Deliverable D5.3

Design for Sustainability Guidelines

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

Feasible Recovery of critical raw materials through a new circular Ecosystem for a Li-Ion Battery cross-value chain in Europe

WP5 - Impact assessment and battery passport

D5.3 - Design for Sustainability Guidelines

Due date of deliverable
31/08/2026

Actual submission date:
31/08/2026

Organisation name responsible for this deliverable: IREC-CERCA

Dissemination Level

SEN	Sensitive	
PU	Public	X

Project Acronym
FREE4LIB

Grant Agreement No.
101069890

Project Start Date
01-09-2022

Project End Date
31-08-2026

Duration
48 months

Disclaimer

©2022 FREE4LIB Consortium Partners. All rights reserved.

Free4lib is an EU-funded project that has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no. 101069890. The sole responsibility for the content of this report lies with the authors. It does not necessarily reflect the opinion of the European Union. The European Commission is not responsible for any use that may be made of the information contained therein.

While this publication has been prepared by the consortium partners of the project, the authors provide no warranty with regards to the content and shall not be liable for any direct, incidental or consequential damages that may result from the use of the information or the data contained therein.

Versions

DATE	VERSION	AUTHOR	COMMENT
24/07/2026	1	IREC-CERCA	Initial draft for internal review
31/07/2026	2	IREC-CERCA	Draft after review. Format adjustments and addition of references
31/08/2026	3	CARTIF, IREC-CERCA	Final version

Content

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

List of Abbreviations

ACRONYMS	DESCRIPTION
AI	Artificial Intelligence
BESS	Battery Energy Storage System
BMS	Battery Management System
CAM	Cathode Active Material
CRM	Critical Raw Material
DBP	Digital Battery Passport
DfD	Design for Disassembly
DfR	Design for Recycling
DfS	Design for Sustainability
EEE	Electrical and Electronic Equipment
EoL	End-of-Life
ESPR	Ecodesign for Sustainable Products Regulation
GHG	Greenhouse Gas
ICP	Inductively Coupled Plasma
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LIB	Lithium-Ion Battery
NMC	Lithium Nickel Manganese Cobalt Oxide
OEM	Original Equipment Manufacturer
PCM	Phase Change Material
PV	Photovoltaic
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SoC	State of Charge

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

SoH	State of Health
SSbD	Safe and Sustainable by Design
TRL	Technology Readiness Level
WEEE	Waste Electrical and Electronic Equipment

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

1. Executive Summary

The transition towards a circular battery value chain requires that sustainability considerations be integrated throughout the entire battery life cycle, beginning at the earliest stages of product development. While significant efforts have traditionally focused on improving recycling technologies, the effectiveness of End-of-Life (EoL) treatment is largely determined by decisions taken during battery design. Eco-design therefore plays a fundamental role in increasing material recovery, extending battery lifetime and reducing the environmental impacts associated with battery manufacturing and recycling.

Within the FREE4LIB project, a comprehensive Design for Sustainability (DfS) approach has been adopted to support the development of advanced recycling technologies while ensuring that future battery systems are designed to maximise their circularity. This deliverable presents the eco-design framework developed in FREE4LIB within task 5.3, together with practical guidelines derived from the technological developments, environmental assessment and demonstrators implemented throughout the project, and specifically tasks 2.5 and 4.8.

The document first introduces the principles of sustainable battery design and reviews the current regulatory framework driving eco-design requirements for lithium-ion batteries. It then presents the environmental implications identified through the Life Cycle Assessment, highlighting the main environmental hotspots associated with battery recycling and translating these findings into design recommendations. The recycling pathways developed within FREE4LIB are subsequently analysed to identify the design features that facilitate dismantling, material recovery and closed-loop manufacturing.

Practical experience obtained from the second-life battery demonstrator and the battery manufactured using recovered materials confirms that many eco-design principles—including modularity, reversible joining techniques, simplified material composition and improved traceability can support the battery circularity while facilitating future repair, reuse and recycling.

Finally, the deliverable provides a comprehensive set of Design for Recycling guidelines that integrate environmental performance, circular economy principles and recycling requirements into battery development. These recommendations are intended to support battery manufacturers, designers and researchers in developing next-generation lithium-ion battery systems that are compatible with future circular battery value chains.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

2. Introduction to this document

The rapid deployment of electric mobility, renewable energy integration and stationary energy storage systems is driving an unprecedented increase in the production and use of lithium-ion batteries worldwide. While these technologies are essential to achieving Europe's climate neutrality objectives, they also raise significant sustainability challenges related to the consumption of critical raw materials, manufacturing impacts, battery lifetime and end-of-life management[1] [2]. The growing demand for lithium, cobalt, nickel, graphite and other strategic materials has highlighted the need to develop more resource-efficient and circular battery value chains capable of reducing dependence on primary raw materials while maintaining the performance, safety and competitiveness of battery technologies.

Recognising these challenges, the European Union has introduced an ambitious legislative framework that promotes sustainability throughout the battery life cycle. The Battery Regulation (EU) 2023/1542[3] establishes new requirements concerning carbon footprint, recycled content, due diligence, collection and recycling efficiencies, battery passport and EoL-management. Together with the Circular Economy Action Plan and the Critical Raw Materials Act, these policies acknowledge that improving battery sustainability requires interventions across the entire value chain rather than focusing exclusively on recycling technologies.

In this context, eco-design has emerged as a key approach for improving the environmental sustainability and circularity of battery systems, as design decisions can directly influence resource efficiency, product lifetime, repairability, reuse and recyclability[4]. Decisions taken during the design phase determine not only the performance and safety of batteries but also their repairability, reuse potential, ease of dismantling, recyclability and ultimately the environmental impacts associated with end-of-life treatment. Studies have shown that a large proportion of a product's environmental performance is effectively determined during its design stage, making Design for Sustainability a key enabler for circular battery systems.

---

[1] https://publications.jrc.ec.europa.eu/repository/handle/JRC141715

[2] Xin Lai, Quanwei Chen, Xiaopeng Tang, Yuanqiang Zhou, Furong Gao, Yue Guo, Rohit Bhagat, Yuejiu Zheng, Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective, eTransportation,https://doi.org/10.1016/j.etran.2022.100169.

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542

[4] https://environment.ec.europa.eu/news/sustainable-products-be-norm-consumers-new-regulation-2024-07-19_en

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

The FREE4LIB project contributes to this transition by developing an integrated circular value chain for lithium-ion batteries, combining innovative recycling technologies with sustainable battery design principles. The project addresses the complete battery life cycle, from dismantling and material recovery to the manufacture of new battery components using recovered materials, while simultaneously evaluating the environmental performance of these processes through Life Cycle Assessment.

The objective of this deliverable is to translate the knowledge generated throughout FREE4LIB into practical Design for Sustainability guidelines focused on Recycling for lithium-ion batteries. By integrating environmental assessment, technological developments and practical demonstrators, the document provides evidence-based recommendations that support battery designers, manufacturers and researchers in developing battery systems that maximise material recovery, facilitate recycling and contribute to the transition towards a circular European battery value chain.

3. Eco-design framework

3.1 Introduction

Design for Sustainability (DfS) is a systematic approach that integrates environmental, technical and circular economy considerations into product development with the objective of minimising environmental impacts throughout the entire life cycle while maintaining the required functionality, safety and economic viability. Within the battery sector, extends beyond material selection and manufacturing optimisation to include maintenance, repair, second-life applications, remanufacturing and end-of-life recycling.

Unlike generic eco-design methodologies, the DfS framework developed within FREE4LIB within task 5.3 has been constructed using the technical knowledge generated throughout the project and specifically tasks 2.5 and 4.8. The resulting guidelines therefore represent practical recommendations supported by experimental validation rather than theoretical design principles with the aim of improving the recycling and recovery operations.

The FREE4LIB DfS framework integrates four complementary sources of evidence:

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

- **Regulatory requirements**, including the European Battery Regulation, Circular Economy Action Plan and related European sustainability policies, which define the future regulatory context for battery design.
- **Environmental assessment**, where the Life Cycle Assessment identifies the environmental hotspots associated with battery recycling technologies and determines the design parameters that most strongly influence environmental performance.
- **Technological developments**, where the recycling pathways developed within WP3 and WP4 establish the technical requirements necessary to maximise the recovery of battery materials, components and critical raw materials.
- **Project demonstrators**, where the implementation of eco-design strategies in both the second-life battery and the battery manufactured from recovered materials provides practical evidence regarding the feasibility and limitations of different design approaches.

By combining these complementary perspectives, the Eco-design framework of FREE4LIB ensures that the proposed recommendations are technically feasible, environmentally justified and compatible with future industrial implementation. Rather than focusing on a single recycling technology, the framework adopts a systems perspective that recognises the interactions between battery design, manufacturing, operation, maintenance, reuse and recycling.

Consequently, the guidelines presented in this deliverable should not be interpreted as technology-specific recommendations but as a comprehensive eco-design framework intended to facilitate multiple circular economy strategies throughout the battery life cycle, with the aim of improving the recycling and recovery operations.

3.2 Methodologies

The eco-design guidelines presented in this deliverable were developed through an iterative process combining scientific evidence, technological developments and practical validation carried out throughout the FREE4LIB project.

The methodology consisted of four sequential steps.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

First, the regulatory framework governing sustainable batteries was reviewed in order to identify the current and forthcoming design requirements established at European level.

Secondly, the environmental assessment performed within WP5 identified the principal environmental hotspots associated with battery recycling processes and determined which design decisions most strongly influence environmental performance.

Thirdly, the recycling technologies developed within WP3 and WP4 were analysed to identify the design characteristics that facilitate dismantling, material separation, recovery of critical raw materials and closed-loop manufacturing.

Finally, the practical implementation of these strategies was evaluated through the FREE4LIB demonstrators, allowing the consortium to identify both successful approaches and practical limitations encountered during battery development and discussed during a dedicated online workshop held in May 2025.

The combination of these four sources of knowledge resulted in a set of Design for Sustainability recommendations that are supported simultaneously by environmental assessment, technological development and experimental validation.

3.2.1 EU Batteries regulation

This section provides a preliminary approach for establishing, implementing, and evaluating eco-design at product level in the scope of the development of Free4LIB innovations. According to the Directive 2009/125/EC [5]establishing a framework for the setting of eco-design requirements for energy-related products, eco-design consists of the integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle.

For the aim of this project, eco-design is approached following the requirements and recommendations of ISO 14006:2020[6] on Environmental management systems – Guidelines for incorporating eco-design, and the circular economy principles and aspects of design for circularity defined in the

[5] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0125
[6] https://www.iso.org/obp/ui#iso:std:iso:14006:ed-2:v1:en

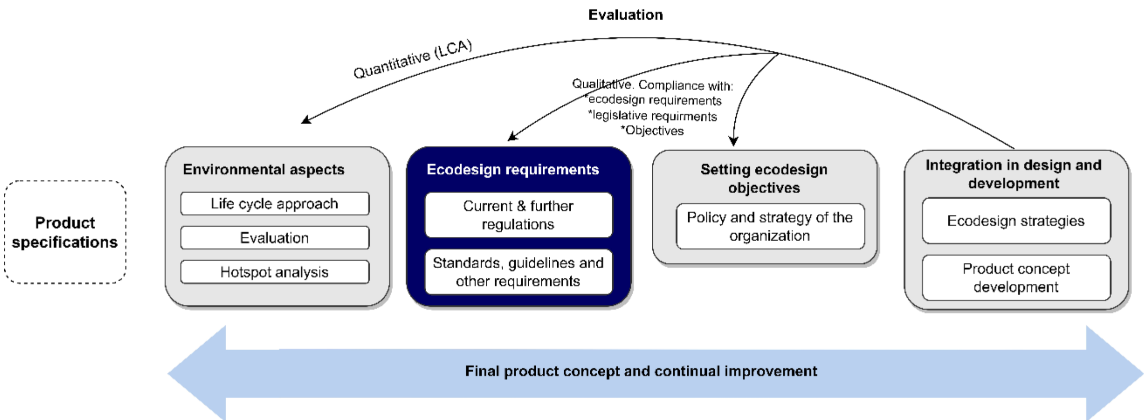
Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

ISO/DIS 59004[7] Circular Economy — Terminology, Principles and Guidance for Implementation.

Figure 1 shows an overview of the main steps for adopting eco-design strategies. It starts by understanding the product and defining its specifications into detailed product functions. Next, environmental aspects of the product are evaluated from the life cycle approach to determine which aspects have a significant environmental impact. Then, eco-design requirements are identified considering current and future legislation concerning product specifications, restrictions, or obligations, as well as other requirements established by international and national standards, and from interested parties related to the organization or development of the product. Eco-design objectives are then set by the organization and interested parties focused on improving the environmental performance of the product based on the results of the environmental evaluation, legal requirements and the strategy of the organization/project, e.g. increase energy efficiency by 20%, reduce disassembly time for easy repair, reduce the content of critical raw materials, etc. Lastly, these objectives are transformed into eco-design strategies that result in the product concept development, which is evaluated to ensure compliance with the goals of environmental impact reduction and eco-design requirements.

Figure 1. Steps for the implementation of the eco-design approach. Source: own elaboration based on ISO 14006:2020



In the scope of T5.3, this document is focused on the identification of the eco-design requirements of the project.

[7] https://www.iso.org/obp/ui/es/#iso:std:iso:59004:ed-1:v1:en

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

3.2.2 Regulatory requirements and obligations

3.2.2.1 New European Commission regulation on batteries and waste batteries.

This new regulation is part of The European Green Deal and it's built on the Strategic Action Plan on Batteries, the New Circular Economy Action Plan, the New Industrial Strategy for Europe and the Sustainable and Smart Mobility Strategy.

The new rules aim strengthening the functioning of the internal market (including products, processes, waste batteries and recyclates), promoting a circular economy and reducing environmental and social impacts throughout all stages of the battery life cycle.

The scope covers electric vehicle batteries and rechargeable industrial batteries with internal storage and a capacity above 2 kWh.

Eco-design and sustainability related obligations and requirements are listed as following:

Restrictions of hazardous substances

Batteries shall not contain the following hazardous substances:

- Mercury. Batteries used in vehicles to which Directive 2000/53/EC[8] applies shall not contain more than 0,1% of mercury (expressed as mercury metal) by weight in homogeneous material.
- Cadmium. Batteries shall not contain more than 0,01% of cadmium (expressed as cadmium metal) by weight in homogeneous material, except those vehicles included in Annex II of the regulation.
- Substances listed in Annex XVII of REACH Regulation (EC) No 1907/2006[9] – Registration, Evaluation, Authorisation and Restriction of Chemicals.

Exceptions on the use of risking substances are set for scientific research and development (of batteries) as defined in Article 3(23) of REACH: "scientific research and development: means any scientific experimentation, analysis or chemical research carried out under controlled conditions in a volume less than one ton per year".

[8] https://eur-lex.europa.eu/resource.html?uri=cellar:02fa83cf-bf28-4afc-8f9f-eb201bd61813.0005.02/DOC_1&format=PDF

[9] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02006R1907-20241218

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

Carbon footprint

- From 1st of July 2024, technical documentation shall be provided including a carbon footprint declaration of the battery per life cycle stage following the methodology established by the EC.
- From January 1st 2026, a label indicating the carbon footprint performance class of the battery must be included according to the performance classes set by the EC and labelling formats.
- From 1st of July 2024, technical documentation shall be provided demonstrating that the declared life cycle carbon footprint value is below the maximum threshold established by the EC.

Recycled content

- From January 1st 2027, technical documentation shall be provided containing information about the amount of **cobalt, lead, lithium or nickel recovered from waste** present in active materials in each battery model and batch per manufacturing plant.

Based on the methodology established by the EC for the calculation and verification of recycled content, technical documentation shall be provided demonstrating batteries contain the following minimum shares of materials recovered from waste present in active materials:

- From 1 January **2030**:
    a) 12% cobalt;
    b) 85% lead;
    c) 4% lithium;
    d) 4% nickel.
- From 1 January **2035**:
    a) 20% cobalt;
    b) 85 % lead;
    c) 10% lithium;
    d) 12% nickel.

Where justified and appropriate due to the availability of cobalt, lead, lithium or nickel recovered from waste, or the lack thereof, the EC shall be empowered to adopt, by 31 December 2027, a delegated act to amend the targets laid down for 2030 and 2035.

Responsible sourcing (due diligence policy)

Twelve months after entry into force of the Regulation, a set of the following responsible sourcing requirements shall be adopted:

- A company policy for the supply chain of raw materials shall be adopted. It includes:

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

a) cobalt;
b) natural graphite;
c) lithium;
d) nickel;
e) chemical compounds based on the raw materials listed in previous points which are necessary for the manufacturing of the active materials of batteries.

- Establish and operate a system of controls and transparency over the supply chain, including:
  a) description of the raw material, including its trade name and type;
  b) name and address of the supplier that supplied the raw material present in the batteries to the economic operator that places on the market the batteries containing the raw material in question;
  c) country of origin of the raw material and the market transactions from the raw material's extraction to the immediate supplier to the economic operator;
  d) quantities of the raw material present in the battery placed on the market, expressed in percentage or weight.
- Identify and assess the adverse impacts associated to the risk categories:
  a) air;
  b) water;
  c) soil;
  d) biodiversity;
  e) human health;
  f) occupational health and safety;
  g) labour rights, including child labour;
  h) human rights;
  i) community life

Performance and durability requirements

Obligation to provide technical documentation containing values for the electrochemical performance and durability. In terms of eco-design, it considers information on indication of the **expected life-time** of the battery under the conditions for which it has been designed.

Labelling and information

- From 1 January 2027, batteries shall be marked with a label containing the **information on hazardous substances** contained in the battery other than mercury, cadmium or lead; critical raw materials contained in the battery.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

- From 1 July 2023, batteries shall be labelled with the symbol indicating '**separate collection**'
- Batteries shall be marked with a QR code with access to the following information:
    - From 1 January 2026, the carbon footprint performance class
    - From 1 January 2027, the amount of cobalt, lead, lithium or nickel recovered from waste and present in active materials in the battery

Information accessible to accredited remanufacturers, second-life operators, and recyclers (as part of the digital battery passport)

- Detailed composition, including materials used in the cathode, anode and electrolyte;
- Part numbers for components and contact details of sources for replacement spares;
- Dismantling information, including at least:
    - Exploded diagrams of the battery system/pack showing the location of battery cells,
    - disassembly sequences,
    - type and number of fastening techniques to be unlocked,
    - tools required for disassembly,
    - warnings if risk of damaging parts exist, and
    - amount of cells used and layout
- Safety measures

3.2.3 Eco-design strategies

¡Error! No se encuentra el origen de la referencia. presents the main strategies to consider for the appropriate design of electric vehicle batteries from the eco-design and circularity perspective. These strategies have been identified from different reports and literature[10]

[10] (Montes et al., 2022; Picatoste et al., 2022a, 2022b; Circular Economy Initiative Deutschland, 2020; Committee on Trade and Investment, 2005).

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

Table 1. Eco-design strategies for electric vehicle batteries by life cycle stage[11][12][13][14]

Life cycle stage	Eco-design strategies
Cell/ pack manufacturing	Concept/product related - Design for modularity and standardization of battery components for better maintenance, repairment, repurposing and recycling. - Design for long life - Simplicity of product architecture. - Lower the weight of the battery to achieve better performance during use (depending on the application). - Design for a minimum volume of battery components (depending on the application). - Design for easy dismantling to facilitate repair and recovery of battery components. Material selection - Avoid using toxic materials and substances as indicated in the New regulation on batteries and waste batteries and REACH regulation. - Avoid composite materials. - Avoid/reduce the usage of critical-scarce materials. - Use recycled and recyclable materials, especially recycled cobalt, lead, lithium or nickel in compliance with the 2030 & 2035 content targets established in the new Batteries and waste batteries regulation. - Use light materials. - Use durable materials. Manufacturing - Avoid high energy-intensive production processes. - Prioritize the usage of renewable energies. - Recycle scrap (pre-consumer waste) Assembly - Simplicity of assembly process: reduce assembly/disassembly steps and energy processes. - Avoid the use of adhesives, glues or soldered in joints and connections, instead use detachable joints. - Minimize the number and type of fasteners (use same type), ensuring they do not require special tools and are easy to unlock. - Ensure joints are easily accessible and there is enough space to allow disassembly for repairment and at the end-of-life.

[11] Circular Economy Initiative Deutschland. (2020). *Resource-Efficient Battery Life Cycles*.
[12] Montes, T., Etxandi-Santolaya, M., Eichman, J., Ferreira, V. J., Trilla, L., & Corchero, C. (2022). Procedure for Assessing the Suitability of Battery Second Life Applications after EV First Life. *Batteries*, *8*(9).
[13] Committee on Trade and Investment. (2005). *ECODESIGN. Best Practice of ISO/TR 14062*.https://doi.org/10.3390/batteries8090122
[14] Picatoste, A., Justel, D., & Mendoza, J. M. F. (2022b). Exploring the applicability of circular design criteria for electric vehicle batteries. *Procedia CIRP*, *109*, 107–112. https://doi.org/10.1016/j.procir.2022.05.222

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

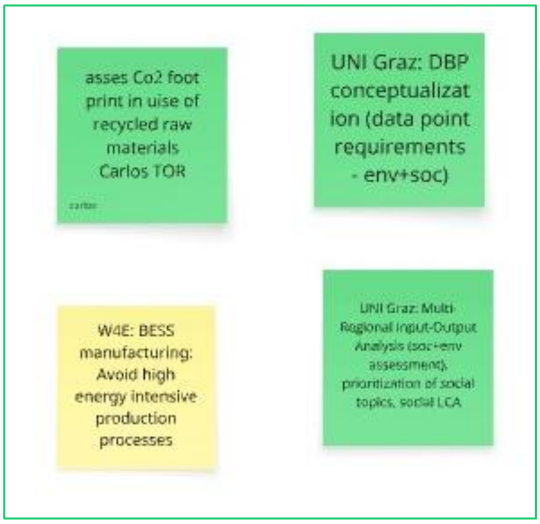
Life cycle stage	Eco-design strategies
Cell/ pack manufacturing	Information access and communication Provide sustainability information in compliance with the requirements of Digital Battery Passport and set in the new Batteries and waste batteries regulation (carbon footprint, recycled content, responsible sourcing, labelling, performance and durability, dismantling and safety)
Use	- Provide information on part numbers for components and contact details of sources for replacement spares. - Indicate dismantling instructions to facilitate repair and replacement of battery components. - Repair/recondition battery pack or individual modules to extend first life in the same or another vehicle.
End-of-life	Disassembly - Provide Dismantling information, including: i) Exploded diagrams of the battery system/pack showing the location of battery cells, ii) Disassembly sequences, iii) Type and number of fastening techniques to be unlocked, iv) Tools required for disassembly, v) Warnings if risk of damaging parts exist, vi) Amount of cells used and layout. - Provide information for the appropriate treatment of battery components and materials. - Automatize disassembly operations to reduce time and resources. - Reduce the type and number of tools for disassembly. - Use standard tools during disassembly processes. - Ensure traceability of separated battery components according to the information requirements of the Digital Battery Passport established in the new Batteries and waste batteries regulation. Reuse - Repair/recondition battery pack or individual modules to extend first life in the same or another vehicle. - Repurpose battery pack or individual modules for 2nd life applications when the battery is sufficiently degraded to meet first life requirements in vehicles. Recycling - Ensure recyclates quality comparable to that of original materials. - Recycle critical materials, particularly those specified in the new Batteries and waste batteries regulation (cobalt, lead, lithium, nickel). - Guarantee traceability of recycled battery components and materials.

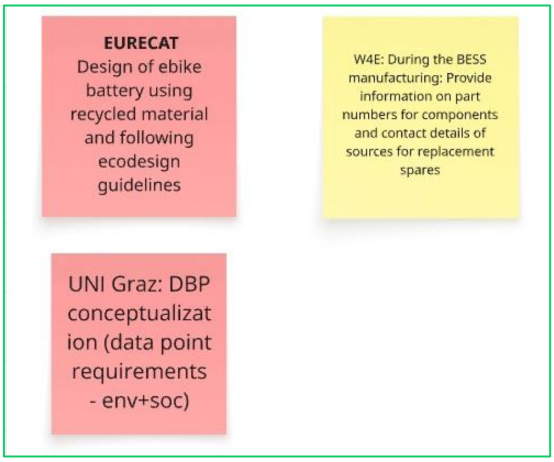
In order to identify which of the strategies above indicated were considered during the development of the different recycling, recovery, design and reuse of batteries in the project, a specific online workshop was held in may 2025. In this workshop, all the project partners where invited to indicate the strategies or initiatives they were carrying out or plan to carry out in the different stages

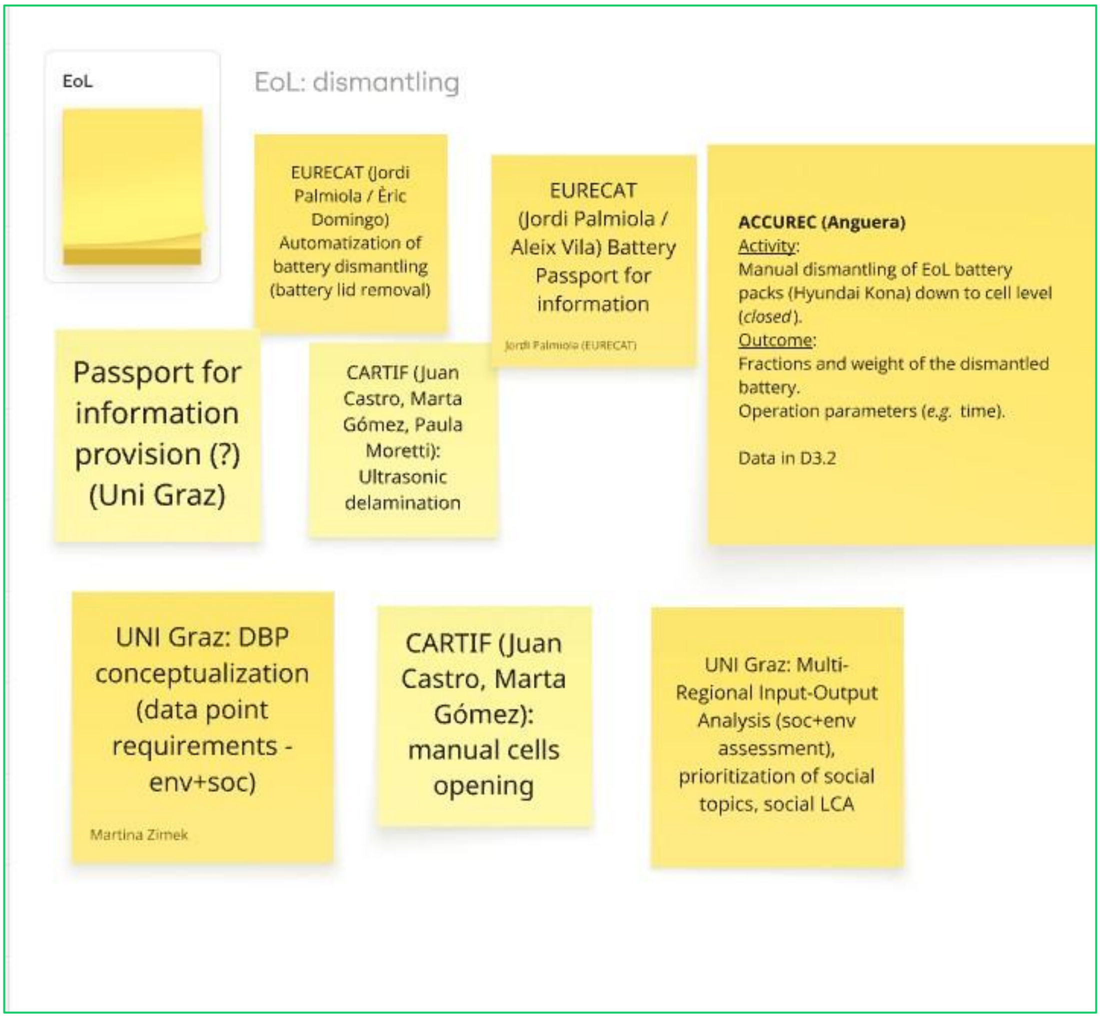
Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

of the battery cells lifecyles: manufacturing, use phase, dismantling and material recovery. Figures below show the results of the workshop.







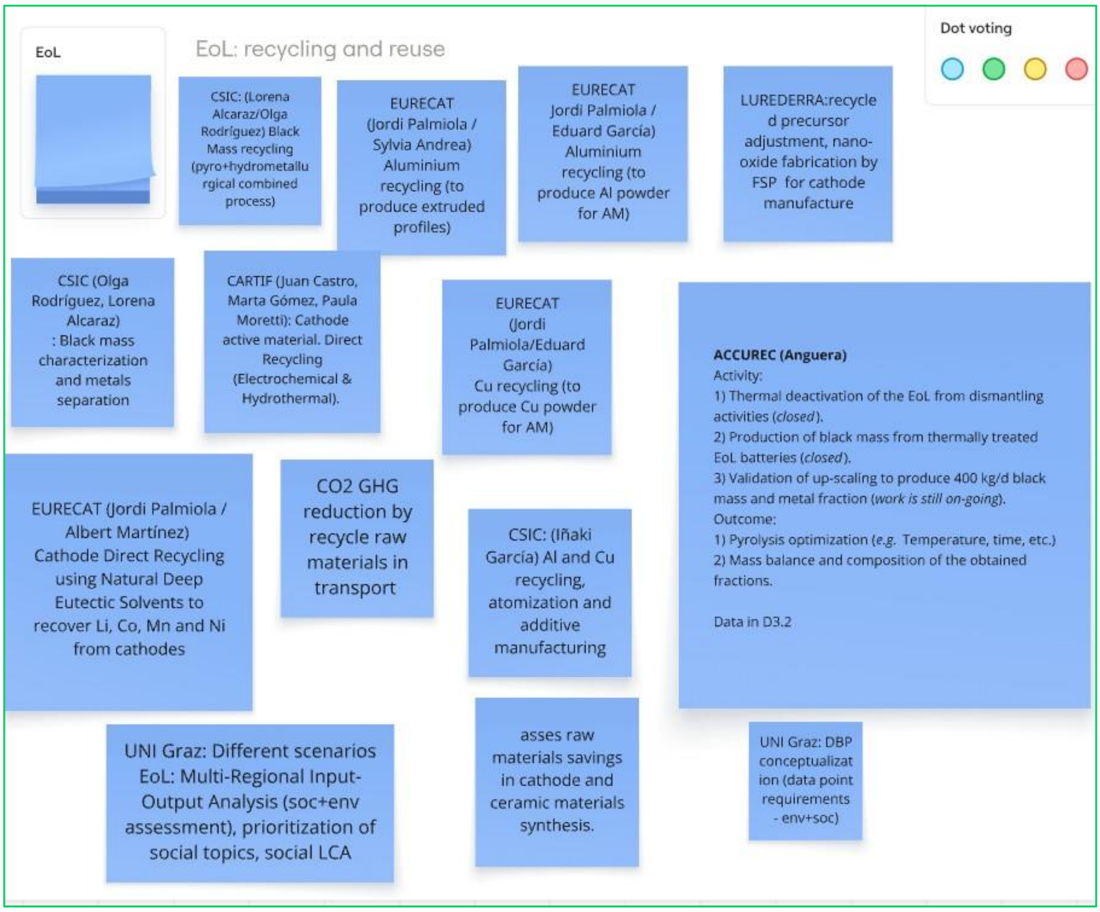


Figure 2. Screenshot of the feedback received during the workshop: a) Manufacturing b) Use phase c)EoL-dismantiling, d) EoL recycling and reuse

Results of the workshop was used to identify the different actions that each partner was undertaking and then go in detail by analysing the deliverables or by bilateral meetings.

4. Analysis of the recycling results

4.1 Summary of the recycling pathways

FREE4LIB addresses the complete circular value chain of lithium-ion batteries by developing and validating innovative technologies for battery dismantling, material recovery, material upgrading and battery remanufacturing. Rather than focusing on a single recycling process, the project investigates complementary recycling pathways that recover battery modules, cathode materials, black mass, polymers, metals and precursors, which are subsequently reintroduced into battery manufacturing or other high-value

Funded by the European Union
Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

applications. This integrated approach aims to maximise resource recovery while reducing dependence on virgin raw materials and improving the sustainability of battery production.

Although each recycling technology has specific technical requirements, the project demonstrates that many of the factors determining recycling efficiency originate during battery design. Decisions related to product architecture, material selection, joining techniques and product information directly influence the feasibility, efficiency and environmental performance of the different recycling routes. Consequently, understanding the relationship between battery design and recycling technologies is essential for developing effective Design for Recycling guidelines.

Table 2 summarises the recycling pathways investigated in FREE4LIB together with the main design implications identified throughout the project.

Table 2. Free4LIB recycling pathways and design implications

Recycling pathway	Main recovered product	Design considerations to facilitate recycling
Battery dismantling	Battery modules	Modular architecture; accessible battery enclosure; standardised fasteners; safe electrical isolation; standard connectors
Pre-treatment	Electrodes, metals, polymers	Easy separation of components; clear material identification; minimise material mixing
Cathode direct recycling	Cathode active materials	Preserve cathode integrity; minimise contamination; facilitate chemistry identification
Black mass recycling	Metal precursors	Simplify material composition; facilitate separation of foils; reduce contaminants
Polymer recycling	Engineering thermoplastics	Reduce polymer diversity; avoid inseparable composites; identify polymer grades; facilitate cleaning
Metal recycling and reuse	Aluminium alloys and metal powders	Reduce alloy complexity; facilitate alloy separation; avoid mixed-metal assemblies

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

Electrode synthesis	Cathode precursors	Preserve material purity; enable traceability of recovered materials
Cell manufacturing	New lithium-ion cells	Standardise recovered material specifications; ensure compatibility with recycled materials

4.1.1 Design implications of the different recycling pathways

4.1.1.1 Battery dismantling and pre-treatment

The first stage of the recycling chain consists of safely dismantling battery packs and separating the different components before subsequent material recovery. FREE4LIB developed robotic-assisted dismantling together with several pre-treatment technologies, including mechanical, hydromechanical, ultrasonic and manual delamination, to recover battery modules, electrodes, polymers and metallic fractions.

From a design perspective, this stage is strongly influenced by the accessibility of battery components. Modular battery architectures, reversible fastening systems and standardised electrical connections considerably simplify dismantling operations while reducing labour requirements and energy consumption. Conversely, permanent adhesives, welded joints and highly integrated structures increase dismantling complexity and may reduce the quality of recovered materials.

4.1.1.2 Cathode direct recycling

Direct recycling aims to recover functional cathode materials while preserving their structure and value. FREE4LIB investigated several direct recycling approaches, including re-lithiation and hydrothermal regeneration of cathode materials, enabling their subsequent reuse in new battery cells.

These technologies demonstrate that battery design should preserve the integrity of cathode materials throughout the product life cycle. Avoiding unnecessary contamination, facilitating electrode separation and ensuring clear identification of battery chemistry improve the feasibility of direct recycling while reducing the need for energy-intensive material refining.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

4.1.1.3 Black mass recycling

Black mass recycling recovers valuable metals and precursor materials through hydrometallurgical processing. Since black mass contains active materials from several battery components, its quality depends directly on the efficiency of upstream dismantling and separation operations.

Battery design can substantially improve this pathway by reducing material complexity, minimising contamination from auxiliary materials and facilitating the separation of current collectors, electrodes and other battery components. Cleaner material streams enable higher recovery efficiencies and reduce downstream processing requirements.

4.1.1.4 Polymer recycling

FREE4LIB developed recycling and upcycling technologies for engineering thermoplastics recovered from battery packs, including decontamination through supercritical CO_2 processing and the production of recycled polymer compounds suitable for new battery applications. The project demonstrates that recovered polymers can be upgraded and reintroduced into high-value applications provided that sufficient material purity is maintained.

These results reinforce several Design for Recycling principles. Battery packs should minimise polymer diversity, avoid inseparable composite structures and clearly identify polymer grades. Such measures improve sorting efficiency, reduce contamination and increase the quality of recycled polymers.

4.1.1.5 Metal recycling and reuse

Recovered aluminium and other metallic fractions can be transformed into metal powders or reused through manufacturing routes such as extrusion and additive manufacturing. The quality of these secondary materials depends largely on the compatibility of alloys recovered during dismantling.

Accordingly, battery designers should reduce unnecessary alloy diversity, avoid permanent combinations of incompatible metals and facilitate the separation of metallic components. These strategies increase the value of recovered metals and enable their direct reuse in new battery components.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

4.1.1.6 Electrode synthesis and cell manufacturing

The final stages of the FREE4LIB value chain demonstrate that recovered precursors and regenerated cathode materials can successfully be incorporated into the synthesis of new electrodes and the manufacture of lithium-ion cells, supporting closed-loop battery production. The project confirms the technical feasibility of manufacturing new cells using recycled active materials while maintaining satisfactory electrochemical performance.

To support these processes, battery design should promote high-purity material recovery, minimise cross-contamination between battery chemistries and enable complete traceability of recovered materials. Standardisation of materials and Digital Battery Passport implementation will further facilitate closed-loop manufacturing.

4.1.2 Cross-cutting eco-design recommendations

Although the recycling technologies developed within FREE4LIB address different battery fractions and employ different recovery principles, they converge towards a common set of design requirements. These common principles should therefore be considered during battery development irrespective of the specific recycling route ultimately employed.

Table 3. Cross-cutting eco-design principles derived from the Free4LIB recycling pathways

Eco-design principle	Benefit for recycling
Modular battery architecture	Facilitates dismantling, repair and second-life applications
Reversible joining techniques	Reduces dismantling effort and improves material recovery
Standardised components and interfaces	Simplifies automated disassembly and replacement
Reduced material diversity	Improves sorting and material purity
Clear material identification	Facilitates separation and recycling
Reduced use of permanent adhesives	Enables mechanical disassembly
Preservation of cathode integrity	Supports direct recycling and material value retention

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

Design for multiple life cycles	Enables repair, repurposing and remanufacturing before recycling
Material traceability and Digital Battery Passport	Improves recycling efficiency and recovered material quality

The recycling technologies developed within FREE4LIB demonstrate that the efficiency of lithium-ion battery recycling is determined not only by the recycling processes themselves but also by decisions taken during battery design. While each recycling pathway presents specific technical requirements, a consistent set of eco-design principles emerges across all technologies. Modular product architectures, reversible joining methods, simplified material composition, clear material identification, standardisation of components and improved traceability facilitate dismantling, enhance the recovery of high-value materials and reduce the environmental impacts associated with end-of-life treatment.

The integration of these principles during battery development supports not only efficient recycling but also higher-value circular economy strategies such as repair, remanufacturing and direct material reuse. Consequently, the design recommendations presented in the following chapter build upon both the technological developments achieved in FREE4LIB and the environmental evidence provided by the Life Cycle Assessment, establishing a comprehensive framework for the design of more circular and sustainable lithium-ion battery systems.

4.2 Environmental analysis results (LCA)

The environmental assessment carried out within FREE4LIB and presented in D 5.1 “Environmental LCA and circularity assessment”[15] provides a quantitative evaluation of the environmental performance of the innovative recycling processes developed in the project and identifies the main environmental hotspots throughout the battery recycling value chain. Rather than comparing individual technologies, the LCA was used to understand which processes, materials and design choices have the greatest influence on the environmental performance of end-of-life lithium-ion battery management. These findings provide valuable input for the development of eco-design guidelines that support more efficient and sustainable battery recycling.

[15] D5.1 “Environmental LCA and Circularty Assessment”, CARTIF and UniGraz, may 2026

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

One of the main conclusions of the environmental assessment is that energy consumption, and particularly electricity use, is the dominant contributor to the environmental impacts of most recycling operations. Mechanical pre-treatment, delamination, material separation, metal recovery and the production of recycled active materials are all highly dependent on electricity-intensive processes. Consequently, design solutions that simplify battery dismantling, reduce the number of processing steps, or facilitate material separation can significantly decrease the environmental burden associated with recycling.

The assessment also highlights the importance of minimising energy-intensive thermal treatments wherever possible. Although thermal processes are often necessary for specific recycling operations, they are generally associated with higher energy demand and additional emissions. From a design perspective, batteries should therefore be developed to favour mechanical disassembly and material separation, reducing the need for complex or high-temperature end-of-life treatments. The use of reversible fastening systems, the limitation of permanent adhesives and the adoption of modular architectures are examples of design strategies that can facilitate these objectives.

Besides process-related impacts, the LCA demonstrates that the environmental profile of battery recycling is strongly influenced by the composition of the battery itself. Critical raw materials, high-purity precursors, solvents and auxiliary chemicals required during material recovery contribute significantly to several environmental impact categories. This finding reinforces the importance of material selection during the design phase. Reducing material complexity, limiting the use of critical raw materials whenever technically feasible, increasing the share of recycled materials and facilitating the recovery of high-value fractions can improve both environmental performance and resource efficiency.

The environmental assessment further indicates that direct recycling approaches capable of recovering functional cathode materials offer significant potential to reduce environmental impacts compared with routes relying exclusively on the production of new active materials from primary raw resources. Preserving the functionality and value of battery materials throughout the recycling process contributes not only to lowering environmental impacts but also to improving resource circularity by maintaining materials at their highest possible value.

An additional outcome of the assessment is the recognition that circularity extends beyond material recycling alone. The circularity indicators evaluated within FREE4LIB underline the importance of designing batteries that support multiple end-of-life strategies, including repair, reuse, remanufacturing and

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

component recovery before material recycling becomes necessary. Design decisions taken during product development therefore have a direct influence on the ability to implement higher-value circular economy strategies throughout the battery life cycle.

Overall, the LCA confirms that many of the environmental impacts associated with lithium-ion battery recycling can be mitigated through appropriate design decisions made at the product development stage. Designing battery systems for easy disassembly, reducing material diversity, enabling efficient identification and separation of components, avoiding irreversible joining techniques and preserving the value of critical materials are all measures that contribute simultaneously to improved recyclability, lower environmental impacts and enhanced circularity.

The environmental findings obtained within FREE4LIB therefore provide the scientific basis for the eco-design recommendations presented in the following sections of this deliverable. Rather than considering recyclability as an isolated requirement, the project demonstrates that eco-design should integrate environmental performance, resource efficiency and circularity from the earliest stages of battery system development.

4.3 Eco-design applied to the development of the Battery Energy Storage Systems

The eco-design principles above mentioned have been shared with W4E and EUT as the partners in charge of the design of the second life battery system and the manufacturing of a material recovered battery for e-bikes respectively (tasks 2.5 and 4.8 of the project). The purpose of sharing eco-design principles with them was of checking which ones could be and have been implemented and which ones could not be included when designing and manufacturing their batteries

W4E and EUT were asked to fill the matrix below that contained an exhaustive list of possible eco-design actions (Figure 3 and Figure 4) and are fully accessible on Annex 1 and Annex 2 to this document.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

Definition of ecodesign strategies for 2nd life and recycled batteries

IREC FREE4LiB

Date:

Application: *Describe the intended application of the battery under design.*

Product specifications: *Describe relevant functions and technical-physical characteristics of the product to be designed/produced.*

Ecodesign objectives: *Define specific objectives. E.g, material recovery, design for recycling, reducing disassembling time, reduce battery size*

Note: *Please select the actions according to the product application and objectives defined.*

Stage	Ecodesign actions	Applicability	Ecodesign strategy (to be implemented)	Baseline (conventional action for comparison)	Comments
Cell/ pack manufacturing	**Concept/product related**				
	• Design for modularity and standardization of battery components for better maintenance, repairment, repurposing and recycling.	☑ ☐			
	• Design for long life				
	• Simplicity of product architecture.	☑			
	• Lower the weight of the battery to achieve better performance during use (depending on the application).	☐ ☑			
	• Design for a minimum volume of battery components (depending on the application).	☑			
	• Design for easy dismantling to facilitate repair and recovery of battery components.				
	Material selection				
	• Avoid using toxic materials and substances as indicated in the New regulation on batteries and waste batteries and REACH regulation.	☐			
	· Use of recycled content in the cells	☐			Specify the % of recycled content in anode, cathode,..
	• Avoid composite materials.	☐			
	• Avoid/reduce the usage of critical-scarce materials.	☐			
	• Use recycled and recyclable materials, especially recycled cobalt, lead, lithium or nickel in compliance with the 2030 & 2035 content targets established in the new Batteries and waste batteries regulation.	☐			
	• Use light materials.	☐			
	• Use durable materials.	☐			
	Manufacturing				
	• Avoid high energy-intensive production processes.	☑			
	• Prioritize the usage of renewable energies.	☐			
	• Recycle scrap (pre-consumer waste)	☐			
	Assembly				
	• Simplicity of assembly process: reduce assembly/disassembly steps and energy processes.	☑			
	• Avoid the use of adhesives, glues or soldered in joints and connections, instead use detachable joints.	☐			
	• Minimize the number and type of fasteners (use same type), ensuring they do not require special tools and are easy to unlock.	☑ ☑			
	• Ensure joints are easily accessible and there is enough space to allow disassembly for repairment and at the end-of-life.				
	Information access and communication				
	• Provide sustainability information in compliance with the requirements of Digital Battery Passport and set in the new Batteries and waste batteries regulation (carbon footprint, recycled content, responsible sourcing, labelling, performance and durability,	☐			
Use	• Provide information on part numbers for components and contact details of sources for replacement spares.	☑ ☑			
	• Indicate dismantling instructions to facilitate repair and replacement of battery components.	☐			
	• Repair/recondition battery pack or individual modules to extend first life in the same or another vehicle.				
End-of-life	**Disassembly**				
	• Provide Dismantling information, including: i) exploded diagrams of the battery system/pack showing the location of battery cells, ii) disassembly sequences, iii) type and number of fastening techniques to be unlocked, iv) tools required for disassembly, v) warnings if risk of damaging parts exist, vi) amount of cells used and layout.	☑ ☐			
	• Provide information for the appropriate treatment of battery components and materials.	☐			
	• Automatize disassembly operations to reduce time and resources.				
	• Reduce the type and number of tools for disassembly.	☐			
	• Use standard tools during disassembly processes.	☑			
	• Ensure traceability of separated battery components according to the information requirements of the Digital Battery Passport established in the new Batteries and waste batteries regulation	☐			
	Reuse				
	• Repair/recondition battery pack or individual modules to extend first life in the same or another vehicle.	☐			
	• Repurpose battery pack or individual modules for 2nd life applications when the battery is sufficiently degraded to meet first life requirements in vehicles.	☑			
	Recycling				
	• Ensure recyclates quality comparable to that of original materials.	☐			
	• Recycle critical materials, particularly those specified in the new Batteries and waste batteries regulation (cobalt, lead, lithium, nickel).	☐			
	• Guarantee traceability of recycled battery components and materials.	☐			

Figure 3. Matrix to select eco-design actions undertaken in the design of the BESS

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

Definition of ecodesign strategies for 2nd life bat

IREC FREE4LiB

Date: 07-oct-24

Application: *FREE4LIB T4.8 Battery for light e-mobility (e-Bike)*

Product specifications: *Capacity:10 Ah, Voltage: 36 V, Current: 7.8 A, Weigth: < 6 Kg, Charging time: 4-6h (42V, 2A); Max Power: 250 W*

Ecodesign objectives:
Maximize use of recycled materials
Design for Recycling
Enable easy cell replacement
Reduce disassembling time

Note: *Please select the actions according to the product application and objectives defined.*

Stage	Ecodesign actions	Applicability	Ecodesign strategy (to be implemented)	Baseline (conventional action for comparison)	Comments
Cell/ pack manufacturing	**Concept/product related**				
	• Design for modularity and standardization of battery components for better maintenance, repairment, repurposing and recycling.	☑ ☑	Standardization of electric and electronic system components. Easy dismantling to facilitate repairment and repurposing of faulty components, and materials' separation for recycling.	Repairment and repurposing is not possible due to fixed unions between components (welded). Faulty components cannot be repaired or replaced.	
	• Design for long life		Extended life through repairment	Difficult to repair due to welded unions.	
	• Simplicity of product architecture.	☑	Minimum number of components	Prioritize price of components	
	• Lower the weight of the battery to achieve better performance during use (depending on the application).	☑ ☑	Reused lightweight components	N/A	Use of baseline battery casing
	• Design for a minimum volume of battery components (depending on the application).	☑	Introduction of other ecodesign actions (maintenance and repairment) with the same volume	N/A	Use of baseline battery casing
	• Design for easy dismantling to facilitate repair and recovery of		Use of weldless connections, no adhesives use.	Use of fixed unions (welds, adhesives)	
	Material selection				
	• Avoid using toxic materials and substances as indicated in the New regulation on batteries and waste batteries and REACH regulation.	☑	No toxic materials in battery casing		
	• Avoid composite materials.	☑	No composite materials		
	• Avoid/reduce the usage of critical-scarce materials.	☑	Use of recycled cell components (C, Si, Co, Li)	Raw materials without recycled content	
	• Use recycled and recyclable materials, especially recycled cobalt, lead, lithium or nickel in compliance with the 2030 & 2035 content targets established in the new Batteries and waste batteries regulation.	☑ ☑	Use of recycled materials for cell production (anode and cathode) and battery casing	Raw materials without recycled content	
	• Use light materials.		Increased aluminum use		
	• Use durable materials.	☑	Use of metals if possible	Major use of plastic materials	
	Manufacturing				
	• Avoid high energy-intensive production processes.	☑	Use of recycled aluminium profiles	Raw materials without recycled content	
	• Prioritize the usage of renewable energies.	☑			
	• Recycle scrap (pre-consumer waste)	☑	Use of recycled aluminum from scraps	Raw materials without recycled content	
	Assembly				
	• Simplicity of assembly process: reduce assembly/disassembly steps and energy processes.	☑ ☑	Mechanical assembly, non-welded joints	Use of welded and permanent joints	
	• Avoid the use of adhesives, glues or soldered in joints and connections, instead use detachable joints.		Mechanical assembly, non-welded joints	Use of welded and adhesive joints	
	• Minimize the number and type of fasteners (use same type), ensuring they do not require special tools and are easy to unlock.	☑ ☑	Minimal number of fasteners	Use of welded and adhesive joints	
	• Ensure joints are easily accessible and there is enough space to allow disassembly for repairment and at the end-of-life.		All the joints are accessible in the same side of the battery	Use of welded and adhesive joints	
	Information access and communication				
	• Provide sustainability information in compliance with the requirements of Digital Battery Passport and set in the new Batteries and waste batteries regulation (carbon footprint, recycled content, responsible sourcing, labelling, performance and durability, dismantling and safety).	☑	Inclusion of Digital Battery Passport QR label at battery pack and cell levels.	Digital Battery Passport QR label not included	Not included in this prototype because of its maturity level.
Use	• Provide information on part numbers for components and contact details of sources for replacement spares.	☑ ☑	Include References replacement spares in BOM		
	• Indicate dismantling instructions to facilitate repair and replacement of battery components.	☑	Inclusion of drawings and diagrams explaining the design and assembly process	Information not available	
	• Repair/recondition battery pack or individual modules to extend first life in the same or another vehicle.		Extended life through repairment	Difficult to repair due to welded unions.	

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

End-of-life	**Disassembly**				
	• Provide Dismantling information, including: i) exploded diagrams of the battery system/pack showing the location of battery cells, ii) disassembly sequences, iii) type and number of fastening techniques to be unlocked, iv) tools required for disassembly, v) warnings if risk of damaging parts exist, vi) amount of cells used and layout.	☑ ☐	Inclusion of drawings and diagrams explaining the design and assembly process	Information not available	
	• Provide information for the appropriate treatment of battery components and materials.	☑			Given the current product maturity level, which is still in the prototype (laboratory) phase, this is not applicable.
	• Automatize disassembly operations to reduce time and resources.				
	• Reduce the type and number of tools for disassembly.	☑			
	• Use standard tools during disassembly processes.	☑	Use of standard elements		
	• Ensure traceability of separated battery components according to the information requirements of the Digital Battery Passport established in the new Batteries and waste batteries regulation.	☑	Inclusion of Digital Battery Passport QR label at battery pack and cell levels.	Digital Battery Passport QR label not included	Not included in this prototype because of its maturity level.
	Reuse				
	• Repair/recondition battery pack or individual modules to extend first life in the same or another vehicle.	☑	Mechanical assembly, non-welded joints	Use of welded and permanent joints	
	• Repurpose battery pack or individual modules for 2nd life applications when the battery is sufficiently degraded to meet first life requirements in vehicles.	☐			It is already being used for a second life; this would be a third one. Let it degrade completely. We extend the product's life in this application. With the repair, the second life is already prolonged.
	Recycling				
	• Ensure recyclates quality comparable to that of original materials.	☐			Cell quality does not depend on the design process. Complementary parts (metallic parts) have been selected to be recyclable, they don't degrade the quality.
	• Recycle critical materials, particularly those specified in the new Batteries and waste batteries regulation (cobalt, lead, lithium, nickel).	☐ ☑			The cell recovery process will be respected, but the quality won't be the same as at the beginning (there may be impurities or a lower amount of recyclable material). The performance will be worse for batteries, but the material can still be reused for other applications.
	• Guarantee traceability of recycled battery components and materials.		Inclusion of Digital Battery Passport QR label at battery pack and cell levels.	Digital Battery Passport QR label not included	

Figure 4. Matrix to select eco-design actions undertaken in the design of e-bike battery

Based on the two matrices, the two demonstrators follow different eco-design philosophies:

- Case 1 (Second-life battery): focuses on repurposing an existing battery pack, so many design strategies are constrained by the original battery architecture.
- Case 2 (Battery manufactured using recovered materials/components): starts from a new battery design, allowing many more eco-design principles to be incorporated from the outset.

Case 1:

The second-life battery demonstrator illustrates the opportunities and limitations of applying eco-design principles when repurposing an existing lithium-ion battery for a new application. Since the battery architecture is inherited from the original product, the implementation of eco-design measures is largely constrained by decisions taken during the first-life design phase. Consequently, the assessment demonstrates that the success of second-life applications strongly depends on whether the original battery was designed with future reuse, repair and recycling in mind.

Among the strategies successfully adopted, particular emphasis was placed on preserving modularity wherever possible, simplifying the overall system architecture, facilitating dismantling operations and minimizing the number of components and fastening systems. The demonstrator also includes the provision of dismantling information, part identification and replacement information, together with the use of standard tools for disassembly. Most importantly, the battery itself is repurposed for a second-life application, extending its useful lifetime and delaying material recycling.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

However, a significant number of eco-design strategies could not be implemented because they depend on the original battery design. These include the incorporation of recycled materials, reduction of critical raw materials, selection of lightweight or more durable materials, elimination of welded joints and permanent adhesives, implementation of Digital Battery Passport requirements, automated disassembly, and traceability of recovered materials. Likewise, manufacturing-related strategies such as the use of renewable energy or recycling of production scrap fall outside the scope of a second-life repurposing process.

The assessment confirms that second-life applications are an effective strategy for extending battery lifetime and improving resource efficiency, but they cannot compensate for design decisions made during the original manufacturing stage. Batteries intended to support multiple life cycles should therefore be designed from the outset with modular architectures, reversible joining techniques, standardized components and comprehensive product information that facilitate inspection, repair, repurposing and final recycling. The experience gained in this demonstrator clearly demonstrates that eco-design decisions taken during first-life battery development determine the feasibility and efficiency of future circular economy strategies.

Case 2

Unlike the second-life demonstrator, the battery developed using recovered materials and recycled components provided the opportunity to integrate eco-design principles from the earliest stages of product development. The resulting design demonstrates that circularity objectives can be incorporated simultaneously into product architecture, material selection, assembly methods and end-of-life management without compromising the intended functionality of the battery.

The adopted strategies include a modular and standardized architecture, simplified product design, easy dismantling through mechanical and weld-free connections, minimization of fasteners, accessible joints and the elimination of permanent adhesives wherever possible. Particular attention was also given to material selection by maximizing the use of recycled materials in battery cells and casing, reducing the use of virgin critical raw materials, increasing the use of aluminium and durable materials, and avoiding composite materials that complicate recycling. Manufacturing strategies further promote the use of recycled aluminium, recovery of production scrap and lower-energy manufacturing approaches.

The demonstrator also incorporates several measures that facilitate maintenance, repair and end-of-life management, including dismantling instructions, replacement part identification, standard disassembly tools and

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

provisions for Digital Battery Passport implementation and component traceability. Although some of these digital solutions were not fully implemented due to the prototype maturity level, the battery has been designed to accommodate them in future industrial developments.

Some eco-design strategies could not be fully demonstrated. Digital Battery Passport implementation and complete traceability of recovered materials were not deployed because the demonstrator remains at laboratory prototype level. Similarly, recommendations concerning information for waste treatment, recyclate quality and complete recovery of critical raw materials depend on future industrial recycling processes rather than on battery design itself. The possibility of further repurposing was also considered outside the project scope, since the demonstrator already represents a circular application based on recovered materials.

Overall, this case study demonstrates that integrating eco-design requirements from the beginning of product development enables substantially higher levels of circularity than those achievable through the adaptation of existing batteries. The demonstrator confirms that design choices such as modularity, reversible assembly, use of recycled materials, simplified material composition and improved disassembly can significantly facilitate maintenance, repair, material recovery and recycling. These experiences provide practical evidence that eco-design is a key enabler for increasing both the environmental performance and the circularity of future lithium-ion battery systems.

These two conclusions are complementary: the first highlights the **limitations imposed by legacy battery designs**, while the second shows the **benefits of integrating eco-design from the initial design stage**.

5. Eco-design guidelines-lessons learned

The environmental assessment performed within the FREE4LIB project has identified the key factors influencing the environmental performance of lithium-ion battery recycling processes. The LCA results demonstrate that decisions taken during the battery design phase have a significant impact on the efficiency of end-of-life treatment, the environmental burdens associated with recycling operations, and the quantity and quality of materials that can be recovered for subsequent reuse.

Based on the findings of the environmental assessment and the case studies (case 1 and case 2 reported in the previous section), the following key aspects should be considered when designing battery systems to minimise the

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

environmental impacts associated with recycling operations while maximising the recovery and retention of valuable materials. These considerations provide the environmental rationale underpinning the eco-design recommendations presented in this deliverable.

5.1 Environmental priorities (supported by the LCA)

- **Electricity is the main environmental hotspot**

This is probably the most consistent conclusion of the environmental assessment. Across nearly all the recycling technologies evaluated, electricity consumption is identified as the main contributor to environmental impacts, particularly in processes such as:

- Pre-treatment
- Delamination
- Polymer recycling
- Metal recycling
- Electrode synthesis
- Cell manufacturing

This finding translates directly into an eco-design recommendation:

Design battery systems that minimise the energy demand of dismantling and recycling operations. Reducing the number of energy-intensive processing steps and use a renewable source energy mix contribute directly to lowering the environmental impacts of end-of-life treatment**.**

- **Avoid unnecessary thermal processes**

The LCA shows that high-temperature treatments are generally associated with increased environmental impacts due to their significant energy and fuel consumption.

These results support design strategies aimed at reducing the need for thermal processing during end-of-life management, including:

- Facilitating mechanical separation of components;
- Designing batteries for easy disassembly;

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

- Avoiding permanent adhesives whenever possible;
- Minimising the need for high-temperature treatment during recycling.

- **Material selection is as important as the recycling process**

The environmental assessment demonstrates that, for several downstream recycling technologies, a significant share of the environmental impacts originates from the materials and chemicals required by the process rather than from the process itself.

Major contributors include:

- Nickel (Ni) precursors;
- Cobalt (Co) precursors;
- Organic solvents;
- Inert gases;
- Auxiliary alloys and chemicals.

These findings reinforce several key eco-design principles:

- Reduce the use of Critical Raw Materials (CRMs) whenever technically feasible;
- Maximise the incorporation of recycled materials;
- Simplify the material composition of battery components;
- Avoid unnecessary alloys and complex material combinations that hinder recycling.

- **Direct recycling offers significant environmental benefits**

The LCA compares the production of cathode active materials from primary raw materials with the FREE4LIB direct recycling route based on recovered materials.

The results indicate that recovering functional cathode materials through direct recycling has considerable potential to reduce the environmental impacts associated with the production of primary raw materials, while preserving the value of critical materials within the circular economy.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

- **Circularity goes beyond recycling**

The D5.1 assessment includes a comprehensive evaluation of circularity using indicators based on the ISO 59020 framework.

The results highlight that battery design should not focus exclusively on material recycling, but should also facilitate higher-value circular strategies throughout the product life cycle, including:

- Reuse,
- remanufacturing,
- component recovery, and
- material recovery.

Considering these strategies during the design phase increases the overall circularity of battery systems and helps maximise resource efficiency while reducing environmental impacts.

5.2 Design priorities (validated through the case 1 and case 2 demonstrators)

Design for modularity and multiple life cycles

The second-life demonstrator clearly shows that the feasibility of battery repurposing is largely determined during the original design phase. Modular architectures, standardized components and accessible assemblies greatly facilitate inspection, repair, replacement and repurposing, extending the useful life of batteries before material recycling becomes necessary.

This supports recommendations such as:

- Adopt modular battery architectures.
- Standardise components and interfaces.
- Enable replacement of modules and critical components.
- Design batteries with multiple life cycles in mind.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

Facilitate dismantling through reversible joining techniques

Both demonstrators highlight that battery disassembly is one of the most critical steps influencing maintenance, repurposing and recycling efficiency. The use of mechanical fasteners and reversible joining methods significantly reduces dismantling time and complexity while improving the recovery of high-value components and materials.

Design strategies include:

- Use reversible mechanical fasteners instead of permanent joining techniques.
- Minimise the use of adhesives and welded joints.
- Ensure accessibility to critical components.
- Design for disassembly using standard tools.

Integrate traceability and information throughout the battery life cycle

Although some digital solutions could not be fully implemented within the demonstrators, both case studies emphasise the importance of product information for enabling circular economy strategies. Reliable information on battery composition, component identification and dismantling procedures facilitates maintenance, second-life applications and high-quality recycling.

Key recommendations include:

- Implement Digital Battery Passport requirements.
- Provide dismantling and repair instructions.
- Identify materials and components clearly.
- Improve traceability of recycled and recovered materials.

5.3 Lessons learned

The activities carried out within FREE4LIB demonstrate that achieving highly circular lithium-ion batteries requires integrating Design for Sustainability principles from the earliest stages of product development. The combination of Life Cycle Assessment, innovative recycling technologies and demonstrator

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

development has enabled the identification of several key lessons that can support future battery developments beyond the scope of the project.

Lesson 1 – Recycling efficiency begins during battery design

The effectiveness of battery recycling is largely determined by decisions taken during product development. Battery architecture, joining methods, material selection and component accessibility directly influence dismantling efficiency, material recovery rates and recycling costs.

Lesson 2 – Modularity enables multiple circular economy strategies

Modular battery architectures facilitate maintenance, repair, module replacement, second-life applications and final recycling. Designing batteries as modular systems significantly increases their flexibility throughout the entire life cycle.

Lesson 3 – Simplified material composition improves recyclability

Reducing material diversity, limiting unnecessary alloying and avoiding complex material combinations improve material separation and increase the quality of recovered secondary raw materials.

Lesson 4 – Reversible joining techniques facilitate material recovery

Mechanical fastening systems and reversible connections considerably simplify dismantling while reducing energy consumption and preserving the integrity of battery components.

Lesson 5 – Direct recycling preserves material value

The technologies developed within FREE4LIB demonstrate the environmental and economic potential of preserving cathode materials through direct recycling, maintaining materials at higher value than conventional metallurgical recovery routes.

Lesson 6 – Environmental performance and circularity are complementary objectives

Life Cycle Assessment confirms that many eco-design strategies that improve recyclability also reduce environmental impacts by lowering energy consumption, reducing processing requirements and increasing material recovery.

Lesson 7 – Traceability will become increasingly important

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

The implementation of Digital Battery Passport requirements and improved material traceability will facilitate dismantling, recycling and the incorporation of recovered materials into future battery manufacturing.

Lesson 8 – Eco-design requires collaboration across the entire value chain

Designing truly circular batteries cannot be achieved by battery manufacturers alone. Effective implementation requires collaboration between designers, material suppliers, recyclers, equipment manufacturers and policymakers to ensure that battery systems remain compatible with future recycling technologies.

6. Conclusions

The work carried out within FREE4LIB demonstrates that battery recycling efficiency is determined not only by advances in recycling technologies but also by decisions taken during battery design. The environmental assessment, technological developments and demonstrators consistently show that Design for Sustainability represents one of the most effective approaches for increasing battery circularity while reducing the environmental impacts associated with manufacturing and end-of-life treatment.

The Life Cycle Assessment identifies energy consumption, material selection and material recovery efficiency as the principal factors influencing the environmental performance of recycling operations. These findings confirm that battery architecture, joining techniques and material composition directly affect both recycling efficiency and environmental impacts.

The recycling pathways developed within FREE4LIB further demonstrate that different recycling technologies share common design requirements. Modular battery architectures, simplified material composition, reversible joining methods, improved accessibility, material traceability and standardisation facilitate dismantling, improve the recovery of high-value materials and enable the production of secondary raw materials suitable for closed-loop manufacturing.

The case 1 and case 2 developed within the project provide valuable practical lessons. The second-life battery highlights how many circular economy opportunities are constrained by design decisions made during the first product life, while the battery manufactured using recovered materials demonstrates the benefits of integrating eco-design principles from the earliest stages of product development. Together, these case studies confirm that

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890

Design for Sustainability must be considered as a fundamental engineering requirement rather than an additional environmental consideration.

Overall, FREE4LIB demonstrates that integrating environmental assessment, recycling technologies and eco-design into a unified framework enables the development of battery systems that are better prepared for future circular value chains. The guidelines presented in this deliverable provide practical recommendations for battery designers and manufacturers seeking to maximise resource efficiency, facilitate recycling and support compliance with emerging European sustainability requirements. They also contribute to accelerating the transition towards more resilient, resource-efficient and sustainable lithium-ion battery systems.

Funded by the European Union

Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them. This project has received funding from Horizon Europe research and innovation programme under Grant Agreement No.1069890