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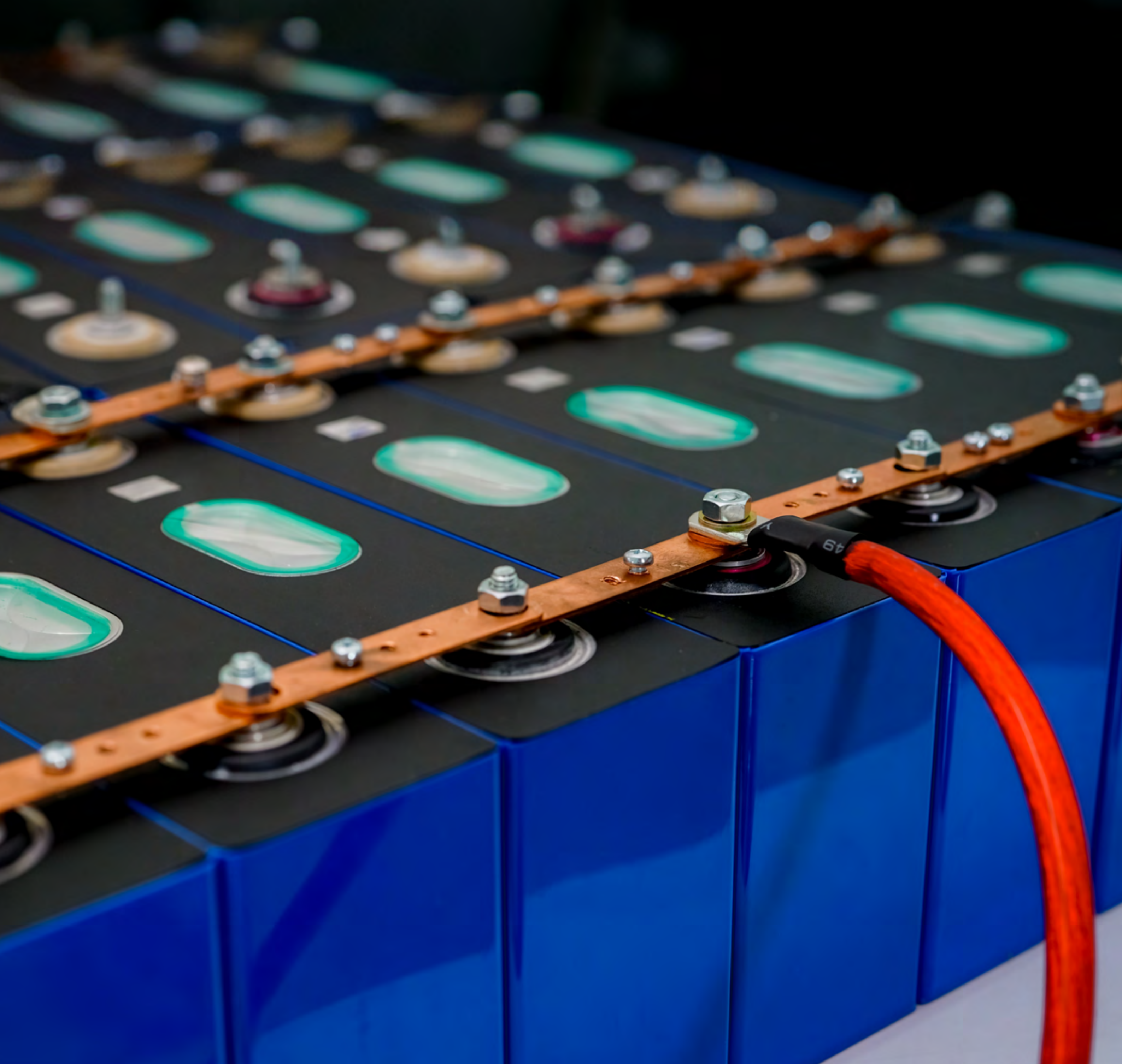
ADVANCING SUSTAINABLE BATTERY RECYCLING: TOWARDS A CIRCULAR BATTERY SYSTEM

EXECUTIVE SUMMARY



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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.

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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 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.