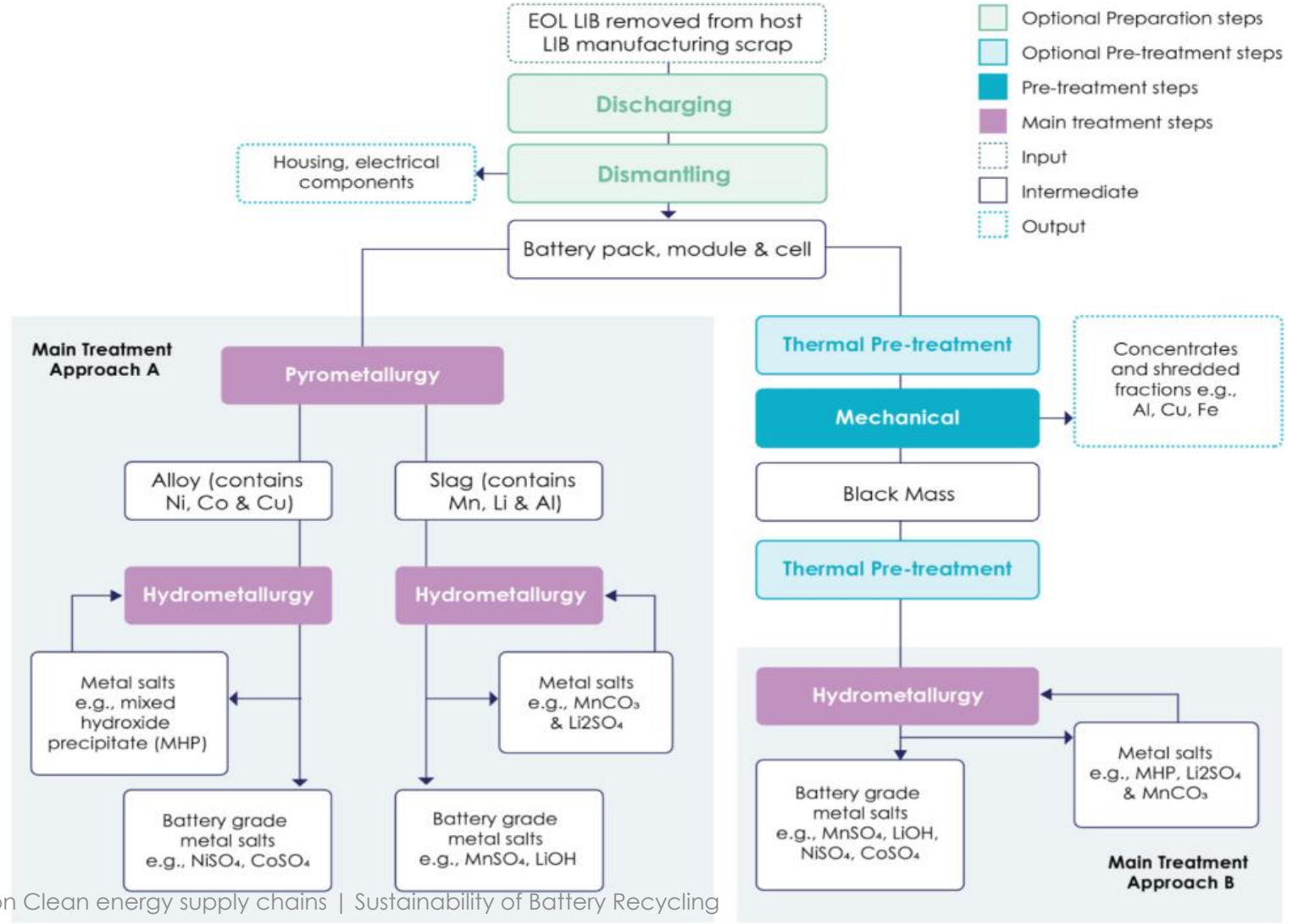
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KEY FINDINGS

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LIB RECYCLING IS TECHNICALLY COMPLEX DEMANDING A MULTI-STEP APPROACH

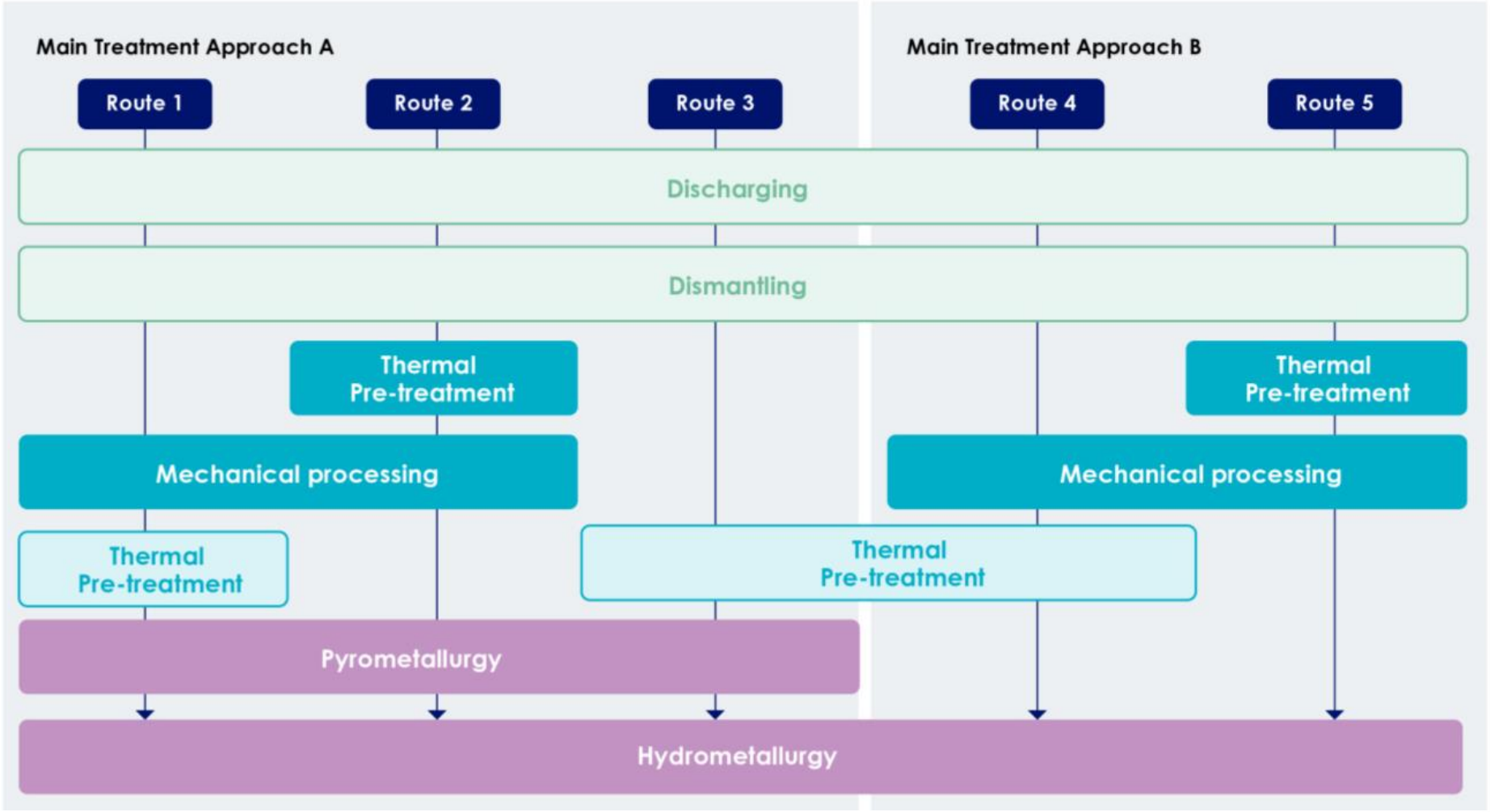
Operational steps for LIB recycling can be ordered in multiple ways and some steps may be omitted, resulting in many potential permutations for recycling routes



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5 ARCHETYPAL ROUTES WERE IDENTIFIED IN THIS REPORT

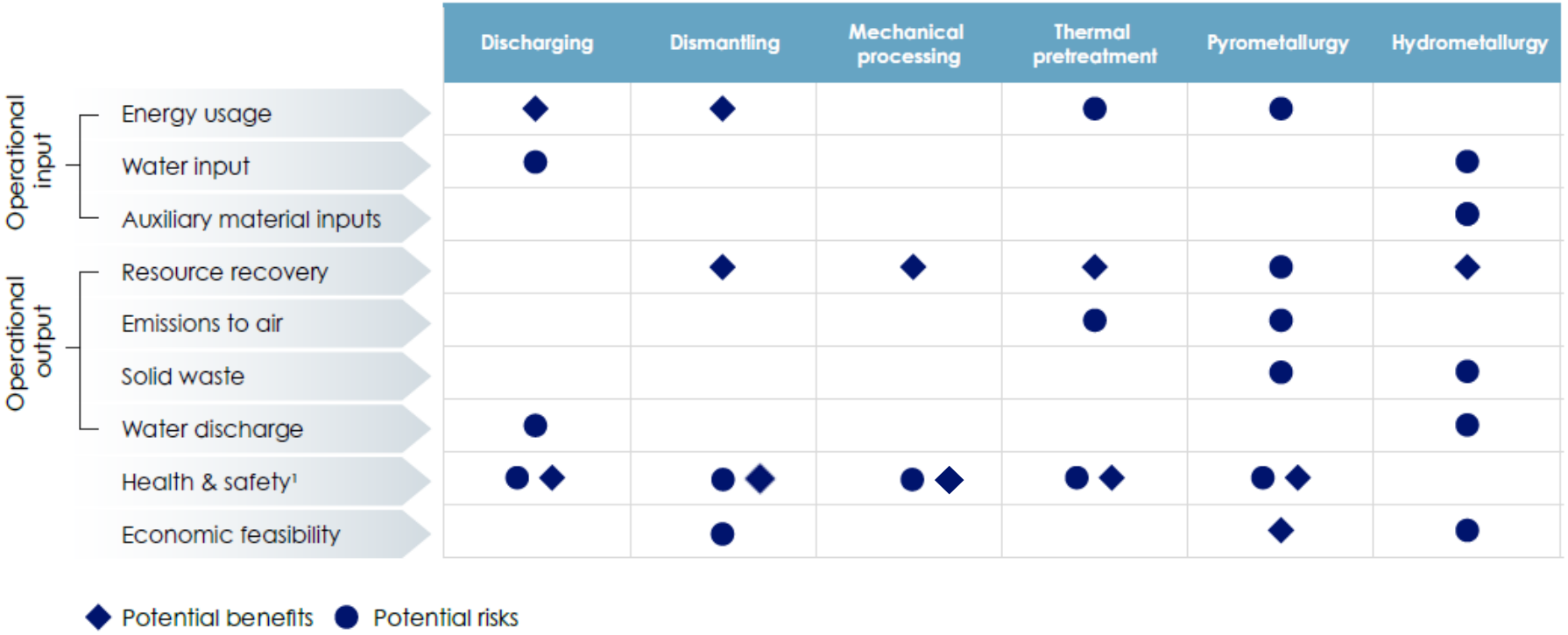
In order to streamline the potential treatment pathways and allow for clear mapping of capacities, the industrial battery recycling process flows can be summarised into 5 archetypal routes



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THERE IS NO "ONE-SIZE-FITS-ALL" ASSESSMENT OF LIB RECYCLING SUSTAINABILITY, RECYCLERS FACE A SERIES OF TRADE-OFFS

- Each operational step has inherent sustainability implications, and the sequencing of steps also gives rise to distinct considerations
- Different sustainability dimensions often compete with one another, meaning recyclers must navigate a series of trade-offs



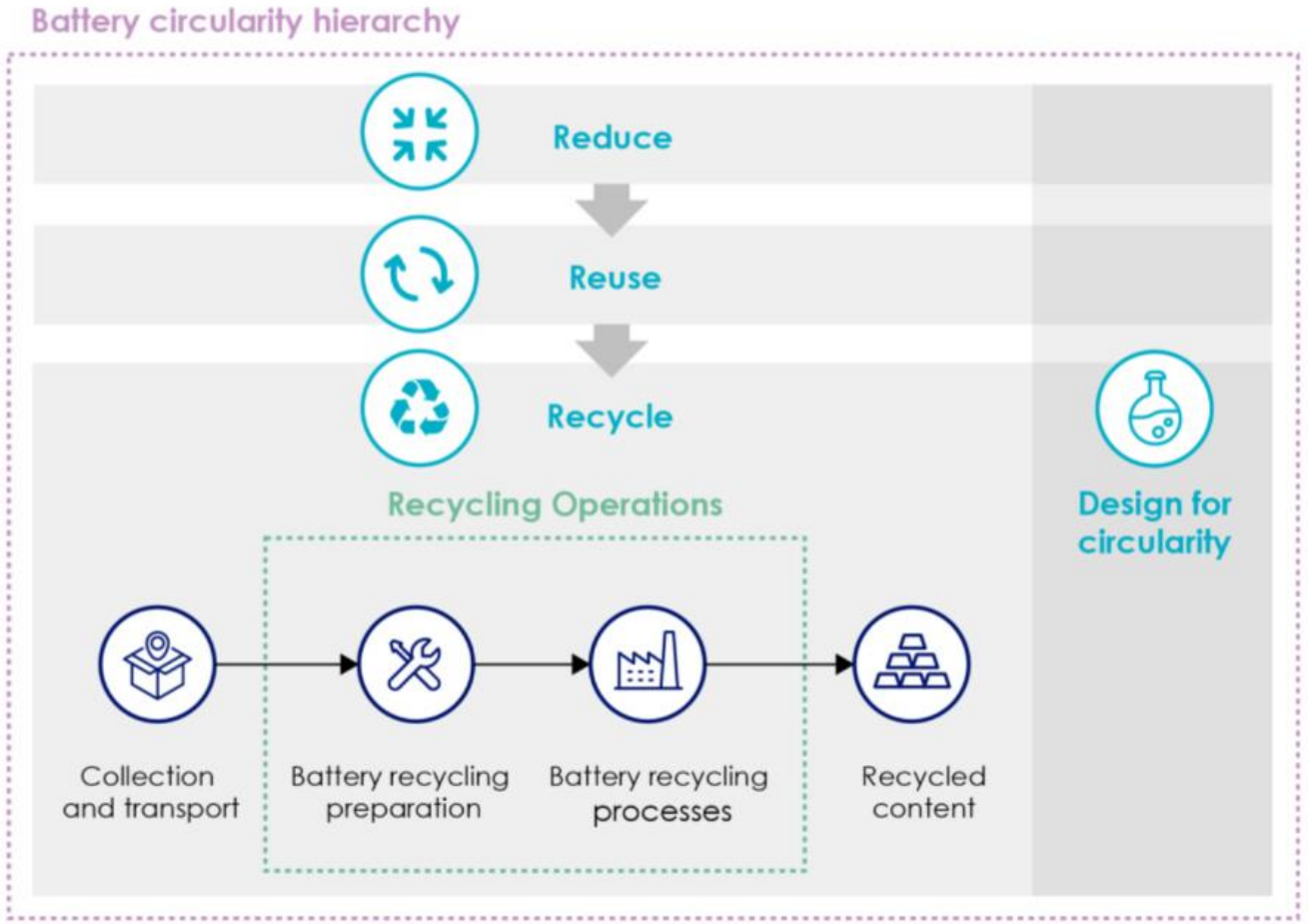
Potential risks and potential benefits are illustrated for each indicator and considered independently across the six process steps. Potential risks and potential benefits are based on published literature, therefore empty boxes signify that the indicator was not identified as a key concern or advantage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

1 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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BATTERY RECYCLING IS A PART OF THE WIDER CIRCULARITY FRAMEWORK AND SHOULD NOT BE AN ISOLATED LEVER

- Recycling is part of a wider circular economy framework. Other strategies like battery **reduction, reuse, and design** should be followed first based on the Circular Economy hierarchy.
- Alongside the recycling process itself, **transport and collection** as well as the **usage of the recycled content** need to be optimised for sustainability



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DESPITE THE DIVERGENCE IN BATTERY RECYCLING TECHNOLOGIES AND APPROACHES, UNIVERSAL SUSTAINABILITY PRINCIPLES COULD BE APPLIED

Operations	1 **Safe operations**	Prioritise stringent health and safety standards in recycling operations
Operations	2 **Technology selection and process design**	Incorporate sustainability impact assessment when selecting battery recycling technologies and processes
Operations	3 **High ambition recycling**	Maximise materials and energy recovery and prioritise recycling to high grades of recycled materials
Operations	4 **Water management**	Adopt best practices for water reduction and wastewater management
Operations	5 **Minimal waste**	Design and operate recycling processes to minimise waste streams and ensure all waste is treated and disposed in accordance with international standards
Operations	6 **Energy usage and Greenhouse gas emissions**	Decarbonise recycling operations
Value chain	7 **Supplier engagement**	Employ sustainability assessment criteria and robust controls to ensure that suppliers of auxiliary materials follow internationally accepted environmental, social and labour standards
Value chain	8 **Auxiliary materials**	Minimise consumption and GHG emissions of used chemicals, gases and other input materials
Value chain	9 **Transport**	Optimise transport routes and electrify modes of transportation
Value chain	10 **Data availability**	Implement digital tools and enhanced traceability in line with the digital ecosystem along the value chain

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THERE ARE OPEN AND DEBATED TOPICS IN SUSTAINABLE BATTERY RECYCLING THAT NEED FURTHER INDUSTRY ALIGNMENT

Selected topics

1. Classification of black mass
2. Trade of End-of-life (EOL) batteries and black mass
3. Circular battery design
4. Access to materials and second-life applications
5. Co-Production of primary and secondary materials
6. End-to-end recycler capabilities versus a multi-stakeholder recycling value chain

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GET INVOLVED!

1. Check out the **full report** on our website at systemiq.earth/sustainable-battery-recycling
2. Work with us to **co-design and endorse the industry principles**
3. Work with us to **champion sustainability** and **set gold standard** in battery recycling and promote key areas of collaborative action

Reach out to us: tilmann.vahle@systemiq.earth & contact@sytemiq.earth

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