

# Enabling a circular lithium-Ion battery ecosystem for Europe's strategic autonomy goals

*Feasible Recovery of Critical Raw Materials through a New Feasible Recovery of Critical Raw Materials through a New Circular Ecosystem for a Li-Ion Battery Cross-Value Chain in Europe Circular Ecosystem for a Li-Ion Battery Cross-Value Chain in Europe*



A healthy European battery sector is central to achieve EU's decarbonisation and competitiveness goals. Lithium-ion batteries have become an important foundation of Europe's energy, mobility, and industrial systems. They enable electrified transport, renewable energy integration, and the decarbonisation of strategic value chains. As demand accelerates, batteries in Europe has become a matter of **industrial competitiveness, economic resilience, and strategic autonomy**.

Europe has already recognised batteries as strategic through the Batteries Regulation, the Critical Raw Materials Act, Horizon Europe, Important Projects of Common European Interest (IPCEIs), and emerging industrial policy tools, among others. However, the battery ecosystem remains exposed to structural vulnerabilities, including dependence on imported critical raw materials, high energy costs, global competition, fragmented permitting and waste-shipment rules, and shortages of specialised technical skills.

FREE4LIB - *Feasible Recovery of Critical Raw Materials through a New Circular Ecosystem for a Li-Ion Battery Cross-Value Chain in Europe* - is a Horizon Europe project focused on developing sustainable and efficient solutions for the recovery, reuse and reintegration of critical materials from end-of-life lithium-ion batteries. The project aims to support a more circular, resilient and competitive European battery ecosystem.

FREE4LIB demonstrates that circularity can be translated into concrete technologies, data systems and design approaches across the lithium-ion battery value chain. The project combines end-of-life value-chain analysis, electrochemical testing, materials characterisation, recycling and material-reuse technologies, scale-up methodologies, battery pack eco-design, and Battery Passport concepts and prototypes. This evidence shows that circularity is not only an environmental necessity, but also a strategic industrial opportunity for Europe.



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To transform innovation into impact, policy action at EU level is required. The recommendations below outline policy priorities and are structured around three pillars:

**Pillar 1 – Circularity as an opportunity for strategic autonomy**

**Pillar 2 – Scaling innovation to bridge research, industry, and circular deployment**

**Pillar 3 – Data and digital systems as the backbone of circular batteries**

## Pillar 1 - Circularity as an opportunity for strategic autonomy

### Circularity as a core component of competitiveness and strategic autonomy

A fully circular battery value chain is essential for Europe's competitiveness. Recycling, reuse and remanufacturing of battery materials can strengthen Europe's domestic lithium-ion battery industry while reducing dependence on critical raw materials. FREE4LIB results show that circularity must be addressed across the full battery system.

#### Policy recommendations

- **Ensure effective implementation of the EU Batteries Regulation:** Ensure full and consistent enforcement of recycling efficiency and material recovery targets across Member States. The EU has now adopted both binding recycling efficiency and material recovery targets under the Batteries Regulation (adopted in 2023), as well as the harmonised methodology to calculate and verify them (adopted in 2025). The first recycling efficiency targets were mandated by 31 December 2025, and the first material recovery targets by 31 December 2027, with further increases by 31 December 2030 and 31 December 2031 respectively. The priority is therefore to ensure effective implementation across Member



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States, as well as to scale and support industrial recycling capacity so that these targets can be achieved in practice.

- **Reward domestic green production and recycling:** Use carbon footprint and recycled content rules to incentivise batteries produced or recycled in Europe, aligning sustainability standards with industrial competitiveness and providing predictable regulatory frameworks for investors and manufacturers. Predictable rules should help investors and manufacturers integrate secondary raw materials into European battery production.
- **Retain strategic end-of-life materials within Europe:** Building on the Commission's 2025 decision to classify black mass from batteries as hazardous waste, which will strengthen shipment controls and prohibit exports to non-OECD countries once applicable, the EU should ensure effective implementation and prevent circumvention.
- **Harmonise battery, waste, transport and chemicals legislation:** Align the Batteries Regulation with waste shipment, hazardous waste, transport and chemical safety frameworks to prevent contradictory or duplicative compliance requirements and reduce costs for circular operators.

## Pillar 2 – Scaling innovation to bridge research, industry, and circular deployment

### From lab-scale success to industrial deployment

Our project demonstrates that Europe has a strong technological base to move towards closed-loop lithium-ion battery systems. The results include lab-scale development of dismantling, pre-treatment, cathode direct recycling, plastics recycling, metals recycling and black mass recycling, while similarly providing



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scale-up methodologies and pathway towards higher Technology Readiness Level (TRL) deployment. The next step is systemic scale-up support so promising technologies can reach commercial maturity and contribute to industrial resilience.

## Policy recommendations



- **Support a pipeline of pilot-to-commercialisation programmes:** Support the transition of successful research projects into commercially viable recycling and circular battery operations, bridging the gap between R&D and industrial scale. The EU has begun addressing this challenge through initiatives such as the Industrial Accelerator Act, which proposes European content requirements for battery cells as well as Battery Booster, which provides targeted support for industrial scale-up and aims to overcome the “valley of death” between initial investment and large-scale production. However, further efforts are needed to ensure a fully coherent pipeline from research to deployment, particularly for recycling and circular battery solutions. To achieve this, the EU should strengthen synergies between Horizon Europe, the Innovation Fund, and Important Project of Common European Interest (IPCEIs) on batteries, ensuring continuity of support across all technology readiness levels and enabling innovative recycling technologies to reach commercial scale within Europe.
- **Support pilot-scale and first-of-a-kind recycling and circular battery facilities:** FREE4LIB results show the need for continued EU support to move promising circular battery technologies from laboratory results towards pilot-scale validation and, where appropriate, first-of-a-kind deployment. Project results demonstrate the relevance of robot-assisted dismantling, safe pre-treatment and sorting, black mass recycling, cathode direct recycling, metal and polymer recovery, active material synthesis from recycled precursors, material reuse in new pouch cell production, and circular battery pack design, manufacturing, assembly and validation. Support should also target advanced routes such as hydrometallurgical and combined pyro-hydrometallurgical processing, hydrothermal and electrochemical re-lithiation of cathode materials, and greener solvent-based extraction, where technical maturity, safety,



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environmental performance and economic feasibility can be demonstrated.

- **Diversify Europe's critical raw material supply sources:** Mitigate geopolitical risks through partnerships with trusted allies, strategic stockpiling, and investment in domestic extraction and processing capacities.
- **Invest in human capital and technical expertise:** Strengthen Europe's skills base and technical capacity for circular battery value chains by expanding specialised training programmes, fostering closer industry – academia collaboration, and supporting dedicated centres of excellence in battery recycling and circular technologies. Similarly, the attention should be given to developing skills for emerging battery chemistries and next-generation technologies, ensuring that expertise evolves in parallel with innovation. As new chemistries approach commercialisation, the coordinated action at EU and Member State level should be taken, including targeted funding for skills development, integration of circular battery topics into vocational and higher education, and support for cross-sector mobility of expertise.

## Pillar 3 – Data and digital systems as the backbone of circular batteries

### Battery Passport data must be operational for circular actors

Digital tools and standards are essential to make circularity operational. FREE4LIB's Battery Passport work shows how data can close the information gap between beginning-of-life and end-of-life, support sorting, enable second-life, guide recycling process design and create feedback loops to battery designers.



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 **Policy recommendations**

- **Mandate clear access rights for Battery Passport data:** Clear access levels identified under the Batteries Regulation is needed for the different Battery Passport user groups across the battery value chain, including manufacturers, assemblers, distributors, users, regulatory bodies, collectors, treatment facilities, recyclers and second-life operators. Access rules should clarify which data can be viewed, updated or exchanged by each actor, while ensuring protection of confidential business information. Certified End of Life (EoL) operators should have secure and reliable access to the data required for sorting, logistics planning, safe handling, treatment preparation and recycling process optimisation.
- **Standardise data fields for circular operations:** FREE4LIB work showcases the importance of ensuring that Battery Passport data covers all the information needed to manage batteries across the full lifecycle. Our work outlines the need of battery chemistry, State of Health (SoH), State of Charge (SoC), usage history, safety instructions, disassembly guidelines, battery specifications, material origin, logistics tracking, hazardous substances, substances of concern, critical raw materials and recycling-relevant material information, among others. These data fields should be sufficiently detailed to support practical decisions by collectors, logistics operators, treatment facilities, recyclers and second-life actors, not only compliance reporting. Data generated during the use phase and at End of Life (EoL) should not be lost, but used to support decisions on reuse, repurposing, dismantling, treatment and recycling. In particular, SoH, SoC, usage history, material composition, safety-relevant information and, where available, testing results should help authorised operators assess second-life suitability and select appropriate dismantling, treatment or recycling routes. Battery Passport data should also create a reverse information flow from the use and EoL phases back to producers and designers, supporting Design for Recycling and providing evidence on battery condition, disassembly constraints, material recovery, safety issues and recycling-process optimisation. This would help reduce future recycling complexity while improving battery safety, repairability, dismantlability and material recovery.

- **Ensure interoperability with the EU Digital Product Passport framework:** Aligning Battery Passport deployment with the broader Digital Product Passport approach is valuable. FREE4LIB results showcase the importance of using interoperable data models, standardised identifiers, common Application Programming Interfaces (APIs), machine-readable data-interchange formats and secure data-exchange protocols. Battery Passport platforms should be designed to connect with external systems, enterprise systems and other Battery Passport solutions so that lifecycle, sustainability and EoL data can be exchanged across the EU battery value chain.
- **Support public-private data infrastructure innovation:** Continue supporting the development, testing and scale-up of Battery Passport prototypes, traceability systems and secure digital platforms. These tools need to move from promising prototypes to solutions that can be used in real industrial settings by manufacturers, recyclers, regulators, logistics operators and other value-chain actors. Support should cover the technical building blocks, such as role-based access, APIs, smart contracts, QR-code access, hybrid on-chain/off-chain data management, analytics and lifecycle traceability, while also making the systems practical and trusted in daily use. This means addressing usability for non-digital specialists, cybersecurity, data confidentiality, governance and regular feedback from the stakeholders who will rely on these systems.



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## Implementation challenges to address

A balanced policy approach should recognise that circular battery deployment still faces significant implementation barriers. FREE4LiB project point to some of key challenges faced:

### Key technical challenges:

- **Safety and logistics complexity:** EoL lithium-ion batteries can present thermal runaway, fire, explosion, electrolyte leakage, toxic chemical emissions, state-of-charge and transport risks, particularly if they are damaged, improperly stored or incorrectly handled. Their collection and shipment require appropriate packaging, labelling, ADR-compliant transport - under the Agreement concerning the International Carriage of Dangerous Goods by Road- sorting by chemistry and type, and, where necessary, cross-border shipment to suitable treatment plants. Recovered materials also vary by chemistry, source, degradation state and process route, requiring robust characterisation, impurity control and quality-control measures to build confidence in secondary materials.
- **Data confidentiality and access rights:** Battery Passport systems must balance operational data needs for EoL actors with protection of commercially sensitive information, personal data and cybersecurity requirements.
- **Digital interoperability:** Without common APIs, identifiers, data models and governance rules, Battery Passport systems risk becoming fragmented and difficult to use across borders and value-chain stages.



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## Regulatory challenges:

- **Regulatory uncertainty:** Circular battery actors need clear and predictable rules to plan investments, organise logistics and decide whether recovered materials can be reused, recycled, traded or reintegrated into production.

## Other challenges:

- **Cost competitiveness and investment risk:** Advanced recycling and remanufacturing processes must compete with primary materials and established global supply chains. First-of-a-kind facilities need risk-sharing support and long-term demand signals.
- **Skills and workforce needs:** Circular battery value chains require specialised expertise in electrochemistry, materials characterisation, safe dismantling, logistics, data governance, software systems and advanced manufacturing.

## Conclusion - a call to action

FREE4LIB stands ready to support policymakers in delivering a circular, competitive and resilient European battery ecosystem. The project provides evidence across the full circular chain: EoL value-chain mapping, logistics and testing; recycling technologies and material reuse; scale-up methodology and battery pack eco-design; and Battery Passport concepts and platforms. Together, these results show how critical raw materials can be recovered, characterised, reintegrated and tracked across the battery value chain.

Europe should now move from regulatory ambition to practical implementation. This requires coherent funding pipelines, safe and harmonised logistics, high-quality secondary material standards, industrial scale-up support, interoperable Battery Passport infrastructure and strong feedback loops from end-of-life to battery design. By acting on these priorities, the EU can turn circular battery innovation into strategic autonomy, industrial competitiveness and environmental value.



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## Annex I – Evidence base for policy recommendations

The following table summarises the FREE4LIB results that underpin the recommendations in this paper. Its purpose is to make the link between project evidence and policy asks explicit. The table does not provide the technical detail of each deliverable; instead, it highlights the main evidence areas and explains how they support the policy recommendations across circularity, scale-up, logistics, eco-design and Battery Passport deployment.

Result area	Concrete FREE4LIB work	Policy relevance
<b>EoL value-chain, logistics and safety</b>	FREE4LIB analyses the current end-of-life lithium-ion battery value chain, including collection, transport, safety, battery composition, second-life applications, recycling and relevant policies. FREE4LIB further examines practical issues in packaging, collection and logistics for automotive lithium-ion batteries, including safety procedures, transport requirements, sorting and the expected role of the Digital Battery Passport.	Supports recommendations on ensure effective implementation of the EU Batteries Regulation, harmonisation of battery, waste, transport and chemicals legislation; rewarding domestic green production and recycling, retain strategic end-of-life materials within Europe.
<b>Recycling and material reuse technologies</b>	FREE4LIB develops laboratory-scale recycling and material-reuse routes for dismantling, pre-treatment, cathode direct recycling, plastics recycling, metals recycling and black mass recycling. The project also addresses metal oxides, metals and polymers recovery, recycled precursors, active material synthesis, material reuse in new pouch cells and possible use of non-reusable elements in other applications.	Supports recommendations on first-of-a-kind and pilot-scale recycling facilities, support for black mass and cathode recycling.

<b>Scale-up and industrial validation pathway</b>	FREE4LIB describes methodologies for scaling recycling and material-reuse technologies, including robot-assisted dismantling, pre-treatment routes, recovery of metals from black mass, cathode direct recycling, plastics recycling, metals recycling, active material synthesis based on recycled precursors and material reuse in new pouch cell production. The project also highlights the need to refine technologies and scale them to meet industrial demands.	Supports recommendations on pilot-to-commercialisation funding, continuity of support across technology maturity levels, industrial validation and risk-sharing for first-of-a-kind circular battery plants.
<b>Circular battery pack design and validation</b>	FREE4LIB translates circularity principles into battery pack design, manufacturing, assembly and validation, including eco-design principles, modularity, accessible joints, reduced use of adhesives, easier dismantling, use of recycled or recyclable materials, and documentation for manufacturing, assembly and disposal phases.	Supports recommendations on information requirements for the Battery Passport.
<b>Battery Passport concept, data needs and access rights</b>	FREE4LIB defines Battery Passport data needs and information flows between beginning-of-life and end-of-life. It identifies data clusters such as State of Health, material composition and chemistry, lifecycle information and repair-related information. It also defines user roles, access rights and the need to consider data sensitivity, granularity, relevance and certainty.	Supports recommendations on Battery Passport access rights, standardised data fields, confidentiality safeguards, data availability for EoL operators, and use of data for sorting, logistics, second-life decisions and recycling optimisation.
<b>Battery Passport platform and digital infrastructure</b>	FREE4LIB develops Battery Passport Platform prototypes.	Supports recommendations on interoperable Battery Passport infrastructure, role-based access.
<b>Feedback loops from EoL to design and process optimisation</b>	FREE4LIB showcases the process design optimisation and how it can benefit from State of Health, material composition and hazardous-substance data.	Supports recommendations on using Battery Passport data to create optimise future battery design and recycling processes.