



BUILDING AN EU INDUSTRIAL ECOSYSTEM OF CIRCULARITY APPLICATIONS FOR BATTERY PACKS

**State of play, challenges and conditions for
further development**

Vasileios Rizos, Patricia Urban, Gustavo Quintana Cabrera,
Deniz Tekin, Hien Vu and Marika Moreschi

SUMMARY

Electric vehicles (EVs) are rapidly transforming the transportation landscape. In this context, circularity solutions, namely recycling and second-life applications, are central to addressing environmental impacts and securing access to valuable materials in electric vehicle batteries (EVBs). While the EU is at the forefront of regulatory action in this domain, with the 2023 Batteries Regulation as a cornerstone, further efforts are needed to develop viable circular supply chains and a domestic recycling market.

Consolidating lessons learnt from the 4-year BATRAW project, this report dives into the evolving landscape of battery circularity applications and draws lessons from their implementation. Based on a review of the landscape, it shows that both recycling and second-life use of EVBs remain at an early stage of development in the EU with some positive trends noted.

With regard to recycling, an expansion trend is evident, with available capacity exceeding 436,000 t/year as of Q1 2026, according to our mapping. However, interviews highlight several policy, economic and market-related constraints. A cluster of these relates to the evolving EU policy landscape, where the EU Batteries Regulation is perceived as a key enabler of circularity, but also introduces implementation uncertainties. The economics of battery recycling remain challenging, pointing to the need for further cost-reduction efforts.

Our mapping also identified various repurposing facilities across the EU, indicating growing interest in second-life applications. However, a variety of challenges, including regulatory uncertainties with regard to allocation of responsibilities and liabilities for second-life batteries and the difficult economic case for second-life batteries, which need to compete with new batteries experiencing declining costs may constrain the further development of such applications.

We identify three key enabling conditions for scaling up circularity applications for EVBs in the EU: (i) effective implementation of the EU policy framework underpinned by the Batteries Regulation; (ii) strengthened financial support for scaling up battery circularity applications; and (iii) further harmonisation of the standardisation landscape impacting EVB circularity.



Vasileios Rizos is a Senior Research Fellow and Head of the Energy, Resources and Climate Change (ERCC) unit at CEPS. Patricia Urban is an Associate Researcher in the ERCC unit at CEPS. Gustavo Quintana Cabrera is a Research Assistant in the ERCC unit at CEPS. Deniz Tekin is a Research Assistant in the ERCC unit at CEPS. Hien Vu is an Associate Researcher in the ERCC unit at CEPS. Marika Moreschi was an Associate Research Assistant in the ERCC unit at CEPS. The authors thank Francisco Rios and Gaia Cavaglioni from the CEPS Data Science team for providing support with data visualisation.

This paper was prepared in the context of the [BATRAW](#) project, which has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101058359.

CEPS In-depth Analysis papers offer a deeper and more comprehensive overview of a wide range of key policy questions facing Europe. Unless otherwise indicated, the views expressed are attributable only to the authors in a personal capacity and not to any institution with which they are associated.

CONTENTS

FIGURES AND TABLES	II
ABBREVIATIONS	III
INTRODUCTION.....	1
1. POLICY DEVELOPMENTS.....	3
1.1. EU BATTERIES REGULATION	3
1.2. STANDARDS FOR RECYCLING AND REUSE OF BATTERY PACKS IN THE EU	10
1.3. GLOBAL POLICY DEVELOPMENTS	16
2. BATTERY RECYCLING.....	20
2.1. KEY TECHNOLOGIES.....	20
2.2. STATE OF PLAY	23
2.3. OVERARCHING CHALLENGES AND ENABLING CONDITIONS FOR EVB RECYCLING	26
3. SECOND-LIFE APPLICATIONS	35
3.1. KEY APPLICATIONS	35
3.2. STATE OF PLAY	37
3.3. OVERARCHING CHALLENGES AND ENABLING CONDITIONS FOR SECOND-LIFE EVBS	41
4. CREATING THE BUSINESS CASE FOR EVB CIRCULARITY.....	50
4.1. RECYCLING	50
4.2. REPURPOSING	54
CONCLUSIONS AND ENABLING CONDITIONS	60
ANNEXES	63
ANNEX A: LIST OF INTERVIEWEES.....	63
ANNEX B: OVERVIEW OF BATTERY RECYCLING AND REPURPOSING FACILITIES IN EUROPE	65
ANNEX C: RECYCLABLE VALUE ASSESSMENT OF LIB PACKS	70
ANNEX D: METHODOLOGY AND DATA FOR EVB PRICE PROJECTIONS FOR NEW AND REPURPOSED EVBS	72
REFERENCES	75
ABOUT THE BATRAW PROJECT.....	87

FIGURES AND TABLES

FIGURE 1: MAP OF EXISTING AND ANNOUNCED BATTERY RECYCLING CAPACITY IN EUROPE.	25
FIGURE 2: OVERARCHING CHALLENGES AND ENABLING CONDITIONS FOR EVB RECYCLING.....	26
FIGURE 3: MAP OF EXISTING BATTERY REPURPOSING FACILITIES IN EUROPE.	40
FIGURE 4: OVERARCHING CHALLENGES AND ENABLING CONDITIONS FOR SECOND-LIFE EVBs.	41
FIGURE 5: HISTORICAL RETAIL PRICES OF NEW AND REPURPOSED LITHIUM-ION EVBs, ALONG WITH INDICATIVE SCENARIOS TO 2030.	57
TABLE 1: OVERVIEW OF SELECTED REQUIREMENTS OF THE BATTERIES REGULATION FOR ELECTRIC VEHICLE BATTERIES (EVBs).....	5
TABLE 2: OVERVIEW OF STANDARDS FOR THE RECYCLING AND REUSE OF BATTERY PACKS IN THE EU.....	13
TABLE 3: EXAMPLES OF SECOND-LIFE BATTERY ENERGY STORAGE IN EUROPE.....	38
TABLE 4: WEIGHTED VALUE POTENTIAL OF LFP AND NMC BATTERIES CONSIDERING SPECIFIC RECYCLABLE METALS.....	51

ABBREVIATIONS

Abbreviation	Term
BESS	Battery Energy Storage System
BMS	Battery Management System
CF	Carbon Footprint
CRM	Critical Raw Material
DPP	Digital Product Passport
EoL	End of Life
EPR	Extended Producer Responsibility
EV	Electric Vehicle
EVB	Electric Vehicle Battery
LCA	Life Cycle Assessment
LCOS	Levelised Cost of Storage
LIB	Lithium-ion Battery
LMT	Light Means of Transport
PV	Photovoltaic
RUL	Remaining Useful Life
SoC	State of Charge
SoH	State of Health
SLI	Starting, Lighting and Ignition

INTRODUCTION

Battery technologies are expected to drive a major transformation of the transportation landscape, gradually replacing the internal combustion engine, which has been the dominant source of power for cars for more than a century (IEA, 2025a; Upadhyay et al., 2021). Signs of this transformation are becoming visible worldwide, with sales of electric vehicles (EVs) growing and reaching 17 million in 2024, and the total EV fleet having tripled over the past 3 years (IEA, 2025b). In addition to having lower life-cycle emissions than combustion engine vehicles (Fuinhas et al., 2021; Pipitone et al., 2021), EVs offer new economic opportunities and enable the emergence of new business models across their full value chain (Ellen MacArthur Foundation, 2026).

Although EVs offer emission reduction benefits, especially when powered by clean electricity, the battery production stage is material-intensive and causes significant environmental impacts (Crenna et al., 2021; Dunn et al., 2022). Lithium-ion batteries (LIBs) – the predominant battery technology in current applications – contain various materials such as cobalt, nickel, lithium, manganese, aluminium and copper whose demand is expected to increase substantially in the coming years due to rising sales of EVs, thereby raising environmental concerns due to the mining and refining of these materials (Bobba et al., 2025; Peiseler et al., 2023). Implementing circularity applications for battery packs – such as second-life applications and recycling – holds promise for mitigating some of the impacts linked with the growing demand for materials and supporting a more sustainable supply chain for EVs (Sopha et al., 2022; Widiawati et al., 2025).

Beyond the environmental benefits of circular applications, their broader adoption is becoming increasingly important in an era where access to critical raw materials (CRMs) is a central pillar of geopolitical competition. As global EV production expands and drives demand for CRMs, the risks associated with dependence on a limited number of supplier countries are becoming more acute for economies aiming to develop domestic battery production. This has prompted governments to implement relevant policies and financing programmes to support the development of domestic recycling capacities (IEA, 2025c; Righetti & Rizos, 2024).

Faced with the above risks, the EU has taken action in recent years to support battery circularity and the automotive sector more broadly. This sector has traditionally been a significant value-creating sector of the EU economy, but is currently facing intense global pressure (Dietz et al., 2025). The [EU Batteries Regulation](#), which entered into force in 2023, represents a cornerstone in these efforts, introducing, among other things, binding recycling targets and sustainability information sharing. More recently, the [Clean](#)

Industrial Deal and the Industrial Action Plan for the European automotive sector, both published at the beginning of the present 2024-2029 political cycle, reaffirmed the Union's commitment to adopt dedicated measures for boosting circularity in the sector. Nevertheless, the majority of battery pre-treatment and material recovery facilities are currently located in China¹, which means that the EU will need to step up its efforts in the coming years to develop viable circular supply chains for battery materials and a domestic recycling market (IEA, 2025c).

This report navigates into the evolving landscape of battery circularity applications (recycling and second-life), exploring policy and market developments, economic competitiveness aspects, key challenges and ultimately the conditions required to build an effective EU industrial ecosystem for such applications. It draws on knowledge and insights generated during the 4-year (2022-2026) implementation of the BATRAW EU-funded project, which developed and piloted reuse and recycling solutions² for battery packs in the EU. Desk research findings were complemented by insights from 29 companies (see Annex A) spanning the entire battery circularity value chain.

The report starts by outlining policy developments linked to battery circularity in the EU and globally (Section 1). It then dives into the battery recycling applications, exploring the current state of play, key technologies, documented challenges and enabling conditions (Section 2). This is followed by a similar analysis of second-life applications (Section 3). The final substantive section (Section 4) explores the economics and the conditions for creating a viable business case for battery circularity. The last part of the report is devoted to the conclusions and policy recommendations.

¹ According to IEA (2025c), China currently holds the majority (80 %) of pre-treatment and material recovery capacity (including both the pyrometallurgy and hydrometallurgy methods) globally, while Europe and North America together hold a combined share of 10 % in pre-treatment and 4 % in the material recovery.

² The recycling pilot involved both a pre-treatment and hydrometallurgy material recovery method, while the reuse pilot deployed a semi-automated battery pack disassembly process aimed at reusing battery components. Further information is available on the project [website](#).

1. POLICY DEVELOPMENTS

This section reviews key policy developments shaping battery circularity. It first outlines the broader framework of the EU Batteries Regulation (1.1) with a focus on the provisions relevant to recycling and second-life applications. It then examines standards supporting battery reuse and recycling in the EU (1.2), followed by a brief overview of global policy developments in the field (1.3).

1.1. EU BATTERIES REGULATION

The EU Batteries Regulation (2023/1542) was adopted in 2023 to modernise and strengthen the regulatory framework for batteries, replacing the 2006 [Batteries Directive \(2006/66/EC\)](#). To minimise the environmental and social impacts of rapidly increasing battery demand—driven by the ongoing electrification of transportation and energy systems—the Regulation introduces various requirements for battery design, performance, and end-of-life (EoL) management.

These EU-wide sustainability obligations target all batteries placed on the European market. The 2006 Directive has been expanded to cover a wider range of batteries, including electric vehicle batteries (EVBs), industrial batteries, waste portable batteries, and batteries for light means of transport (LMT), such as electric bicycles, as well as starting, lighting, and ignition (SLI) batteries. The Regulation also adopts a life-cycle approach to battery sustainability, circularity and safety, rather than merely focusing on restricting hazardous substances and improving waste management, as was previously the case.

A key innovation of the Regulation is the introduction of binding battery design and manufacturing requirements that explicitly anticipate EoL management needs, while aiming to enhance performance throughout batteries' life cycles. As such, manufacturers need to comply with stricter requirements related to durability, safety and performance, including for the environmental footprint of batteries (see Table 1).

Sustainability and safety provisions encompass, among others, restrictions on hazardous substances and obligations for documenting carbon footprint and recycled content. The Regulation also sets minimum recycled content targets for specific materials used in EVBs, industrial batteries, and SLI batteries, which are discussed further below. In addition, the Regulation introduces electrochemical performance and durability requirements, such as for battery capacity and discharge performance. Moreover, portable batteries must be designed to be readily removable and replaceable by end users, and specific safety provisions apply to stationary battery energy storage systems.

Beyond sustainability and safety, the Regulation introduces labelling and information obligations for economic operators. From 2026, batteries placed on the market must carry labels containing information such as manufacturer details, battery capacity, hazardous substances and critical raw materials. From 2027 onwards, all batteries must be equipped with a QR code providing access to labelling information and additional documentation, including declarations of conformity and due diligence reports. A carbon footprint declaration – accessible via the QR code – will be required for each battery model per manufacturing plant for EVBs, rechargeable industrial batteries above 2 kWh and LMT batteries. These battery categories must also provide access to a digital battery passport via the QR code. To facilitate decision-making at EoL and to enable reuse, repurposing or remanufacturing, EVBs, LMT batteries and stationary energy storage systems must be equipped with a Battery Management System (BMS), an electronic system containing information on State of Health (SoH), charging cycles, and expected remaining useful life (RUL).

The digital battery passport (a Digital Product Passport – DPP – for batteries, henceforth, ‘battery passport’) is a crucial novelty of the Batteries Regulation. Mandatory for EVBs, LMT and industrial batteries with a capacity above 2 kWh as of 2027, the battery passport serves as an electronic record of the battery’s life cycle. It will need to include standardised information in an interoperable format on both the battery model and the individual battery, on different layers of visibility. General information on the battery model (e.g. the manufacturer, material composition, and capacity), as well as relevant sustainability data (e.g. the carbon footprint, recycled content, and responsible sourcing) and waste prevention information, will be available to the public. The battery passport also contains data related to dismantling, repairing, remanufacturing, and recycling, which will only be available to the actors performing these operations (as well as the Commission, in some cases, and persons with legitimate interest). The economic operator placing the battery on the market will be responsible for verifying, updating, and storing the information in the battery passport. The battery passport will cease to exist after recycling. For waste batteries, battery transport responsibilities will be taken over by the producer or the waste management operator.

The Batteries Regulation also puts in place extended producer responsibility (EPR) and EoL management obligations. These require producers placing batteries on the EU market to finance the separate collection and transport of waste batteries, to establish take-back and collection schemes, and to provide information on waste prevention and management to end users and distributors. Minimum collection targets are set to increase over time. For waste portable batteries, a minimum collection rate of 45 % applies as of 31 December 2023, rising to 73 % by 31 December 2030. For LMT batteries, collection targets increase from 51 % by 31 December 2028 to 61 % by 31 December

2031. All waste batteries must be collected separately, and disposal in landfills is prohibited. The Regulation also establishes minimum recycling efficiency thresholds and material recovery targets, which are detailed below.

The Regulation further introduces due diligence obligations aimed at minimising environmental and social impacts across battery life cycles. These requirements apply to economic operators placing batteries on the market, except for those with a net turnover below 40 million EUR in the preceding financial year. By August 2027³, affected operators must establish, implement and verify due diligence policies covering raw materials such as cobalt, lithium, nickel and natural graphite, as well as associated social and environmental risk categories, including human rights, environment, climate, human health, and community life. Due diligence policies and responsible sourcing information must be publicly communicated and made accessible through the battery passport as part of an annual due diligence report. Companies are also required to align their due diligence systems with internationally recognised standards, ensure supply chain transparency and traceability, and document information on suppliers, countries of origin and raw material transactions from extraction onwards. In addition, operators must identify, assess and mitigate adverse impacts within their supply chains.

Table 1: Overview of selected requirements of the Batteries Regulation for electric vehicle batteries (EVBs)

Sustainability and safety requirements	Carbon footprint	2025: Carbon footprint declaration (label) 2026: Carbon footprint performance class requirements 2028: Maximum life cycle carbon footprint threshold (levels to be determined)
	Recycled content	Minimum shares of recovered materials in batteries from 2031: - 16 % cobalt - 85 % lead - 6 % lithium

³ While the Batteries Regulation had foreseen August 2025 as the starting date, this was moved to 2027 by Regulation (EU) 2025/1561 in the context of the European Commission's Omnibus package. The date was delayed for several reasons, including to account for geopolitical developments and associated challenges with raw material sourcing, delays in identifying notified bodies for third-party verification, and the need for establishing Commission guidelines on due diligence best practice (which were pushed back to July 2026).

		<ul style="list-style-type: none"> - 6 % nickel <p>From 2036:</p> <ul style="list-style-type: none"> - 26 % cobalt - 85 % lead - 12 % lithium - 15 % nickel
Labelling and information requirements	Labelling and marking	<p>2025: Symbol for separate collection</p> <p>2026: Label for general information</p> <p>2027: QR code giving access to the battery passport</p>
	Information on SoH and expected lifetime	2024: Battery management system to include parameters for determining SoH and expected lifetime
Obligations of economic operators as regards battery due diligence policies	Battery due diligence policies	2027: Economic operators placing batteries on the market need to fulfil due diligence obligations and set up battery due diligence policies
	Economic operator's management system	<p>2025: Adoption and communication of due diligence policy on raw materials and social and environmental risks</p> <p>System of controls and supply chain transparency documenting:</p> <ul style="list-style-type: none"> - raw material - supplier - country of origin - market transactions from extraction to the immediate supplier - quantities of the raw material present in the battery, etc.

	Risk management obligations	2025: Identification of risks of adverse supply chain impacts and implementation of a response strategy
Management of waste batteries	Collection of EVBs	2025: Producers of EVBs need to take back waste EVBs free of charge from end users Producers of EVBs need to provide take-back and collection systems and deliver collected waste EVBs to treatment facilities
	Targets for recycling efficiency and recovery of materials	Permitted facilities need to ensure that waste batteries undergo preparation for reuse, repurposing or recycling Recyclers need to achieve these minimum recycling efficiency targets by 2025: <ul style="list-style-type: none"> - 75 % by average weight of lead acid batteries - 65 % by average weight of lithium-based batteries - 80 % by average weight of nickel-cadmium batteries - 50 % by average weight of other waste batteries By 2030: <ul style="list-style-type: none"> - 80 % by average weight of lead acid batteries - 70 % by average weight of lithium-based batteries Recyclers need to achieve these minimum material recovery targets by 2027: <ul style="list-style-type: none"> - 90 % for cobalt, copper, lead and nickel - 50 % for lithium By 2031: <ul style="list-style-type: none"> - 95 % for cobalt, copper, lead and nickel - 80 % for lithium

Battery passport requirements	Battery passport	2027: Establishment of battery passport containing: <ul style="list-style-type: none"> - Information on battery model - Information specific to the individual battery - Different accessibility layers To be accessible through a QR code compliant with specified standards
	Technical design and operation	2027: Fully interoperable with other EU DPPs Access is free of charge based on access rights

Source: Rizos & Urban (2024a), updated by the authors.

The provisions of the Batteries Regulation will be implemented gradually over the coming years. Given its comprehensive life-cycle approach, the framework will be supported by a series of delegated and implementing acts to be adopted until 2028, which will further specify technical requirements and facilitate its implementation. For instance, an [implementing act](#) detailing the format for data reporting and the assessment methods and conditions for collecting and treating waste batteries was published in the Official Journal in November 2025.

1.1.1. Recycling provisions

The Batteries Regulation sets mandatory EoL requirements for battery recycling; this is intended to increase performance and the recovery of valuable metals. It does so through collection and separation obligations, targets for recycling efficiency and material recovery, and minimum recycled content in new batteries. Recycling provisions build on the collection, take-back and EPR framework described above, aiming to increase return rates and secure sufficient feedstock for recycling.

The Regulation sets key provisions specifying recycling efficiency targets based on battery chemistry, as summarised in Table 1. For lithium-based waste batteries, recyclers must achieve at least 65 % by average weight as of 31 December 2025, with the target increasing to 70 % by 31 December 2030. The Regulation introduces benchmarks for the recovery of specific metals from recycling to support the reuse of recovered metals as secondary raw materials in new products and batteries. By 31 December 2027, recyclers must recover 90 % of cobalt, copper, lead and nickel, as well as 50 % of lithium from the waste batteries they process. These targets will increase further by 31 December 2031, rising to 95 % for cobalt, copper, lead and nickel, and 80 % for lithium.

To ensure consistent implementation across Member States, [Delegated Regulation \(EU\) 2025/606](#) provides the calculation rules and documentation requirements for reporting recycling efficiency and material recovery rates. It clarifies which input streams and output fractions should be included in the calculations and how results should be recorded.

In addition, the Regulation stimulates demand for recycled materials by requiring mandatory minimum recycled content in new batteries placed on the market, thereby linking recycling to manufacturing. From 18 August 2031, batteries must contain in active materials at least 16 % cobalt, 6 % lithium, 6 % nickel and 85 % lead from recycled sources. These thresholds increase to 26 % cobalt, 12 % lithium and 15 % nickel, while lead remains 85 % from 18 August 2036.

1.1.2. Second-life provisions

One of the key innovations introduced by the Batteries Regulation is a set of rules aimed at promoting the reuse, repurposing, and remanufacturing of batteries. To support second-life solutions, the Regulation seeks to address key technological and supply chain bottlenecks that occur when battery packs move from the end of their first life to their second-life applications.

Firstly, the Regulation seeks to strengthen second-life operators' access to the battery's history, helping them overcome the technical complexities faced during the repurposing, preparation for reuse and remanufacturing stages. It mandates non-discriminatory access to the BMS for operators purchasing end-of-first-life battery packs. By accessing and decoding this information, operators can perform a more efficient and accurate diagnosis of the overall state of batteries at the end of their first life.

Additionally, the Regulation requires the original BMS to include a 'reset' function to facilitate the installation of new software for second-life applications. This software must be customised to both the technical specifications of the used modules and the requirements of the new application. Second-life batteries must have their own digital battery passport to ensure traceability from their first use through to their second. Specifically, when a used battery pack enters its second life, the passport must be updated to reflect its new status—whether it is repurposed, reused, or remanufactured.

The Regulation also specifies how second-life operators can prove that a battery that has undergone repurposing or processing for its reuse is no longer classified as waste. This involves providing the competent authorities with evidence of the ownership transfer from the first user, proof of precautionary measures taken during transport, and the results of a SoH evaluation of used batteries conducted within the EU. The European Commission is tasked with defining, through a forthcoming implementing act, precise

operational thresholds that used battery packs must meet to no longer be classified as waste. These provisions are particularly significant because transportation rules are closely tied to the legal classification of battery waste (Moreschi & Rizos, 2026).

Finally, to ensure a level playing field in the battery market, the Regulation treats second-life battery manufacturers the same as OEMs, requiring them to comply with due diligence obligations and EU standards for safety, quality, and environmental performance. Similarly, anyone who places a repurposed battery on the market is considered a producer and assumes all associated responsibilities, including extended producer responsibility (EPR) obligations related to the battery passport. Regarding EPR rules, the Batteries Regulation allows both original and second-life manufacturers to share financial responsibilities, thereby preventing cost duplication across the battery's life cycle. This can be achieved through voluntary agreements in which parties agree on an appropriate cost-sharing mechanism.

Regarding EPR rules, the Batteries Regulation allows both original and second-life manufacturers to share financial responsibilities, preventing duplicate costs throughout the battery's life cycle. This can be done through voluntary agreements where the parties agree on an appropriate cost-sharing mechanism. Article 12 of the Batteries Regulation specifically addresses the safety of energy storage systems, a key second-life application for EV batteries. In particular, it sets out safety parameters and documentation requirements to confirm successful testing of potential hazards, applying equally to original, repurposed and remanufactured battery packs.

1.2. STANDARDS FOR RECYCLING AND REUSE OF BATTERY PACKS IN THE EU

This section reviews the existing standards for recycling and reuse of battery packs in the EU. It also identifies upcoming standards to be included or developed by European standardisation organisations at the request of the European Commission under the Batteries Regulation.

Overview of the EU standardisation system

In the EU, standards are developed and adopted by three standardisation organisations: the European Committee for Standardisation (CEN), the European Committee for Electrotechnical Standardisation (CENELEC) and the European Telecommunications Standards Institute (ETSI). Standards relevant to batteries are specifically managed by CEN and CENELEC. Once adopted at the EU level, the standards go through a five-stage

process⁴ to be implemented at the Member State level. While economic operators comply with standards on a voluntary basis, if a standard is published in a Union harmonisation legislation in the Official Journal of the European Union (OJEU), it becomes a harmonised standard. Conformity with an EU harmonised standard is considered conformity with the respective EU regulation, which makes a reference to it. An example is the Batteries Regulation, which makes reference to the ISO 14040:2006 standard on life cycle assessment for the definition of concepts like ‘life cycle’ and ‘reference flow’. Battery economic operators must follow the definition of these concepts when calculating the carbon footprint of batteries, as stipulated in Article 7 of the Regulation.

Inventory of existing standards for recycling and reuse of battery packs

a. Multiple-stage standards

ISO 14040 and ISO 14044 are cross-cutting standards that apply to all stages of the battery life cycle, from the extraction of raw material to EoL disposal or recycling. Together, they provide a comprehensive framework for conducting Life Cycle Assessment (LCA), which is a key tool for evaluating the environmental impacts of LIBs throughout their entire life cycle.

ISO 14040:2006, along with its 2020 amendment, establishes the principles and framework for LCA to ensure studies are consistent, transparent and comparable. The standard defines four key stages of LCA: (i) establishing the goal and scope, (ii) performing a life cycle inventory (LCI) analysis, (iii) conducting a life cycle impact assessment (LCIA), and (iv) interpreting the results. When applied to batteries, this framework enables a structured approach for environmental assessments that considers aspects such as the mining of lithium, energy use during manufacturing, emissions during use, and environmental impacts of disposal or recycling.

ISO 14044:2006, together with its 2017 and 2020 amendments, complements ISO 14040 by providing detailed requirements and methodological guidance for applying the LCA framework defined in ISO 14040. It addresses key aspects such as data quality, system boundaries, allocation methods, and impact categories, which are critical factors in the assessment of complex supply chains like those of LIBs. Given batteries’ energy-intensive production processes and the global sourcing of materials (such as lithium, cobalt, and nickel), ISO 14044 ensures that LCA studies are methodologically robust and comparable.

⁴ The five steps include: (i) *Ratification*: the Technical Board of CEN/CENELEC notes the approval of an EN standard; (ii) *Availability*: the definitive text in the official language versions of an approved CEN/CENELEC publication is distributed by the Central Secretariat of CEN/CENELEC; (iii) *Announcement*: the existence of an EN standard is announced at national level; (iv) *Publication*: an EN standard is implemented at national level by publication of an identical national standard or by endorsement; and (v) *Withdrawal*: national standards conflicting with an EN standard have to be withdrawn.

Both standards play a crucial role within the EU regulatory framework. As discussed earlier, the EU Batteries Regulation refers to ISO 14040 to define key concepts like 'life cycle' and 'reference flow', which are used, for example, in calculating the carbon footprint of batteries as outlined in Article 7 of the Regulation.

b. Standards for the recycling stage

Regarding EoL management of batteries used for portable applications, the IEC 63218:2021 standard (and EN IEC 63218:2021 as its EU version) offer guidance and recommendations for the collection, recycling and environmental impact assessment of secondary lithium, nickel-cadmium and nickel-metal hydride cells and batteries. The standards promote environmental sustainability by providing (i) fundamental considerations and information on the environmental aspects and impacts of secondary cells and batteries; (ii) guidance on their collection and recycling; (iii) guidance for environmental impact assessments across all stages of the life cycle during the design and manufacturing stage; and (iv) relevant information regarding regulations on secondary cells and batteries for interested parties.

IEC 62902:2025 and EN IEC 62902 specify marking symbols for the identification of secondary cells and batteries prevailing in the market, including lead acid, nickel-cadmium, nickel metal and LIBs. The standard includes the optional use of the recycling symbol ISO 7000-1135, to indicate that the marked item or its material is part of a recovery or recycling process.

IEC 60086-6 and EN IEC 60086-6 provide guidance on environmental aspects of portable primary cells and batteries. They include requirements for marking symbols used to convey messages for collection and recycling on the battery itself or its packaging. In addition, the standards propose techniques to assess the environmental impact of battery products throughout their life cycle, including the recycling phase.

IEC 63218 and EN IEC 63218 offer guidance to improve the environmental sustainability of secondary batteries. The standards contain specific measures to improve the efficiency and safety of the collection and recycling of secondary cells and batteries. They require batteries to be marked using the recycling symbol to improve sorting and recycling efficiency. They also provide a calculation method to evaluate the efficiency of battery recycling.

c. Standards for the reuse and repurposing stage

Several international standards address the reuse and repurposing of batteries, notably the following three IEC standards. As of the drafting date of this report, no official EU equivalents of these standards have been published.

IEC 63338:2024 provides general guidance on the reuse and repurposing of secondary lithium-ion and nickel-metal hydride cells and batteries. It addresses the reuse and repurposing of secondary cells and batteries, including environmental considerations, safety risks, suitability for reuse or repurposing based on battery lifetime traceability data, and manufacturer warnings regarding the product's appropriateness for reuse or repurposing. For reuse or repurposed application manufacturers, particularly, the standard recommends the removal of the original cell or battery label and markings, and affixation of a label or marking specifying the reuse or repurposing of batteries in the products.

IEC 63330-1 provides general requirements for the repurposing of secondary batteries. It particularly specifies the procedure for evaluating the performance and safety of used secondary batteries and battery systems for repurposing. It also offers general requirements for the application of repurposed batteries. While IEC 63338:2024 (above) provides relatively high-level requirements (environmental aspects, safety risk awareness, traceability, general recommendations) for the reuse/repurposing of cells & batteries, IEC 63330-1 offers a detailed evaluation procedure for performance and safety, and application requirements of the repurposed product.

IEC 62933 (Part 4-4) provides environmental requirements for battery-based energy storage systems (BESS) with reused batteries, e.g. from other electric energy storage installations or EVs. The standard specifies requirements for identifying and preventing environmental issues throughout the life cycle of reused batteries in a BESS, from design to disassembly.

An overview of available standards related to the recycling and reuse of batteries is provided in Table 2.

Table 2: Overview of standards for the recycling and reuse of battery packs in the EU

Standard	LCA stage	Objective
ISO 14040:2006 and its 2020 amendment	Multiple-stage	Principles and framework for LCA, including assessment of environmental impacts of the disposal or recycling of batteries
ISO 14044:2006 and its 2017 & 2020 amendments	Multiple-stage	Complementing ISO 14040 by providing detailed requirements and methodological guidance for applying the LCA framework defined in ISO 14040
IEC 63218:2021 and EN IEC 63218:2021	Recycling	Guidance and recommendations for the collection, recycling and environmental impact assessment of

		secondary lithium, nickel-cadmium and nickel-metal hydride cells and batteries
IEC 62902:2025 and EN IEC 62902	Recycling	Specification of marking symbols for identifying lead acid, nickel-cadmium, nickel metal and LIBs
IEC 60086-6 and EN IEC 60086-6	Recycling	Requirements for marking symbols to convey messages for the collection and recycling of batteries, and techniques to assess the environmental impact of the recycling phase of battery products
IEC 63218 and EN IEC 63218	Recycling	Measures to improve the efficiency and safety of the collection and recycling of secondary cells and batteries
IEC 63338:2024	Reuse and repurposing	Guidance on the reuse and repurposing of secondary lithium-ion and nickel-metal hydride cells and batteries
IEC 63330-1	Reuse and repurposing	General requirements for the repurposing of secondary batteries
IEC 62933 (Part 4-4)	Reuse and repurposing	Environmental requirements for battery-based energy storage systems with reused batteries

Source: Authors' own compilation.

Standards foreseen under the Batteries Regulation

The Batteries Regulation seeks to ensure the smooth functioning of the internal market while reducing the environmental and health risks related to batteries. To be placed on the EU market, batteries must meet the sustainability, safety, labelling and information requirements set out in Articles 6-13 of the Regulation. The Regulation uses standards as one of the key measures to achieve the above objectives.

As discussed above, the Regulation makes a reference to ISO 14040:2006 or an equivalent standard when defining the concepts of 'life cycle' and 'reference flow' in calculating the carbon footprint of batteries under Article 7.

In addition, it specifically requires the Commission to encourage the development of standards that facilitate the maintenance, repair and repurposing of SLI batteries and EVBs (Recital (42)). Furthermore, the Regulation specifies that references to other harmonised standards, including those on battery repurposing, will be published in the Official Journal of the European Union (in accordance with Regulation EU 1025/2012) (Recital (47) and Article 15). If no standard exists in a specific field, the Commission can ask European standardisation organisations to draft one (Article 16). If no standards are available when a given requirement in the Regulation is applied, or the standard

developed by the European standardisation organisations is unsatisfactory, the Commission can adopt its own common specification through an implementing act (Recital (47), Article 16 (1)).

The Regulation also recognises that the Commission and Member States have not been effectively involved in some international standardisation activities. It calls for stronger participation in developing global standards to strengthen Europe's influence in international standardisation and boost the competitiveness of its industries (Recital 48).

Discussion

Most battery standards focus on the manufacturing stage, specifically addressing battery performance and safety. Standards for other stages, including the recycling, reuse and repurposing, are much scarcer (Manaia et al., 2025; Vullum-Bruer et al., 2024). As discussed above, while two IEC international standards address the reuse of secondary batteries to some extent, the EU has not yet developed and adopted equivalent ones at the EU level. Thus, EU standards for repurposing batteries of specific uses, e.g. EVBs, are currently lacking (Manaia et al., 2025).

The Batteries Regulation can help address part of the issue mentioned above. It foresees the development of standards for the performance, durability, repurposing and safety of batteries. However, developing and adopting these standards across Member States will take time, which may delay full harmonisation and widespread adoption of battery recycling/reuse across the bloc (Vullum-Bruer et al., 2024).

Finally, it is also important to note the relation between standards for reuse and recycling with those in other phases of the battery life cycle. For example, standards for the design and testing of batteries can impact their repurposing possibility (Vullum-Bruer et al., 2024; Manaia et al., 2025). When developing new standards under the Batteries Regulation, the EU standardisation bodies and the Commission should consider these interconnections across the different stages of the battery life cycle.

Our interviews with industrial stakeholders in the framework of the BATRAW project bring further insights about standards for battery recycling, reuse, and repurposing in the EU.

Stakeholders pointed to the lack of standardised information on the prior use of battery packs as one of the main barriers to enabling second-life applications. Currently, neither manufacturers nor vehicle operators systematically provide sufficient data about a battery's performance history during its first life. This absence of information hinders the assessment of batteries for potential reuse, repurposing, or recycling. In this context, the implementation of a battery passport could provide advantages for businesses working

with second-life batteries. By providing standardised information on a battery's chemistry, composition, and usage history, such a passport would facilitate better decision-making across the entire value chain – from testing and sorting to repurposing and material recovery.

Another critical issue is the absence of harmonised European standards defining the parameters and methods for evaluating a battery's SoH and other performance indicators such as voltage, charge level, number of cycles, and degradation patterns. These parameters are typically stored in the BMS; generally, manufacturers do not make this data widely accessible or available in standardised formats. As a result, assessing whether a used battery is suitable for reuse or repurposing remains complex and inconsistent across the sector.

Stakeholders also raised concerns about the lack of standardisation in testing procedures and battery formats, which complicates the processing and integration of batteries into second-life applications. Standards on the state of safety of used battery modules are particularly crucial for ensuring that second-life uses meet safety and performance requirements.

Finally, for recyclers, the battery passport could also help address the lack of standardisation and labelling from manufacturers by providing reliable data on the internal chemistry and material composition of batteries. This information would improve sorting processes and enable more efficient recovery of valuable metals. Nevertheless, achieving the right balance between requiring sufficient information and avoiding overly exhaustive data obligations will be essential to maintaining the feasibility of second-life and recycling operations.

1.3. GLOBAL POLICY DEVELOPMENTS

Global EV uptake continues to increase, accounting for around 20 % of new car sales in 2024 and projected to reach higher shares in the coming years (IEA, 2025b). As more EVs retire, the EoL battery stock is expanding, prompting governments to introduce measures to ensure their sustainable management. These measures often seek to promote circularity, reduce reliance on primary critical minerals and improve oversight on the battery value chain. In this context, several countries are adopting comprehensive frameworks that address battery recycling, second-life applications, and supply chain traceability. Some prominent examples of such regulatory initiatives are presented below.

As the world's largest EV market, China accounted for almost two-thirds of global sales in 2024, while EVs made up around half of its domestic vehicle sales, with battery electric vehicles at 28 % (IEA, 2025b; Hertzke et al., 2025). Accordingly, a large share of global

battery recycling capacity is located in China. Battery recycling has recently been elevated to a national priority, with policymakers calling for stronger full-life cycle traceability, faster regulatory development and accelerated standards work, including on green design and carbon footprint accounting. In this context, China has further upgraded and consolidated its regulatory framework.

On EPR and traceability, the current framework is now centred on the Interim Measures for the Management of Recycling and Comprehensive Utilisation of Used Power Batteries from New Energy Vehicles⁵ (NEV), which will take effect in April 2026. The Measures consolidate and replace the earlier 2018 recycling measures, the 2018 traceability provisions, the 2019 service-network guide and the 2021 cascade-utilisation measures. They retain extended producer responsibility, but allocate obligations more explicitly across battery manufacturers, NEV manufacturers, battery-swapping operators, maintenance enterprises and end-of-life vehicle dismantlers. Traceability is also upgraded through a national information platform combined with a digital identity-card system for each battery, including labelling and reporting obligations across the full life cycle.

In parallel, the Industry Standard Conditions for Comprehensive Utilisation of Waste and Used Power Batteries of New Energy Vehicles (2024) updated the whitelist mechanism⁶, tightening market-entry requirements and setting minimum recovery benchmarks – 90 % for lithium, 98 % for nickel, cobalt, and manganese. Currently, China does not require a battery passport; the industry association, CIAPS, released a Battery Passport Guide, a voluntary group standard effective from June 2025. This guideline provides a disclosure framework including battery identification, carbon footprint, and due diligence across multiple battery categories, with the clear goal of facilitating compliance in overseas markets.

With a well-established global manufacturing base for battery cells and materials, South Korea's policy framework focuses on reuse and recycling schemes, as its EV market is projected to reach 20 % of total sales by the end of 2025 (ITA, 2025). Since 2015, the government has backed pilot projects in second-life use, reusing retired EVBs for stationary storage and backup systems (Kostenko & Zaporozhets, 2024). In 2024, the Enforcement Rule of Waste Management Act⁷ was revised to extend the permitted

⁵ In China, NEVs include battery electric vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles and fuel cell electric vehicles.

⁶ China's Ministry of Industry and Information Technology (MIIT) has maintained a 'whitelist' of compliant battery recycling enterprises since 2018 with the latest batch, published in November 2023, listing 156 companies (Tian et al., 2025).

⁷ Originally enacted in 1986, Waste Management Act aims to conserve the environment and improve quality of life by reducing waste generation and demands environmentally sound treatment.

storage period of EV waste batteries held for recycling from 30 to 180 days and clarified technical requirements for repurposing, including state of charge (SoC) and SoH measurement. These revisions give recyclers greater flexibility and aim to lower operational constraints. At the same time, the Ministry of Environment has allowed eligible waste EVBs to be designated as 'circular resources', thereby exempting them from waste management rules for reuse and remanufacture. Requirements on battery traceability are beginning to emerge – since February 2025, OEMs are required to disclose information on key data (e.g. capacity, voltage, and composition), alongside battery certification that includes a unique identifier in the BMS (OBP, 2025; ITA, 2025). In preparation, major manufacturers such as Hyundai, Kia, and Mercedes-Benz began reporting supplier information in late 2024.

In Japan, the Ministry of Economy, Trade and Industry's (METI) roadmap points to rising EV and battery deployment, setting a goal of 100 % electrified new passenger car sales by 2035 and around 150 GWh of domestic battery manufacturing capacity by 2030. However, while the current policy mix covers EoL vehicles, EVBs do not yet have specific regulatory targets (Kishita et al., 2024). In practice, broader EoL and recycling provisions provide the baseline, including battery collection and recovery. Within this framework, repurposing and recovery of EV batteries are largely driven by industry-led initiatives, as illustrated by 4R Energy (Nissan-Sumitomo joint company), which sorts and refurbishes used EVBs for second-life use and eventual recycling (Kishita et al., 2024).

In 2022, the METI's Battery Industry Strategy set a goal to expand second-life applications and establish domestic recycling capacity by 2030, alongside assessments on carbon footprint metrics (METI, 2022). At the same time, two funding instruments support circularity across the battery value chain. Through the METI-JOGMEC critical minerals subsidy programme, projects help secure key materials, such as in Mitsubishi Materials' pilot to recover and refine nickel, cobalt and lithium from LIB black mass. At the same time, the Green Innovation Fund advances recycling technologies, including closed-loop and low carbon dioxide (CO₂) recycling, with the target to verify and update information on facilities around 70 % for lithium and 95 % for nickel and cobalt recovery at battery-grade quality and competitive cost.

The US has a more decentralised policy landscape, combining federal rules with state-level mandates. At the federal level, the Inflation Reduction Act's New Clean Vehicle Credit – which tied eligibility towards domestic assembly and battery sourcing rules – is no longer available for vehicles acquired after September 2025. The main continuing federal instrument for battery circularity is the Department of Energy's programme on electric-drive vehicle battery recycling and second-life applications, established under the Bipartisan Infrastructure Law. More recent federal action has focused on developing

battery collection best practices and voluntary battery labelling guidelines, both due by September 2026. At the state level, New Jersey is the first state to adopt an EPR framework for EV and hybrid batteries, shifting obligations to battery producers for collection, labelling, reporting, and disposal requirements. These obligations will be gradually implemented from 2025 to 2027. The state of Washington is next to follow the ‘battery stewardship’ framework, including portable batteries and medium-format batteries, but not yet covering large traction batteries.

Other countries are moving in the same direction, with varying approaches and levels of implementation. India’s Battery Waste Management Rules (2022), as amended in 2025, provide a comprehensive EPR framework with phased collection and recycling and refurbishment targets for waste batteries, including EVBs, while Australia’s National Waste Policy Action Plan (2024) sets broader circularity objectives and aims to increase resource recovery across waste streams. As technology and markets develop, policy is likely to continue supporting circularity, life-cycle traceability, and battery repurposing and recycling across the value chain.

2. BATTERY RECYCLING

As EV uptake and battery manufacturing scale up, larger volumes of LIBs are expected to enter EU waste streams from manufacturing scrap and end-of-life batteries. This makes recycling increasingly important as a domestic source of secondary raw materials (notably lithium, cobalt, and nickel) and as a way to reduce exposure to supply risks in a battery value chain that remains highly concentrated, with bottlenecks across multiple stages.

At the same time, recycling supports environmental objectives by reducing reliance on primary raw material extraction and by enabling higher circularity in battery materials over time. The Batteries Regulation (see Section 1.1) provides the life-cycle framework for battery sustainability and circularity requirements, including provisions that shape EoL management and quality of recycled outputs.

Beyond the Batteries Regulation, broader EU industrial policy reinforces recycling's strategic role. The Critical Raw Materials Act sets 2030 benchmarks for domestic capacities, including that at least 25 % of the EU's annual consumption should come from recycling, signalling expectations for a stronger European supply of secondary raw materials. In addition, as of March 2025, the Commission updated the European List of Waste and classified black mass (a metal-rich intermediate used in battery recycling) as hazardous waste, tightening shipment controls and restricting exports to non-OECD countries.

This section first reviews the key technologies for battery recycling (2.1), then outlines the current European landscape (2.2), and lastly discusses the main enabling conditions, barriers and stakeholder perspectives shaping deployment and scale-up (2.3).

2.1. KEY TECHNOLOGIES

Once EVBs reach the end of their operational life, they enter the downstream phase of the battery life cycle – namely, collection, transportation, disassembly, and material recovery. Depending on the battery's SoH, second-life applications such as repurposing for stationary energy storage may be possible. However, all EoL batteries ultimately require recycling.

Recycling EoL EVBs involves a multi-stage process in which each step uses specialised technologies to safely handle components and recover valuable materials. While recycling is commonly classified into pyrometallurgical and hydrometallurgical routes, often preceded by pre-treatment steps, these methods are rarely applied in isolation. In practice, most industrial processes combine pre-treatment with thermal and/or chemical refining steps tailored to the battery's chemistry and facility design (Peixoto et al., 2025; Toro et al., 2023).

Before processing can begin, EoL batteries are collected and transported to specialised facilities under strict regulatory controls, given their hazardous nature and substantial weight. They are then stored temporarily before proceeding to pre-treatment and mechanical processing (Cattani et al., 2025). Pre-treatment begins with discharging the battery to a safe voltage, followed by disassembly down to the module or even cell level, which is usually carried out manually due to the wide variation in battery pack designs.

Following disassembly, mechanical processing is used to separate battery components based on their physical characteristics, such as size, density, or magnetic properties, without altering their chemical structure (Racu & Poliscanova, 2024a). This step prepares the materials for later metallurgical treatments. These physical separation methods, e.g. shredding, sieving, and magnetic or eddy current separation, recover materials like aluminium, copper, steel, and black mass. Depending on the battery's chemistry, black mass contains high-value metals such as lithium, cobalt, nickel, and manganese, which are primarily found in cathode active materials (Peixoto et al., 2025; Toro et al., 2023). These elements are essential for producing new batteries and are considered critical to Europe's clean energy transition. In Europe, leading companies such as Umicore and Fortum employ a mix of these approaches, often combining different pre-treatment and refining steps in integrated or distributed facility networks (Racu & Poliscanova, 2024a).

To recover battery metals and compounds, recyclers employ either pyrometallurgical, hydrometallurgical, or hybrid processes.

Pyrometallurgy uses high temperatures to smelt battery cells, modules or black mass and extracts metals such as copper, nickel, and cobalt into an alloy. Depending on the route, organic battery components – such as electrolytes, binders and plastics – may either remain in the feed and contribute to the smelting process itself, including as an energy source (Perocillo et al., 2025) or be removed in a prior thermal treatment step (Toro et al., 2023). Pyrometallurgical routes allow for high throughput and, in some cases, can handle intact modules, bypassing pre-treatment and mechanical processes (Peixoto et al., 2025; Perocillo et al., 2025). However, the pyrometallurgical treatment is generally energy-intensive due to its high-temperature operation, and can generate significant direct CO₂ emissions (Peixoto et al., 2025; Toro et al., 2023). In many routes, lithium often ends up in slag or flue dust – therefore, its recovery requires additional downstream treatment (Egle et al., 2024; Peixoto et al., 2025). Manganese usually remains in slag, while such slag is not directly recovered as a battery material, it is commonly used as a fill material in the construction sector.

Hydrometallurgy recovers metals using chemical leaching, solvent extraction, and precipitation. Depending on the route, it is commonly applied either to black mass

obtained after pre-treatment and mechanical processing or to intermediate outputs from earlier pyrometallurgical treatment (Egle et al., 2024).

In integrated pyro-hydrometallurgical routes, hydrometallurgy serves as the downstream refining stage following the smelting step described above. As the initial pyrometallurgical step can process batteries with different chemistries and formats, this configuration can be applied to mixed battery inputs (Latini et al., 2022). Recovery rates for copper, nickel, and cobalt can reach up to 95 % in such routes (Peixoto et al., 2026). In Europe, Umicore's pyro-hydrometallurgical process has been adapted and optimised for newer EVBs and production scrap, with a lower carbon footprint than its earlier pyrometallurgical route, as well as a lithium recovery step producing lithium carbonate for further refining to battery-grade lithium hydroxide (Van Hoof et al., 2023).

Under hydrometallurgical routes, following pre-treatment and mechanical processing, the black mass is treated with sulfuric acid to dissolve critical metals such as lithium, cobalt, nickel, and manganese. These are then separated and refined into battery-grade materials such as lithium carbonate or nickel sulfate (Peixoto et al., 2025). Hydrometallurgy can achieve recovery efficiencies exceeding 90 % for lithium and nearly complete recovery for cobalt and manganese. At the same time, efficient recovery depends on the quality of the black mass, which is produced during pre-treatment, as it can contain impurities such as binders and residual copper or aluminium alongside valuable metals – requiring further treatment. In addition, incomplete separation of active materials during mechanical processing can reduce black mass output and lead to recoverable material ending up in other streams (Latini et al., 2022). Therefore, these processes require specialised infrastructure as well as strict environmental controls due to the handling of corrosive reagents and the generation of hazardous liquid waste, making large-scale deployment more complex (Racu & Poliscanova, 2024a).

In Europe, large-scale battery recycling initially relied on pre-treatment and pyrometallurgical treatment followed by hydrometallurgical routes. At the same time, hydrometallurgical recovery from black mass is emerging due to its potential for higher recovery efficiency, particularly for lithium, while its wider use still depends on further optimisation for effective material recovery (Bobba et al., 2025; Racu & Poliscanova, 2024a).

Comparative assessments of the environmental footprint of recycling routes remain mixed across the literature, partly because results are sensitive to system boundaries, methodological designs and the extent to which current industrial scale process configurations are reflected in the analysis. For instance, Peixoto et al. (2026) find that hydrometallurgy has lower environmental impact compared to pyrometallurgical recycling, while also showing that this result depends on how graphite is treated. On the

other hand, according to the industrial stakeholders consulted for this study, Umicore's updated pyro-hydrometallurgical route has a lower overall CF at industrial scale, particularly where the comparison includes both on-site emissions and energy use, as well as the different treatment of graphite, electrolyte and other side streams (Van Hoof et al., 2023).

Beyond established industrial methods, several innovative recycling approaches are under development to enhance efficiency and sustainability. One such example is direct recycling, which seeks to recover cathode materials – such as NMC (nickel manganese cobalt) – without fully breaking them down, preserving their structure and electrochemical properties (Toro et al., 2023; Racu & Poliscanova, 2024a). This reduces processing steps and material losses, potentially enabling closed-loop battery recycling for certain waste fractions with minimal chemical input and waste generation. Other emerging technologies include the use of deep eutectic solvents and ionic liquids as more selective alternatives to sulfuric acid in hydrometallurgical leaching, enhancing recovery efficiency and the purity of the final (Toro et al., 2023). Furthermore, automation through robotics and artificial intelligence (AI)-based systems can improve the speed, precision, and safety of battery sorting and disassembly, which are still largely carried out manually. These technologies are currently being developed and tested in laboratories and pilots across Europe.

BATRAW is one such project advancing semi-automated dismantling using modular robotics and smart diagnostic tools to efficiently identify, discharge, and disassemble EVBs of diverse designs. This feeds into optimised pre-treatment steps that deliver high-purity black mass and enable more flexible, lower energy-intensity hydrometallurgical processing.

2.2. STATE OF PLAY

EU recycling feedstock is expected to be led by manufacturing scrap over the next few years, shifting after 2030 toward EoL EVBs as the main source, with second-life batteries contributing more significantly from 2035 (Petersen et al., 2024). Battery waste volumes could reach around 350 000 tonnes per year (t/year) in 2030. Against this backdrop, available recycling capacity in the EU exceeded 300 000 t/year in 2024 and already exceeds 436 000 t/year as of Q1 2026⁸, indicating rapid scale-up alongside the need for sufficient domestic downstream capacity.

Technological readiness varies across processing stages. Mechanical pre-treatment is widely established as the initial processing step, and pyro-hydrometallurgical recycling is

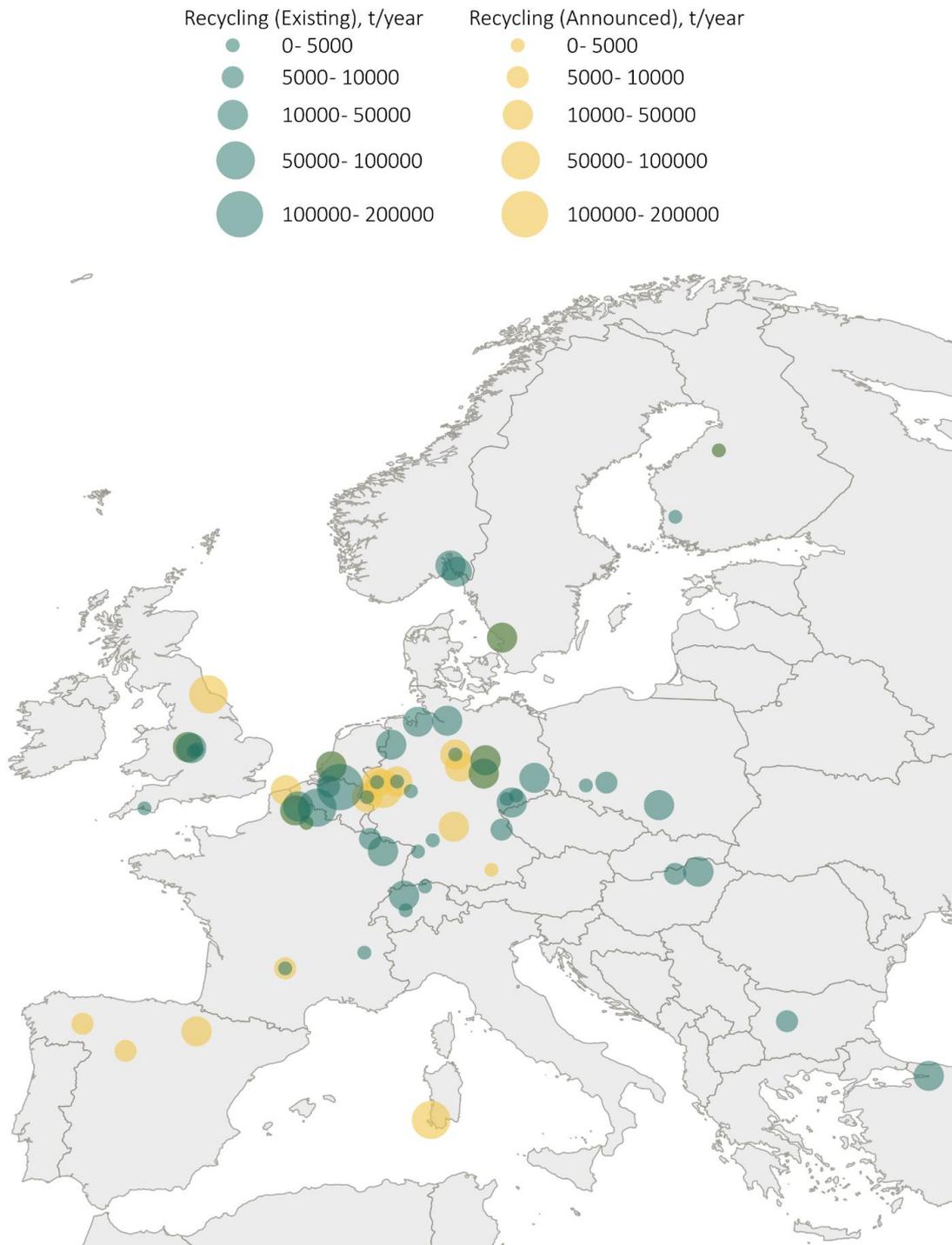
⁸ Value obtained from authors' research. Considers EU-27 Member States only. At a European level, this value exceeds 528 000 t/year in Q1 2026.

commercially used in Europe (Cattani et al., 2025; Bobba et al., 2025). Hydrometallurgical recycling following pre-treatment is moving toward industrial deployment in Europe due to the potential for higher-quality material recovery, particularly for lithium. However, adoption is uneven and constrained by the need for complex infrastructure and large specialised plants. At the same time, domestic recycling capacity is concentrated in a small number of Member States, particularly Belgium, Germany, Finland, France, and Sweden (Peixoto et al., 2025).

A prominent example is Fortum's cross-site recycling operations, linking pre-treatment with hydrometallurgical metal recovery. Its recycling hub in Kircharadt (Germany) can treat over 3 000 t/year of batteries and production scrap, and it is connected to the facility in Harjavalta (Finland) – one of Europe's first commercial-scale hydrometallurgical battery recycling sites. Similarly, Umicore's Hoboken facility in Belgium is among Europe's earliest large-scale LIB recycling, using high-temperature smelting followed by hydrometallurgical leaching to recover metals including cobalt, nickel, copper and lithium, with a capacity to process around 7 000 t/year (Toro et al., 2023).

Looking ahead, announced projects suggest Europe could reach around 830 000 t/year of pre-treatment and 880 000 t/year of material-recovery capacity by 2030, although not all announced projects may be delivered or fully utilised (Racu & Poliscanova, 2024a). Within this pipeline, an emerging example is Orano's planned hydrometallurgical recycling project in the Dunkirk area in France. Project plans indicate a pre-treatment unit designed to process approximately 15 000 t/year of battery modules, combined with a hydrometallurgical plant designed to recycle around 20 000 t/year of black mass and recover nickel, manganese, cobalt and lithium. Figure 1 provides an overview of existing and announced EVB recycling plants in Europe along with their corresponding capacities. Refer to Annex B for a full dataset corresponding to these.

Figure 1: Map of existing and announced battery recycling capacity in Europe.



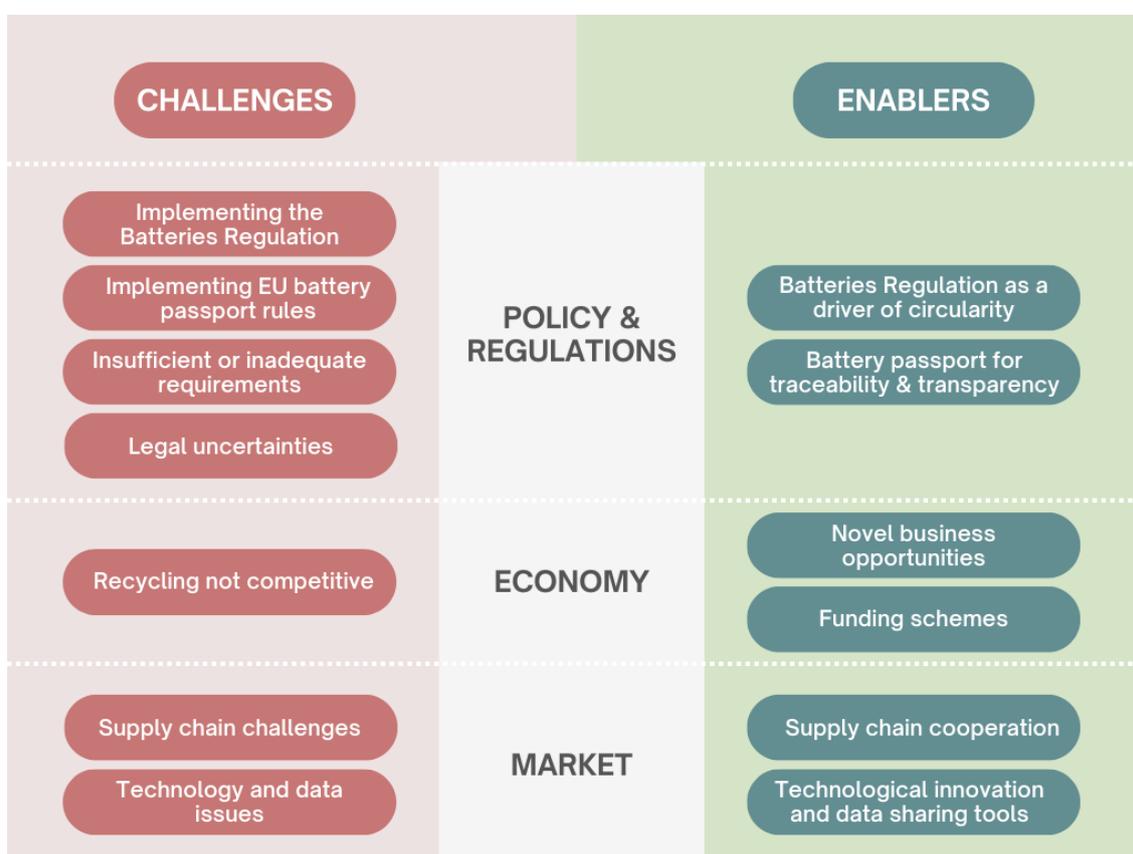
Source: author’s elaboration based on an initial data compilation from [Battery-News \(2025\)](#) and [Fraunhofer \(2024\)](#), complemented by the authors’ desk research to verify and update information on facilities.

Notes: (1) Recycling facilities lacking capacity specifications have been excluded. (2) A map combining both battery recycling and repurposing facilities is presented in Annex B alongside tables containing the underlying data points.

2.3. OVERARCHING CHALLENGES AND ENABLING CONDITIONS FOR EVB RECYCLING

In the changing landscape of transport electrification and parallel efforts to establish a circular system for battery use, a range of challenges remain for scaling up the recycling of EVBs. At the same time, a number of enabling conditions could be leveraged by policymakers and industry actors to support the transition to EVB recycling pathways. Based on our research, which involved interviews with 29 companies across the full value chain segments surrounding battery circularity (see Annex A), conducted over a 3-year period⁹, we identified several key challenges. These are grouped into three major domains: policy, economy, and market, as illustrated in Figure 2. Within each of these domains, we also identified a set of enabling factors that can boost the adoption of recycling processes for EVBs in the EU.

Figure 2: Overarching challenges and enabling conditions for EVB recycling.



Source: Authors' own elaboration.

⁹ From August 2022 to July 2025.

2.3.1. Policy and regulations

Policy challenges

In the policy domain, we identified four major areas where difficulties occur for industry stakeholders: (1) challenges with implementing the requirements of the Batteries Regulation, (2) difficulties with implementing battery passport-related obligations, (3) insufficient or inadequate policy requirements, and (4) legal uncertainties.

Implementing the Batteries Regulation

In anticipation of the introduction of policy requirements under the Batteries Regulation, industry actors across the EVB value chain have reported difficulties in implementing them. A particularly contentious provision of the Batteries Regulation relates to recycled content. Companies from both ends of the value chain (manufacturing and recycling) have indicated that meeting the mandated recycled content requirements for producing new batteries will be challenging in practice.

One issue stems from the current lack of an exact methodology for calculating recycled content shares, rendering it challenging to reach the mandated recycled content targets. More importantly, there is a lack of clarity on the allocation of recycled content in the output fractions, as they will inevitably be blended with primary materials at some point. Criticism also emerged on the practical merits of recycled content targets, as they may discourage other (perhaps environmentally more beneficial) circularity approaches such as battery lifetime extension.

Additional concerns relate to the potential lack of feedstock (Helander & Ljunggren, 2023), given that EVBs that are currently in use should only reach their EoL after several years of operation. As a result, the timelines of the policy requirements and of real feedstock flows may not align. An important concern in this area is black mass leakage, as non-EU recyclers and refiners currently offer higher prices for black mass than EU ones, given differences in subsidy schemes and standardisation. Finally, some interviewees also expressed concerns over the technological readiness and industrial capacity for large-scale EVB recycling and material recovery in Europe.

Implementing battery passport-related obligations

One novelty of the EU Batteries Regulation is the obligation for a DPP for batteries, referred to simply as the battery passport. Industry actors have voiced concerns over implementing the related policy requirements. Both the collection and the verification of the relevant battery performance and sustainability information present challenges for industry actors. Many companies have expressed worries about access rights to the data

stored in the battery passport, and particularly about ensuring the confidentiality of sensitive data – although continuous developments in policies and standardisation that provide clarifications on access rights may alleviate these concerns in the long run.

These concerns may complicate the large-scale adoption of the battery passport requirements, as supply chain partners may be reluctant to share the relevant data. Another critical issue is the lack of interoperability between different IT systems and data formats, which is exacerbated by the current absence of harmonised interoperability standards. There were also concerns about who would be responsible for meeting the battery passport requirements in practice, as there are cases where the rules may not be as clear-cut, and the economic operator placing the battery on the EU market cannot be as easily identified (see more details in Rizos & Urban, 2024a).

Insufficient or inadequate requirements

Insufficient or unclear policy requirements can also create challenges for recycling EVBs, as revealed by our interviews. Cross-border transportation of waste batteries is one example where such challenges emerge, as shown during the BATRAW project. The current policy framework in this area creates a complicated environment for industry stakeholders, who need to adhere to both EU and varying national legislation. Until future harmonisation is achieved, certain waste batteries are currently categorised as hazardous waste in some countries but not in others. This discrepancy leads to high transportation costs and administrative burdens, making the recycling process more expensive while reducing profit margins. With waste codes changing from country to country, shipping and transporting batteries with 'waste' status requires country- or region-specific approval procedures, which can result in time-intensive and costly EoL processes (Rizos & Urban, 2024b; National Board of Trade Sweden, 2023).

Our empirical research also revealed that some actors are concerned that ecodesign or due diligence requirements may not be ambitious enough to have a real impact on improving the social and environmental sustainability and circularity of EVBs. Limiting due diligence rules to annual reporting on economic actors' due diligence policies was seen as insufficient to address complex issues such as traceability and chain-of-custody. Moreover, industry actors warned against a narrow focus on mineral sourcing, preferring a full value chain approach. Excluding downstream processes such as refining and transport risks, overlooking significant human rights violations, thereby weakening the effectiveness of due diligence.

A lack of standards for different aspects of battery circularity, e.g. battery safety or battery status evaluation, can pose a challenge to EoL decision-making (Ma et al., 2021; Rallo et al., 2022). The lack of interoperability standards also poses challenges for

implementing the battery passport, given the fragmented landscapes of solutions for tracking and tracing, and calculating batteries' carbon footprints (CF) (see also Rizos & Urban, 2024a; Rizos & Vu, 2024). Since these measures are obligatory under the EU Batteries Regulation, the slow pace of the surrounding policy development is an additional concern, particularly because a harmonised approach is essential for ensuring the comparability of different assessments.

Legal uncertainties

The absence of clear rules and guidelines in the current EU policy mix for battery circularity has created legal uncertainties among industry actors (Giosuè et al., 2021; Parviziomran & Elliot, 2024). Several upcoming obligations for economic operators in the Batteries Regulation are awaiting further clarification in future delegated acts. Some timelines have even been delayed through the Commission's Omnibus package, which aims to simplify sustainability and reporting requirements. This is the case for the due diligence obligations under the Batteries Regulation, where the delayed provision of detailed rules and guidance creates ambiguity around future due diligence obligations and priorities.

Such uncertainties complicate the implementation of measures and potentially lead to delayed investments or simply higher administrative costs. Changing business models, production processes and supply chain relationships is time-consuming and may be difficult to achieve without the steady foundation of regulatory certainty. Clarifications would be necessary to allow industry players to adhere to the policy timelines foreseen and to make decisions about the necessary investments now. As such, the interviews point to the need for additional delegated acts and implementation guidelines by the Commission.

Policy enablers

Our research identified two essential enabling factors in the policy domain that can drive recycling of EVBs: (1) the EU Batteries Regulation and (2) Digital battery passport requirements.

Batteries Regulation as a driver of circularity

Despite the challenges raised earlier, the evolving EU policy framework impacting batteries' circularity, with the EU Batteries Regulation as a cornerstone, emerged as an important enabler during the interview consultations. Experts from across the battery value chain emphasised the potential of the EU Batteries Regulation to drive the transition to EVB recycling by introducing binding requirements such as recycling targets, carbon footprint declarations, and recycled content obligations. The benefits of these

requirements would be amplified if the above ambiguities and uncertainties were resolved. This message is consistent with existing research highlighting the importance of clear legal frameworks and mandatory targets for advancing circularity (Albertsen et al., 2021; Koppelaar et al., 2023).

Battery passport to support traceability and transparency

The battery passport has become a particularly important tool for implementing data-driven recycling value chains by improving supply chain transparency and traceability. Interviewees emphasised that data on battery chemistry and composition would be especially valuable for improving sorting, recycling, and second-life processes, in line with the literature (Götz et al., 2022; Koppelaar et al., 2023). Information on adhesive types or the battery-use phase (e.g. accidents) can support pre-treatment and recycling, while machine-readable dismantling manuals can improve the effectiveness and efficiency of processes. This could also lead to a higher availability of secondary raw materials over time. In addition, several experts noted that battery passports could also help inform and educate consumers about circularity, potentially encouraging more sustainable consumption patterns. Battery passports could further support the availability of recycled materials if linked with customs systems to avoid illegal exports.

2.3.2. Economic factors

Economic challenges

Economic barriers to large-scale battery recycling are less varied than the challenges in policy, and they all revolve around a central issue: recycling is currently not seen as competitive.

Recycling not competitive

The main challenge in this area is the lack of economic and financial viability of recycling pathways. More sustainable and circular approaches, such as EVB recycling, are still significantly more expensive than linear production models. Two factors explain this predicament: The comparably low, and in some cases further decreasing, cost of primary raw materials, and the limited cost-effectiveness of recycling processes (Rizos & Urban, 2024b).

Experts explained that securing the large investments needed for large-scale recycling facilities in Europe can be difficult, particularly because many recycling operations do not turn a profit in their early years¹⁰. In addition to high operating costs, fluctuating market

¹⁰ The construction of new recycling capacities requires significant long-term investment, while EoL EVB volumes still lag behind – limiting profitability.

prices for recovered materials create further investment uncertainty. These challenges reflect broader concerns about the still uncertain economics of battery recycling (Mayyas et al., 2019). Moreover, while prices for first-life LIBs are expected to decline over time, circular approaches continue to face high costs due to the need to store EoL batteries and to manage the associated costs related to handling, transportation, dismantling, and recovery processes (Rönkkö et al., 2021; Sopha et al., 2022).

A lack of financial (policy) incentives for recycling in Europe may further exacerbate the issue. Some of the interviewed industry actors were concerned that the current policy environment would leave the European industry at a disadvantage compared to other countries. At the same time, a lack of harmonised rules and prices across the EU creates unfair competition.

In addition, European recyclers face strong competition from established Asian corporations that benefit from state support. The larger-scale recycling capacity in Asia allows these companies to acquire black mass from European EoL EVBs at higher prices (T&E, 2025). Consequently, the emerging European recycling industry faces an additional challenge that hinders its profitability.

Economic enablers

Economic enabling factors for implementing EVB recycling were identified in two areas: (1) novel business opportunities from circular pathways, and (2) funding schemes to support battery recycling.

Novel business opportunities

Despite the currently challenging business case for recycling, circular economy practices can still offer novel opportunities to generate revenue and reduce costs, which can be important drivers for adopting circular battery solutions. This view is also reflected in the literature, which highlights the economic potential of circular business models in the battery sector (Haram et al., 2021; Wrålsen et al., 2021).

Funding schemes

Several industry actors highlighted the role of EU-funded projects and national funding schemes in supporting circular business models by providing financial support and stimulating demand for recycling. In addition, these projects were seen as creating opportunities for stakeholder cooperation and mutual learning. Funding schemes also play an important role in spurring private investment in battery recycling (Curtis et al., 2021; Götz et al., 2022).

2.3.3. *Market conditions*

Market challenges

The third category of challenges relates to market conditions on both the supply and demand sides. Two core domains can be identified here: (1) supply chain challenges, and (2) technology and data challenges.

Supply chain challenges

In EVB supply chains, a lack of cooperation, transparency and trust between supply chain partners have complicated more data-driven approaches to circularity, such as the implementation of a battery passport and CF calculations. Both the interviews and the literature point to a general reluctance to share data and information on EoL processes, mainly due to confidentiality concerns and existing non-disclosure agreements (Giosuè et al., 2021; Serna-Guerrero et al., 2022).

Suppliers often do not provide detailed information on mineral composition, chemical substances, recycled content, or the original sources of materials. However, information about the BMS, SoH, and charging history is particularly important for enabling circular processes. As a result, the lack of transparency across battery supply chains makes dismantling, recycling, and reuse more difficult (Rizos and Urban, 2024a).

Similar issues exist for acquiring reliable data to calculate the battery CF. Companies face obstacles in obtaining detailed and transparent data from suppliers, including on how certain calculations were performed. This often requires downstream actors to make assumptions, which in turn introduces uncertainty – especially given the global nature of supply chains and the lack of harmonised methodologies worldwide (Rizos & Vu, 2024).

Companies also highlighted problems with battery collection, including the lack of adequate collection systems for portable LIBs, the small volumes of large batteries currently available for recycling, and the challenge of gathering batteries from many different sources and then sorting them by chemistry. The limited availability of facilities for the collection, storage, and transportation of EoL LIBs makes it difficult to optimise material flows (Rajaeifar et al., 2022; Rallo et al., 2022), while the lack of secondary materials can hinder recycling processes (Helander and Ljunggren, 2023; Mayyas et al., 2019).

Technology and data barriers

Persistent challenges also emerge in the realm of technology and data. Companies involved in collection, vehicle dismantling, and recycling noted that many current battery designs do not enable feasible dismantling and recycling (Mayyas et al., 2019; Murdock

et al., 2021). For instance, the widespread use of glues and other permanent joining methods renders dismantling processes time-consuming. The large variety of battery pack designs, often combined with missing information about the use stage, makes it difficult to establish standardised and efficient dismantling and recycling processes. The continuous evolution of battery chemistries further creates uncertainties, leading to inconsistent assessments of battery SoH and RUL (Rajaeifar et al., 2022; Albertsen et al., 2021).

In addition, safely discharging certain types of batteries before recycling can be complex. There is often a lack of specialised personnel and tools for EoL handling, which increases health and safety risks during dismantling, discharging, and reassembly (Rajaeifar et al., 2022).

In the digital realm, data-quality issues complicate fulfilling both battery passport and CF-related obligations. Insufficient and poor-quality data hinder the implementation of digital tools such as battery passports (Götz et al., 2022) and make it harder to accurately assess environmental impacts (Curtis et al., 2021; Haram et al., 2021). For instance, suppliers tend to submit data in different reference units, causing a lack of interoperability, rely on (potentially untransparent or incorrect) assumptions, or even omit certain parameters. At the same time, tracking the emissions of certain phases, like the transportation of EoL batteries, can be very difficult in practice, requiring the use of average values and assumptions. Although secondary sources, like databases, can help address missing data, they may themselves contain gaps, optimistic values, or inconsistencies across datasets.

Market enablers

At the same time, there are important enabling factors in the market category that could help resolve challenges and support implementing an EVB recycling value chain: (1) supply chain cooperation, and (2) technological innovation and data sharing tools.

Supply chain cooperation

Regarding supply chain enablers, our research revealed the importance of establishing partnerships and enhancing supply chain collaboration (Baars et al., 2021; Wrålsen et al., 2021). According to the interviewees, partnerships help build trust between companies, which is essential for increased information sharing and a better understanding of circularity processes. Relationships of trust can increase the willingness to share data and increase supply chain traceability and transparency in the long term. This is particularly important given the need to secure the European recycling industry in amid growing external competition and geopolitical developments.

Technological innovation and data sharing tools

In the category of technological enablers, digital technologies such as blockchain were mentioned as important tools for facilitating information exchange, while also improving supply chain visibility and traceability (da Silva et al., 2023; Júnior et al., 2023). In addition, innovations in dismantling and recycling technologies are key enablers of EoL processes. New LIB recycling technologies can increase process flexibility and improve the recovery of valuable materials. The use of robotics was also mentioned during the interviews as a way to increase the cost efficiency of recycling operations while reducing risks to human health.

3. SECOND-LIFE APPLICATIONS

EVBs are typically retired at 70-80 % of their original capacity, meaning they often retain sufficient performance for less demanding applications. Following their first life, EVBs can follow various pathways that enable a secondary use. In general, second-life applications can be divided into two categories: those that retain the battery's original function and those that consist of a change in application. Reuse and remanufacturing fall into the first category, whereas repurposing falls into the second.

According to the EU Waste Framework Directive (2008/98/EC), reuse means using a product or its components for the same purpose for which they were originally designed. Due to the strict performance and safety standards in EVs, the reuse of EVBs is mostly limited to packs that are prematurely removed as a result of accidents or vehicle failures unrelated to the battery itself. In these cases, damaged modules may be replaced, and the battery can still retain enough capacity for vehicle traction (Zapico et al., 2024).

Remanufacturing similarly aims to restore batteries to their original function, but involves more extensive processing. It consists of dismantling the pack, testing individual cells and modules, and reassembling the battery. Under the EU Batteries Regulation, remanufactured batteries must restore at least 90 % of their original capacity and variation among cells must not exceed 3 %.

In contrast, repurposing – the second pathway – assigns a battery to an application different from its original. Repurposed EVBs are most often integrated into stationary energy storage systems. This process typically entails assessing the pack's RUL, selecting suitable modules, and configuring a new battery to meet the performance needs of the second-life application.

This section first outlines the main applications for repurposed EVBs (3.1), then reviews the current state of development of these practices in Europe (3.2) and finally presents the key policy, economic and market challenges affecting the second-life business model (3.3).

3.1. KEY APPLICATIONS

Second-life EVBs can be used for a wide range of purposes. These are typically categorised by end-user type or functional context.

With respect to repurposed EVB end-uses, these can serve energy storage services in residential, commercial, and industrial settings (Hossain et al., 2019; Zhao et al., 2021). In residential applications, second-life batteries can store electricity generated by rooftop photovoltaic (PV) systems during the day for later consumption in the evening (i.e. load

shifting). As demand for household-level hybrid PV-BESS is on the rise, second-life EVBs can provide a more affordable alternative and improve the cost-effectiveness of such installations (Al-Alawi et al., 2022).

In commercial settings, such as hospitals or office buildings, storage systems must satisfy larger power demands (Hossain et al., 2019; Zhao et al., 2021). In this context, battery storage reduces grid consumption during high-demand periods by enabling the use of stored energy instead (i.e. peak shaving). Benefits include lower pressure on the grid and lower utility bills for commercial operators (Hossain et al., 2019; Zhao et al., 2021).

Finally, industrial users, including manufacturing plants and data centres that require a continuous, substantial power supply, may see limited benefit from installing reduced-capacity batteries. Due to the scale of demand and performance requirements, these systems in industrial settings may only be suitable for less-demanding industrial applications (Hossain et al., 2019; Gu et al., 2024; Zhao et al., 2021). Section 4 provides additional details on the viability of residential, commercial and industrial applications for second-life EVBs.

In terms of their functional context, grid-based applications, i.e. batteries connected to the power grid, include participation in ancillary services such as frequency regulation and power smoothing (Song et al., 2024). Owing to escalating shares of electricity generation from variable renewable energy sources across Europe, namely, from wind and PV, grid-based storage can play a critical role by storing surplus generation in periods of low demand and discharging during high demand peaks (Al-Alawi et al., 2022; Hossain et al., 2019). Second-life EVBs have been shown to perform well in this realm, offering a cost-effective means to foster renewable integration and grid stability (see Strupeit & Tojo, 2023; Omrani & Jannesari, 2019).

In off-grid applications, second-life EVBs can support energy access in underserved or remote regions or act as back-up power during outages (Colarullo & Thakur, 2022), although the duration of the latter service is limited. Examples of deployment sites reviewed in the literature include microgrids, telecom towers, and urban mining sites (Gu et al., 2024; Song et al., 2024). Beyond their societal value, Al-Alawi et al. (2022) it is important to highlight the environmental benefits, as life-cycle assessments show that these applications can reduce both carbon footprint and resource depletion compared to conventional diesel-based generators.

Lastly, repurposed EVBs can be used in off-grid EV charging stations or integrated in low-speed EVs such as forklifts and e-scooters (Hossain et al., 2019; Gu et al., 2024). These mobile applications are well-suited to second-life EVBs due to their relatively modest performance requirements, although broader uptake is still constrained by costly

diagnostic tools necessary to determine the RUL of end-of-first-life batteries (Gu et al., 2024). Due to the growing demand for EV infrastructure roll-out, repurposed EVBs could offer a strategic opportunity to combine affordability with circularity, while simultaneously minimising pressure on the grid as the electrification of the transport sector accelerates (Gu et al., 2024; Song et al., 2024).

3.2. STATE OF PLAY

The use of second-life EVBs as BESS has been well explored in both academic research and across real-world initiatives. Current technological readiness, however, remains uneven across different stages of the repurposing process. Steps such as collection, basic assessment and disassembly are well understood in theory, but their practical viability remains constrained by the lack of standardised practices (Akram & Abdul-Kader, 2024; Al-Alawi et al., 2022; Gu et al., 2024). For instance, efforts are still needed to develop cost-effective and efficient diagnostic tools to improve the sorting of retired packs and the evaluation of their RUL (Gu et al., 2024). Likewise, while robotics and AI have been successfully applied to automate disassembly in academic contexts, the heterogeneity in original EVB designs and configurations continues to limit the commercial uptake of such techniques (Akram & Abdul-Kader, 2024; Gu et al., 2024; Moreschi & Rizos, 2026).

On the other hand, BMS and converters required for the electronic management of repurposed packs are regarded as technically advanced and capable of ensuring efficient integration into second-life applications (Akram & Abdul-Kader, 2024). Market maturity in Europe remains limited, and a comprehensive mapping of second-life storage systems based on repurposed EVBs is still lacking (see Podias et al., 2018; VDE Renewables, 2022). Nevertheless, several flagship projects illustrate growing interest in second-life batteries and their applications.

The integration of repurposed EVBs in PV systems represents one of the most advanced market opportunities (see Strupeit & Tojo, 2023). Projects are commonly driven by joint ventures involving EV manufacturers, energy operators and startups exploring battery repurposing, with substantial funding from institutional actors. A notable example is the Johan Cruijff ArenA in Amsterdam, which operates a 3 MW second-life storage system partly financed by EU and national programmes (i.e. the EU Interreg programme and the Amsterdam Climate and Energy Fund). Similarly, the EU Innovation Fund awarded 3.1 million EUR to the PIONEER project, which developed a second-life battery storage system at Rome's Fiumicino Airport. The plant can deliver 2.5 MW and store up to 10 MWh from PV sources. A non-exhaustive overview of second-life storage systems deployed across Europe is presented in Table 3.

Table 3: Examples of second-life battery energy storage in Europe

Project	Country	Power Rating / Capacity	Status	Relevant Operator(s)
<u>SECONDLIFEBATTERIES 4STORAGE</u>	Austria	96 MWh	Operational	Smart Power; AVL List; AVL DiTest; Energie Steiermark; Saubermacher
<u>PIONEER – ROME FIUMICINO AIRPORT</u>	Italy	2.5 MW / 10 MWh	Operational	Enel X; Nissan; Mercedes-Benz, Stellantis
<u>Johan Cruijff ArenA</u>	Netherlands	3 MW	Operational	Eaton; Nissan
<u>LÜNEN AND ELVERLINGSTEN BESS</u>	Germany	20 MW / 21 MWh	Operational	Mercedes-Benz Energy; Daimler; The Mobility House
<u>GEORGES BESSE RENAULT FACTORY</u>	France	4.9 MWh	Developed	Renault Group
<u>Emilas Project</u>	Germany	81 kW / 194 kWh	Developed	Fraunhofer ISE; DSG Energiekonzepte ; Deer; Beck Automation; VDE Renewables
<u>Fluxicon</u>	Germany	1 MWh	Planned	RWTH Aachen; PEM Motion; ConAC; DEKRA
<u>EUREF CAMPUS (BERLIN)</u>	Germany	1.9 MWh	Operational	Audi; EUREF Campus consortium

<u>Thumaide Waste-to-Energy plant</u>	Belgium	1.3 MW	Developed	Octave; Ipalle
<u>MELILLA GLOBAL THERMAL GENERATION PLANT</u>	Spain	4 MW / 1.7 MWh	Operational	Enel; Nissan
<u>EXTREMADURA I-II-II</u>	Spain	2 MW / 5 MWh	Operational	BeePlanet Factory; ACCIONA Energia
<u>BRISTOL DIGITAL FUTURES INSTITUTE</u>	United Kingdom	600 kW / 720 kWh	Planned	Connected Energy; University of Bristol
<u>MILDENHALL HUB</u>	United Kingdom	300 kW / 360 kWh	Ongoing	Connected Energy

Source: Authors' own compilation

Furthermore, there is a growing number of specialised European entities dedicated to developing second-life BESS. Examples include BeePlanet Factory (Spain), which is a partner in the BATRAW project and Connected Energy (UK). EV manufacturers such as Nissan, Mercedes-Benz and Renault, as well as energy companies like Enel X and Eaton, are also actively exploring EVB repurposing for stationary energy storage applications. Together, these actors demonstrate a willingness to transition from small-scale pilots to industrial-scale installations, despite ongoing technical challenges. Figure 3 identifies battery repurposing facilities in Europe. A detailed list of these can be found in Annex B.

Figure 3: Map of existing battery repurposing facilities in Europe.



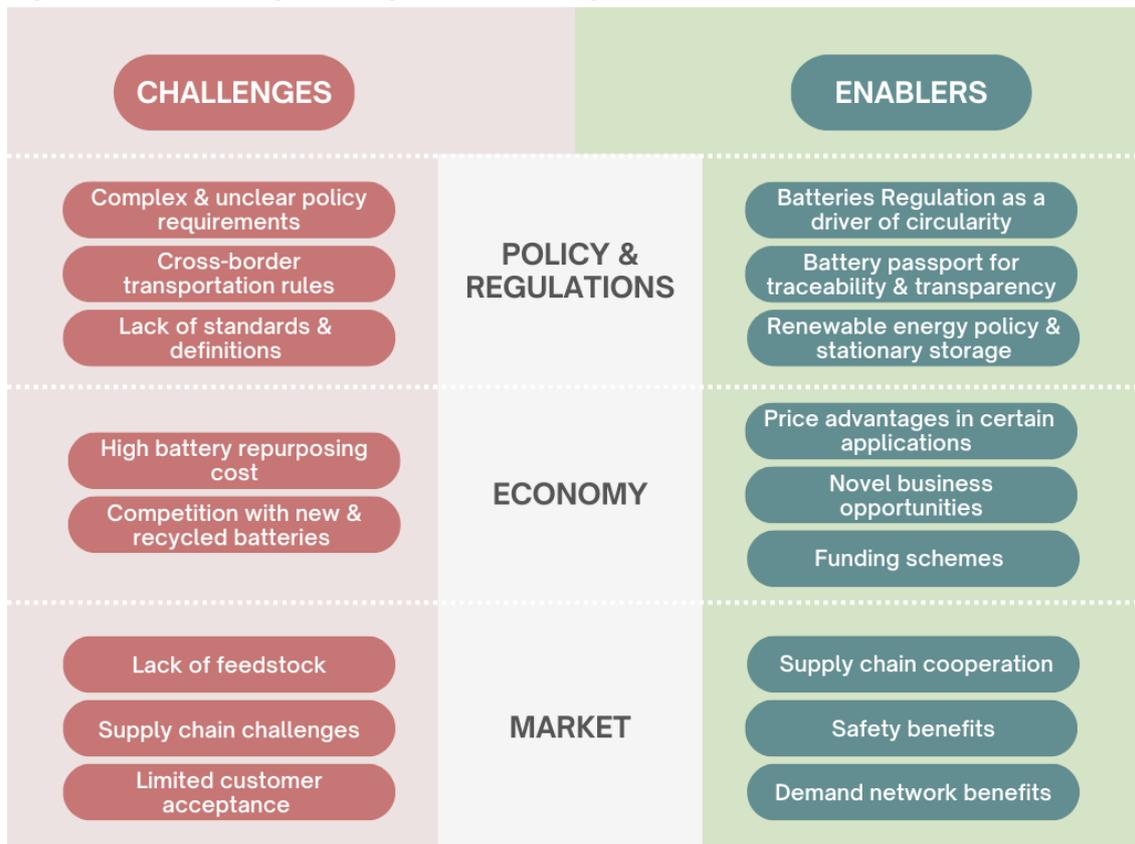
Source: Author's elaboration. Based on the author's own research and an initial data compilation from [Battery-News](#) (2024).

Notes: A map combining both repurposing and recycling facilities is presented in Annex B, alongside their corresponding datasets.

3.3. OVERARCHING CHALLENGES AND ENABLING CONDITIONS FOR SECOND-LIFE EVBs

During our empirical research, consisting of desk research and interviews with companies from across the battery value chain over a 3-year period (see Annex A), we identified several overarching challenges to second-life applications. At the same time, potential enabling conditions that could support second-life pathways for EVBs also emerged (see Figure 4).

Figure 4: Overarching challenges and enabling conditions for second-life EVBs.



Source: Author's elaboration.

3.3.1. Policy and regulations

Policy challenges

In the policy realm, we identified three major obstacles for second-life EVBs: (1) complex and unclear policy requirements, (2) cross-border transportation rules, and (3) lack of standards and definitions.

Complex and unclear policy requirements

The current policy and regulatory framework for second-life EVB applications has sometimes been criticised for lagging behind the rapid growth of the EV market, creating uncertainties and deterring investments (Akram & Abdul-Kader, 2024; Salek et al., 2024). Evidence from qualitative studies shows that companies in the battery ecosystem have limited capacity to plan for CBM implementation, as they perceive the related legal requirements to be overly complex or too fragmented (Prenner et al., 2024a; Toorajipour et al., 2024). Policy gaps and uncertainties translate directly into high compliance costs, undermining the viability of second-life applications (Gu et al., 2024).

Regulatory ambiguities primarily concern the allocation of responsibilities and liabilities for second-life EVBs. Without clear rules, different business models have emerged, with ownership distributed differently among OEMs, EV owners and intermediaries purchasing used batteries for repurposing (see Júnior et al., 2023; Rizos & Urban, 2024b). Since ownership also determines liability during secondary uses, current regulatory uncertainties may discourage companies from entering second-life markets (Hellström & Wrålsen, 2024; Toorajipour et al., 2024).

The EU Batteries Regulation aims to address such issues by broadly assimilating second-life operators with OEMs and assigning compliance responsibilities to the actor placing the battery on the market. Nevertheless, concerns arise from the wide variety of actors involved in the second-life supply chain, making it challenging to determine who ultimately bears responsibility for repurposed EVBs (Júnior et al., 2023).

Cross-border transportation rules

Regulations impacting the cross-border transportation of batteries generate an additional layer of regulatory complexity, as most EVB chemistries are classified as hazardous under the European List of Waste. This entails that used EVBs are subject to prior informed consent procedures under the Waste Shipment Regulation, even when transboundary transport is intended for recycling, reuse or repurposing (Rizos & Urban, 2024b). Operators often view these requirements as disproportionately strict, arguing that procedural obligations should be simplified when circularity is the primary motive of reverse logistics operations (Prenner et al., 2024a; Moreschi & Rizos, 2026). Additionally, insights from qualitative studies reveal fragmented practices for collecting and storing batteries across EU Member States, due to differing permitting rules adopted by national authorities (Strupeit & Tojo, 2023; Toorajipour et al., 2024).

Lack of standards and definitions

The literature further emphasises the lack of technical standards and common definitions around EVB repurposing. For instance, the lack of harmonised testing procedures for second-life EVBs makes it difficult to establish reliable certification and warranty systems (Mulder et al., 2022; Salek et al., 2024). Although stationary storage standards are typically less demanding than those for EV use, certification and safety testing cannot be directly transferred from batteries' first life to second-life applications. This is driven by safety concerns related to battery ageing, as well as additional testing required to ensure reliability and performance during secondary use. However, the lack of standard methods to determine SoC, SoH, and ageing undermines warranties for second-life batteries (Prenner et al., 2024a). Ongoing efforts to establish repurposing guidelines and technical parameters for second uses of EVBs aim to address such issues.

Policy enablers

At the same time, our research revealed three policy enablers for second-life EVB applications: (1) the EU Batteries Regulation, (2) battery passports to provide crucial data, and (3) renewable energy policy incentives.

Batteries Regulation as a driver of circularity

Most interviewees viewed the EU Batteries Regulation as an important development for advancing second-life business models. Provisions ensuring access to BMS data and the introduction of EPR obligations were highlighted as especially promising (see Albertsen et al., 2021; Prenner et al., 2024).

Battery passport to support traceability and transparency

Respondents also identified the battery passport as an important enabling instrument, as it provides essential information regarding a battery pack's first-life use that is relevant to second-life pathways (Meyer et al., 2024; Rizos & Urban, 2024b). By improving transparency and thereby facilitating processes such as automated disassembly and streamlined performance testing, the battery passport can significantly lower repurposing costs (Zhao et al., 2021).

Renewable energy policy and stationary storage

Beyond battery-specific legislation, broader renewable energy policies were seen as additional drivers of second-life EVB deployment. EU-level renewable energy targets were considered relevant for increasing the demand for stationary storage solutions to help manage the intermittency of renewable power generation. Interviewees therefore

noted that such policy measures indirectly stimulate interest in repurposing EVBs, as second-life batteries can contribute to meeting this emerging storage demand (see Albertsen et al., 2021; Strupeit & Tojo, 2023).

3.3.2. Economic factors

Economic challenges

Economic barriers to implementing second-life applications of EVBs at scale are connected to a range of conditions resulting in (1) high battery repurposing costs and (2) competition with new and recycled batteries.

High battery repurposing cost

The main economic barrier to second-life applications lies in the high costs involved in the repurposing process, which arise at each of the stages – from collection to disassembly, testing, and reassembly.

Evidence suggests that the purchase of retired batteries and modules is the single largest cost component for second-life operators (Gu et al., 2024; Prenner et al., 2024a; Moreschi & Rizos, 2026). Transporting end-of-first-life batteries to repurposing facilities is also frequently identified as overly expensive, mainly due to regulatory complexities and safety requirements, as discussed above (Gu et al., 2024; Prenner et al., 2024a).

Current practices for disassembly and testing constitute an additional cost driver for repurposing EVBs, as such processes are currently labour intensive and difficult to scale (Meyer et al., 2024; Terkeş et al., 2024). As repurposing largely relies on manpower, wage disparities across world regions play a crucial role in the competitiveness of European operators involved in second-life EVB manufacturing (Zhao et al., 2021).

At the same time, inadequate original pack designs and the variety of EVB configurations currently on the market challenge the possibility of standardising disassembly procedures, thus, to achieve economies of scale (Ahmed et al., 2025; Shahjalal et al., 2022). The lack of data transparency is another factor driving up repurposing costs. Since OEMs typically do not share information on the battery's history, operators need to perform extensive diagnostic processes to evaluate the SoH of used modules and assess their suitability for secondary uses (Meyer et al., 2024; Terkeş et al., 2024).

Uncertainty about the operating profile and initial SoH of used packs limits the ability to estimate their RUL and the potential value they can provide in second-life applications (Prenner et al., 2024b; Toorajipour et al., 2024). Consequently, this can discourage investment, since companies cannot reliably predict whether purchased EVBs will generate sufficient economic value to offset procurement costs (Gu et al., 2024).

Finally, additional expenses arise from efforts required to develop a new BMS, as well as the purchase and integration of novel components such as wiring, fuses and connectors (Mulder et al., 2022; Podias et al., 2018).

Competition with new and recycled batteries

High repurposing costs can erode the price advantage of second-life batteries compared to newly manufactured ones, undermining their cost-effectiveness (Mulder et al., 2022; Prenner et al., 2024a). This dynamic is further reinforced by the ongoing decline in new battery prices, which could diminish the price advantage of repurposed ones, increasing competitive pressure (Gu et al., 2024; Shahjalal et al., 2022). This is an issue as the main demand driver for second-life applications lies in the ability of repurposed EVBs to deliver comparable performances at lower market prices than new storage batteries (Akram & Abdul-Kader, 2024; Gu et al., 2024).

Battery recycling might create additional competitive pressures (Prenner et al., 2024a). While rapid technological developments are improving the financial returns of material recovery, operational complexities around repurposing remain. This raises concerns that, without regulations, investments may shift away from second-life towards recycling, prioritising other approaches such as battery lifetime extension (Albertsen et al., 2021; Seika & Kubli, 2024).

Economic enablers

Economic enabling factors for implementing second-life EVB applications emerged in three areas: (1) price advantages in certain applications, (2) novel business opportunities, and (3) funding schemes.

Price advantages in certain applications

Across the interviews, the price competitiveness of second-life EVBs was identified as a central economic enabling factor. The cost difference between repurposed EVBs and newly manufactured batteries largely determines their attractiveness for applications with lower performance requirements, such as residential energy storage systems and microgrids (see Akram & Abdul-Kader, 2024; Gu et al., 2024). In this context, a price advantage can strengthen the economic case for households adopting domestic battery energy storage systems (Júnior et al., 2023). Residential storage can enable households to reduce electricity purchases from the grid during peak-price periods, potentially lowering overall energy expenditures (see Akram & Abdul-Kader, 2024).

Novel business opportunities

The rapid expansion of the EV market is another potential driver of the economic potential of second-life business models. With increasing EV adoption, the volume of retired battery supply is expected to grow, creating stronger incentives to invest in repurposing pathways (see Júnior et al., 2023). More broadly, second-life EVB applications can generate diverse value streams for multiple stakeholders (see Bai et al., 2019; Schulz-Mönninghoff & Evans, 2023), including grid service providers, EoL operators, and OEMs (see Ahmed et al., 2025). One example that emerged during the interviews highlighted how selling retired batteries to second-life operators may allow OEMs to extract additional value from the costly raw materials embedded in EVB production (see Zhao et al., 2021). Second-life applications may also help meet rising electrification demand while potentially alleviating short-term pressure on scarce and price-volatile materials such as nickel and cobalt (see Gu et al., 2024; Júnior et al., 2023).

Funding schemes

Public funding mechanisms provide further incentives for second-life business models. Publicly supported pilot projects create opportunities to demonstrate the viability of CBMs and attract private investment (see Toorajipour et al., 2024). Interviewees emphasised the importance of EU funding programmes such as Horizon Europe, which supports the BATRAW project, particularly in providing financial support for small and medium-sized enterprises (SMEs), e.g. for developing skills and strengthening technical capacities.

3.3.3. Market conditions

Market challenges

Our research identified three adverse market conditions that constitute challenges for second-life business models: (1) lack of feedstock, (2) supply chain challenges, and (3) limited customer acceptance.

Lack of feedstock

The market for second-life EVB applications remains limited despite the proliferation of proof-of-concept demonstrations and small-scale pilots (Albertsen et al., 2021; Meyer et al., 2024). Industrial-scale commercialisation is hindered by an overall underdevelopment on both the supply and demand sides, driven by market uncertainties and low stakeholder awareness.

A primary challenge is the currently low availability of used EVBs, driven partly by the above-mentioned cost factors that complicate collection, and partly by the relatively

early stage of EV market development (Toorajipour et al., 2024). The issue is further aggravated by difficulties in predicting the share of retired EVBs that can meet operational requirements for repurposing, such as a minimum SoH threshold, since these depend on the battery's original characteristics and first-life usage patterns (Strupeit & Tojo, 2023; Toorajipour et al., 2024).

Supply chain challenges

Beyond volume issues, supply-side readiness for second-life markets suffers from limited infrastructure and an underdeveloped reverse logistics system (Toorajipour et al., 2024; Moreschi & Rizos, 2026). Gaps and missing links in the supply chain are compounded by weak cooperation and low trust among actors (Ahmed et al., 2025; Prenner et al., 2024a).

A notable example is OEMs' reluctance to share BMS data, primarily due to intellectual property concerns and fears of reputational damage should batteries fail during their second-life use (Meyer et al., 2024; Prenner et al., 2024a). This lack of cooperation may be a result of the limited knowledge of second-life business models, given that building synergies for EVB repurposing requires not only economic investment but also flexibility to adapt internal structures (Toorajipour et al., 2024).

Limited customer acceptance

On the demand side, limited customer acceptance of second-life battery applications emerged as a key market barrier. Both private and industrial users of energy storage systems tend to perceive second-life solutions as less safe and more prone to failure than new ones (Ahmed et al., 2025; Schulz-Mönninghoff & Evans, 2023). As a result, second-life operators must rely on warranty systems and efficient communication strategies to counteract misconceptions regarding the safety and performance of their products (Ahmed et al., 2025; Albertsen et al., 2021).

Consumer scepticism concerning the reliability of second-life EVBs further reduces their willingness to pay (Meyer et al., 2024; Schulz-Mönninghoff & Evans, 2023). Customers tend to prioritise price considerations over sustainability values, with estimates suggesting that repurposed EVBs only become attractive when priced at least 30-50 % lower than newly manufactured ones (Albertsen et al., 2021).

Market enablers

Nevertheless, potential enabling factors could help alleviate such challenges, falling into the following categories: (1) Supply chain cooperation, (2) Supply chain localisation, (3) safety benefits, and (4) demand network benefits.

Supply chain collaboration

Strong supply chain partnerships emerged as a critical enabler for scaling second-life business models during the interviews. In particular, collaboration with OEMs was described as highly valuable for improving the efficiency and predictability of repurposing operations (see Meyer et al., 2024). Such partnerships typically grant access to BMS data and allow companies to better anticipate the volumes and technical characteristics of incoming EVBs (Meyer et al., 2024; Toorajipour et al., 2024).

Long-term cooperation between supply chain actors can also promote mutual learning on CBMs (Toorajipour et al., 2024). For example, collaborating with more experienced partners could facilitate navigating the – often complex – regulatory landscape, while partnering up with recycling companies may enhance other companies’ understanding of reverse logistics and EoL operations.

Interviewed companies further underscored the advantages of localised supply chains for second-life batteries. While new batteries are currently predominantly imported from Asia and remain vulnerable to global supply chain disruptions, repurposed EVBs may offer a more resilient alternative aligned with the EU’s strategic autonomy agenda. Because repurposing activities are often located near end users, transportation costs can be reduced, and traceability improved.

Safety benefits

Several interviewees suggested that repurposed EVBs may offer certain safety benefits compared to newly manufactured stationary storage batteries. EVBs are originally designed to comply with stringent performance and safety standards, which may provide a robust safety foundation for subsequent stationary applications (see Strupeit & Tojo, 2023). Some interviewees also argued that batteries that have already undergone multiple charge and discharge cycles may present more predictable performance characteristics than unused units. However, safety outcomes ultimately depend on rigorous testing and appropriate system integration.

Demand network benefits

Repurposed EVBs have several benefits that can make them attractive to both business customers and final consumers (i.e. the demand network). Interviewees identified different factors that can support the uptake of second-life applications, driven by growing societal awareness of sustainability as well as companies’ strategic interest in CBMs.

Rising consumer demand for residential battery storage systems was highlighted as a potential enabling factor (see Al-Alawi et al., 2022). In this context, interviewees also discussed that geopolitical instability, connected to the risk of blackouts and grid interruptions, is motivating households to seek affordable backup power solutions (including those provided by repurposed EVBs).

From a corporate perspective, second-life EVBs were associated with potential sustainability benefits (see Toorajipour et al., 2024). For instance, it was argued that integrating refurbished or remanufactured EVBs in automotive manufacturing process could contribute to reducing companies' overall carbon footprint or help fulfil broader environmental commitments.

4. CREATING THE BUSINESS CASE FOR EVB CIRCULARITY

The success of circularity models for EVB packs fundamentally depends on their ability to deliver sustained economic viability. This chapter examines the current and future economic prospects of recycling and repurposing pathways, highlighting critical barriers and potential areas for improvement that could enhance their commercial appeal.

4.1. RECYCLING

The economic viability of pursuing a recycling pathway is contingent on the revenue generated from selling recovered materials and the costs incurred during the recycling process, where the former must exceed the latter. The global battery recycling market was valued at 8 billion EUR in 2022 and is expected to reach 20 billion EUR by 2028, driven by the increasing number of batteries reaching the end of their useful life (Wesselkämper & Von Delft, 2024).

Globally, two LIB chemistries lead the market: NMC (nickel manganese cobalt) and LFP (lithium iron phosphate) batteries. The former are the most prevalent across Europe, although the market share of LFP batteries globally is growing. This section focuses on NMC chemistries and examines key challenges for the recycling sector, including the growing share of batteries in the market with lower high-value metal content, high recycling costs and limited throughput volumes.

4.1.1. *Economic viability of recycling*

Value of recycled EVBs

The recyclable value of battery packs is contained in the battery cells, and more specifically in their cathode active material, which accounts for 45 % to 59 % of the battery pack's total value (Gutsch and Leker, 2024; Fonseca Guimarães et al., 2024). Metal recovery from the black mass at the end of the recycling process allows its sale in the market. LIBs typically contain 5–20 % cobalt, 5–10 % nickel, and 5–7 % lithium, although compositions differ between battery types and manufacturers. These metals are widely recognised as the most valuable to recover through recycling, with cobalt being especially critical due to its relatively high market price (Zheng et al., 2018; Tawonezvi et al., 2023). While other metals and materials are also recyclable, here we focus on the recyclable value of the mentioned metals.

European EV manufacturers have traditionally favoured NMC-based LIBs because of their relatively high energy densities. Early EVs implemented NMC111¹¹ chemistries, but the

¹¹ NMC111 LIBs contain nickel, manganese and cobalt at a 1:1:1 ratio, respectively.

industry has since shifted towards higher-nickel alternatives such as NMC622¹² and NMC811¹³ to further enhance energy density and reduce cobalt content.

Most notably, the industry has also experienced a transition towards LFP-based batteries, particularly from Chinese EV manufacturers. LFP batteries are approximately 30 % cheaper than NMC batteries (McKinsey, 2024) as they contain lower concentrations of cobalt and nickel or may even be cobalt- and nickel-free. Their lower energy densities¹⁴ are economically offset by their lower cost per unit capacity. Table 4 compares the weighted recyclable value of selected metals from typical NMC and LFP batteries.

Table 4: Weighted value potential of LFP and NMC batteries considering specific recyclable metals

Metal	Weighted Metal Value (EUR/kWh)	
	LFP	NMC
Lithium	4.51	5.78
Cobalt	-	6.96
Nickel	-	7.76
<i>Total</i>	<i>4.51</i>	<i>20.51</i>

Source: Author's own elaboration using data from IRENA (2024), LME (2026a), LME (2026b), World Bank (2026).

Note: Assumes metals are recyclable at a 100 % rate. Considers battery-specific composition and metal commodity prices. Details of these are found in Annex C. Calculations assume lithium carbonate composition for LFP batteries and lithium hydroxide composition for NMC batteries. Considers lithium, cobalt, and nickel only.

Efforts to make EVBs cheaper and, in turn, make battery electric vehicles more affordable have led to a global shift in battery composition, with LFP batteries now accounting for almost 50 % of the global market, up from 10 % in 2020 (IEA, 2025b). In the EU, NMC batteries remain dominant, accounting for 77 %, but the market share of LFP chemistries is projected to increase to 40 % by 2030, largely replacing NMC types (IEA, 2025d; S&P Global, 2025a).

While LFP batteries may be instrumental in lowering EV prices, their lower recyclable value raises concerns about the future viability of battery pack recycling pathways. Caldini et al. (2024) indicate that LFP batteries are currently not economically feasible to recycle,

¹² NMC622 LIBs contain nickel, manganese and cobalt at a 6:2:2 ratio, respectively.

¹³ NMC811 LIBs contain nickel, manganese and cobalt at an 8:1:1 ratio, respectively. Their lower cobalt concentrations with respect to the NMC111 type may make them uneconomical to recycle.

¹⁴ At the pack level, LFP batteries have a 5–20% lower energy density than NMC batteries (McKinsey, 2024).

as their costs exceed the profits gained from selling the recycled material. As LFP batteries gain market share, they will make up a greater share of the material processed at recycling plants, which will lower the average salvage value of EVBs. DNV (2023) projects that the average battery value will drop by 17 % by 2036 compared to 2023 levels. However, owing to the growing volumes of EVBs entering their EoL stages, the cumulative scrapped value is expected to escalate from negligible levels to more than 6 billion EUR per year. This growth makes recycling economically viable, even though profits per battery remain low.

Fluctuations in metal commodity prices indirectly influence the economic viability of the recycling pathway. Scenarios in which prices rise, e.g. due to supply shortages, can unlock revenues from metal sales (IEA, 2025e). Battery types like LFP, which are often considered uneconomical to recycle, may become profitable in these scenarios. These external factors are beyond the control of the battery recycling sector itself and depend on broader market conditions.

The Batteries Regulation requires minimum recycled content targets in new EVBs (see Section 1.1.1). Changes in battery chemistry may affect profitability and, if sustained, could reduce incentives to pursue this pathway. This could complicate meeting the recycled content targets, as lower yields of recycled metal could limit supply.

Recycling cost components

Commercial methods for EVB recycling can be broadly divided into two categories, typically following the pre-treatment: (i) pyrometallurgical, and (ii) hydrometallurgical (see Section 2.1 for a description of these routes). Pyrometallurgical recycling has long been the conventional approach to metal recovery. While this method achieves high recovery rates for cobalt and nickel, it does not recover lithium¹⁵, which is lost in the slag. The more novel hydrometallurgical method enables the recovery of lithium alongside cobalt and nickel at higher purity levels than pyrometallurgy (Al-Alawi et al., 2022; Tankou et al., 2023).

Despite being more capital-intensive¹⁶ than pyrometallurgical methods, hydrometallurgy's ability to access higher recovery rates provides room for higher

¹⁵ Standard pyrometallurgical methods do not recover lithium, which oxidises into the slag by-product. Any lithium recovery from pyrometallurgy would require an additional hydrometallurgical stage, forming a hybrid process.

¹⁶ Hydrometallurgical recycling involves a greater upfront capital investment than the pyrometallurgical method, although this may be mitigated by its lower operating costs, e.g. due to lower energy consumption (Saleem et al., 2023).

revenue potential. Today, however, profit margins for pyrometallurgy marginally exceed those of hydrometallurgy¹⁷ (Schlott et al., 2025).

While hydrometallurgy is relatively immature compared to pyrometallurgy, both are increasingly combined in hybrid formats (Zhao & Kaur, 2025). Scaling up hydrometallurgical recycling capacity and lowering its costs is crucial for securing the long-term viability of battery pack recycling pathways. This is particularly important given the shift towards LFP batteries with lower nickel and cobalt content, where the recoverability of other metals such as lithium will become fundamental (Racu and Poliscanova, 2024b). The costs of recycling lithium-ion EVBs have been estimated to range from 1.4 EUR/kg to 19.2 EUR/kg, depending on the method used, feedstock characteristics and the scale of recycling plants (Schlott et al., 2025). Upstream processes, particularly disassembly, account for a significant proportion of the total recycling costs, ranging from 2 % to 21 % across studies (Lander et al., 2021). Today, disassembly is mostly conducted manually, resulting in higher labour costs. Suggestions to scale up automated processes with robotics or semi-automated procedures are widely endorsed as a means to lower final costs (Harper et al., 2019; Feng et al., 2025).

Since EVBs are heterogeneous in structure and composition, recycling techniques must be tailored to the specific characteristics of each battery type. Standardising battery packs, modules, and cell designs and applying 'design-for-recycling' principles can contribute to cost reductions, although widespread standardisation has been deemed highly unlikely (Wesselkämper & Von Delft, 2024). Alternatively, recycling plants could specialise in specific battery types, which may improve overall economic efficiency.

Transport represents a significant cost component of EV battery recycling, accounting for between 2 % and 13 % of the total recycling costs (Lander et al., 2021). Approximately 80 % of the global EV battery recycling capacity is located in East Asia, while the EU accounts for just under 2 % of the global capacity (Zhao and Kaur, 2025; IEA, 2024b). Developing a domestic EU downstream value chain would therefore offer opportunities for substantially reducing transport-related costs (Tankou et al., 2023). However, the economic viability of such a strategy would depend not only on the profitability of the pathway itself but also on indirect factors such as the high energy prices faced in EU Member States.

¹⁷ Schlott et al. (2025) estimate profit margins at 0.3–2.8 EUR/kg for hydrometallurgy and 0.4–3.4 EUR/kg for pyrometallurgy.

Recycling plant viability

Ensuring a sufficient and continuous flow of EVBs to recycling plants is critical to their economic viability (IEA, 2025e). Without this, the feasibility of the entire process could be undermined. Current volumes of EoL EVB packs are insufficient to support the commercial viability of recycling plants, with many EU plants operating at less than 10 % of their capacities (Cattani et al., 2025), and thus remaining largely underutilised. Lander et al. (2021) suggest that the minimum annual throughput for EVB recycling plants should be approximately 7 000 t/year for hydrometallurgical processes and 17 000 t/year for pyrometallurgical processes.

The recent significant growth in EV sales across the EU has led to the current EV fleet reaching 11.1 million¹⁸ vehicles (European Commission, 2025). However, these are mostly in their first operational cycle¹⁹, so it is unlikely there will be a high availability of feedstock for recycling in the near future. Significant volumes of EVB packs are expected to start reaching their EoL around 2030 (IEA, 2023). Beyond that point, recycling plants are expected to become increasingly profitable. This is reflected in the investments being made in scaling up the EU's recycling capacity. Combined plant capacities in the EU are expected to increase from the current 436 000 t/year to 789 000 t/year, according to announced projects. Refer to Annex B for a complete list of existing and announced recycling plants.

4.2. REPURPOSING

From an economic perspective, pursuing a second-life pathway would need to compete directly with new batteries (Patel et al., 2024). At a practical level, this means they would need to be priced lower than new ones to provide an incentive to consumers to choose them over new batteries. This section explores these aspects.

4.2.1. Economic competitiveness

The economic viability of repurposed EVBs depends on a range of case-specific factors. These include second-life application, their RUL, SoH, SoC degradation rate, and ageing, both calendar and cyclic, all of which influence the viability of EVBs for second-life use (Al-Alawi et al., 2022; Liekowski et al., 2024; Dong et al., 2023). These factors, in conjunction with the battery chemistry, investment risk, and utilisation characteristics, will ultimately impact the market price at which second-life EVBs are sold (Patel et al., 2024; Schulz-Mönninghoff & Evans, 2023).

¹⁸ Considers both pure battery electric vehicles and plug-in hybrid electric vehicles (PHEVs).

¹⁹ It has been reported that EVBs' first life may last up to 40% longer than previously expected (Geslin et al., 2024), reducing the rate of SoH degradation and delaying their entry into end-of-life stages.

A favourable techno-economic appraisal is required for each specific application to justify investments in repurposed battery adoptions, as not all repurposed EVBs may be fit for all purposes. Net present value (NPV) is typically used as an indicator for this, where a positive NPV indicates that break-even is achieved, projecting future cash inflows. A negative NPV indicates economic loss from investments. Studies have exhibited high variability in NPV. For instance, Bai et al. (2019) found positive NPV for repurposed batteries when used in some commercial and industrial PV-BESS industrial applications, but negative NPV for residential PV-BESS use²⁰ – showcasing the need for case-by-case assessments.

The Levelised Cost of Storage (LCOS) indicator is widely adopted as a metric to evaluate the costs of battery storage. It incorporates capital and operating expenses, as well as the battery's performance over its second life. Steckel et al. (2021) derived LCOS estimations at 212 EUR/MWh for new EVBs and at 252-296 EUR/MWh for second-life EVBs²¹. Despite lower upfront costs in the market, this indicates that second-life batteries may exhibit lower techno-economic performance than their first-life counterparts, depending on the applications.

With respect to the payback period, which expresses the time required to recover investments, it must remain below the RUL of second-life batteries for adoption to make economic sense. In some applications, second-life batteries can hold shorter payback periods than new batteries, owing to their lower upfront and sunk²² costs.

The payback periods of second-life EVBs directly depend on the market price at which they are purchased, the specific application and usage characteristics, and the revenue streams available. Payback periods can demonstrate high variability depending on these conditions. However, there is consensus that grid service applications, e.g. frequency regulation and energy arbitrage, showcase the most favourable business case – estimated at 3-5 years by Lehmusto and Santasalo-Aarnio (2025). PV applications show longer payback periods, extending beyond 10 years for residential applications, but improving for utility-scale plants.

Investing in a second-life battery carries a high degree of risk surrounding the battery's RUL. Concerns that it may be insufficient to recover the initial investment may deter investors' interest, especially in applications with lengthy payback periods. Standardised

²⁰ This is due to the differences in the load profile.

²¹ These values are only indicative and cannot be generalised. Other than variability in specific applications, granular factors such as PV power generation differences in the case of PV-BESS applications significantly impact LCOS values.

²² EV battery manufacturing costs are already 'paid for' during the first life application.

methodologies for SoH and SoC reporting under the Battery Regulation can help stimulate confidence and encourage investments.

Price margin between new and repurposed batteries

For second-life batteries to be economically viable, the market price of a repurposed battery, i.e. the purchase price of the end-of-first-life EVB, including its refurbishment cost, must not exceed the retail price of a new battery itself. A sufficient price margin between repurposed and new batteries must be sustained in the long term to justify investments into developing the repurposing route. There have been varied suggestions about the minimum requirement; for example, Rallo et al. (2022) have estimated it at 50 %, while Mathews et al. (2020) establish that a 60 % price margin would be necessary to make second-life EVBs economically attractive.

An important aspect to consider is that the retail price of new LIB packs has plummeted from over 1 000 EUR/kWh in the 2000s to around 100 EUR/kWh in 2025. Prices dropped rapidly between 2010 and 2015 as economies of scale began to take effect. More recently, the rate of reduction has decreased and even reversed in 2022 due to hikes in lithium commodity prices. Since 2023, however, battery pack prices have resumed their downward trend, falling by a further 25 %. Recent developments in new battery pack prices are shown in Figure 5. Due to ongoing technological progress and market competition, cost reductions are expected to continue over the coming years (Goldman Sachs, 2024), although the extent remains uncertain.

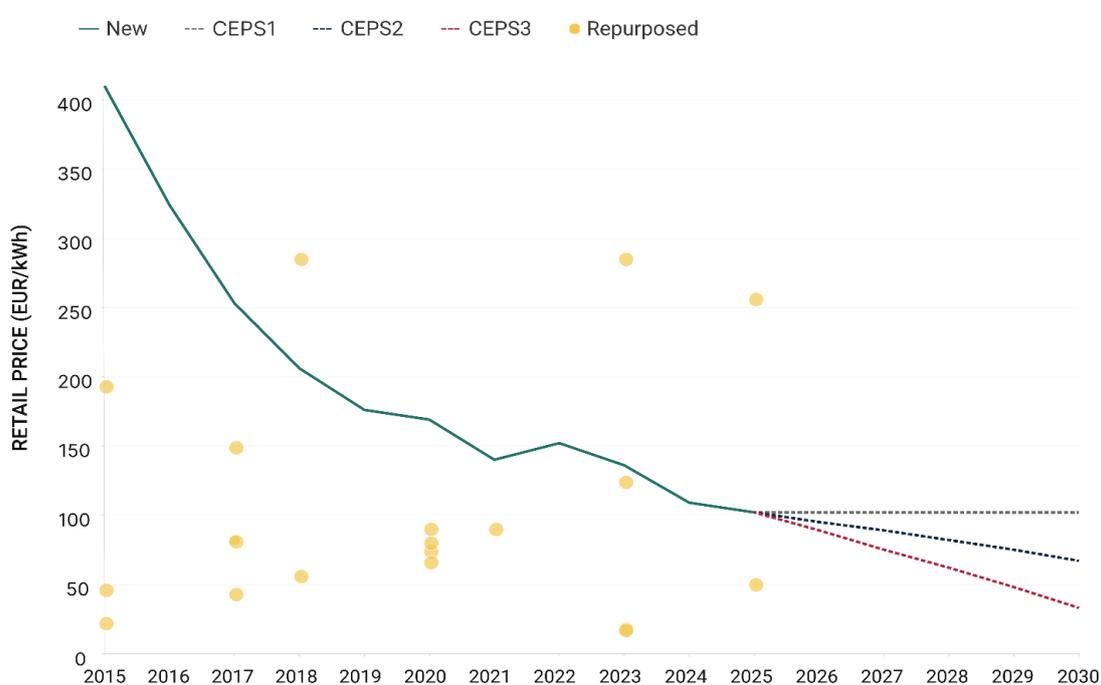
Studies report highly inconsistent estimates of market prices for second-life EVBs, ranging from as low as 18 EUR/kWh to 287 EUR/kWh. This high variability reflects differences in battery characteristics and refurbishment requirements for second-life use. No clear trend in price reduction can be drawn from the available data. While repurposed battery pack prices may start declining in the coming years, these must achieve a significant degree and be generalised and scaled across the sector for repurposing to become an economically viable option.

Because the rate of price reductions for new batteries has outpaced that of repurposed batteries, the price margin between these two has narrowed, making competition between repurposed and new batteries increasingly difficult. Analyses by Liekowski et al. (2024) and McKinsey (2023) indicate that average second-life battery prices may only be about 25 % to 30 % lower than that of new batteries – insufficient to meet the estimates about minimum price margin requirements outlined earlier. To ensure these are achieved, the battery repurposing sector must accelerate cost reductions in refurbishment. Although challenging due to ongoing price declines for new batteries, insufficient second-life price reductions could render them more expensive than new LIBs

in the long term²³. This would limit their economic and technological competitiveness in the market.

To better illustrate this picture, we developed indicative scenarios for upper-limit second-life EVB pack prices relative to new EVB pack price scenarios. This enabled us to estimate future cost reduction needs for second-life batteries to remain competitive in 2030. Our scenarios quantify this at three levels (Figure 5). Refer to Annex D for details on the methodology used.

Figure 5: Historical retail prices of new and repurposed lithium-ion EVBs, along with indicative scenarios to 2030.



Source: Author's own elaboration. Data and sources available in Annex D.

Notes: CEPS' battery pack retail price scenarios to 2030 are shown. The CEPS1 scenario (conservative) assumes no further cost reductions in new battery pack prices. The CEPS2 scenario (intermediate) assumes new battery pack price reductions will continue at half the current rate. The CEPS3 scenario (base case) assumes that cost reductions will continue at the current rate. New battery pack retail price data reflect average values over the time series. Repurposed battery retail prices indicate the range of retail prices of repurposed end-of-first-life EVBs, only. Other sources of repurposed EVBs may exist, but are not considered here. All values are based on compilations from our research.

In the CEPS1 scenario, which assumes no further cost reductions in new battery pack prices from 2025, new battery packs in 2030 would be priced at 102 EUR/kWh, meaning that second-life batteries must be priced below 51 EUR/kWh to be competitive. The

²³ This is dependent on the future market prices of new battery packs.

CEPS2 scenario assumes that new battery pack price reductions will continue at half the current rate, reaching 67 EUR/kWh by 2030. Under this consideration, second-life battery packs should aim to be sold at below 34 EUR/kWh to remain competitive. Finally, scenario CEPS3 assumes price reductions will continue at the current rate. Under this consideration, new battery packs would be priced at 34 EUR/kWh in 2030. Second-life batteries should therefore adhere to prices below 17 EUR/kWh. It is worth noting that while battery pack prices have dropped substantially, they appear to have started plateauing in recent years, making further major declines less likely.

As outlined, the viability of second-life batteries is not only dependent on their ability to reduce their own price, but also to maintain a sufficient difference relative to new battery packs sold in the market.

Narrowing price margins suggests that second-life batteries may remain economically viable primarily in applications with lower repurposing costs, such as off-grid stationary energy storage, while applications with higher repurposing costs could face greater economic challenges.

Cost component breakdown

The market price of second-life battery packs is largely driven by the cost of the battery itself, which is determined by its salvage value. The battery alone accounts for approximately 56–60 % of the final selling price (Patel et al., 2024). This component is dependent on the battery's value following its first life, which in turn depends on the specific battery's state. This cost component is considered external and cannot be directly controlled by the repurposing sector.

The second-most prominent cost component, accounting for 13–25 % of the final price, is attributed to repurposing activities. These involve multiple stages, including collection, discharge, assessment, disassembly and reconfiguration (Al-Alawi et al., 2022; Caldini et al., 2024). Although efforts are being made to increase the automation of repurposing processes, refurbishing still involves manual work to a large extent. Labour costs comprise a significant proportion of these expenses. The greater the need for reconfiguration and disassembly, the higher the labour costs. Increasing the level of disassembly, i.e. to the module and cell level (in that order), has implications for the labour costs. Ideally, battery packs could enter their second-life application with no or very limited disassembly requirements, although this is not feasible for most applications.

Targeting second-life applications that do not require extensive disassembly would cut the labour costs associated with this, enabling lower selling prices to be unlocked. Alternatively, this could also be achieved by scaling up automated processing in

disassembly and testing²⁴ as shown in the BATRAW project. It is estimated that fully automated processes could save up to 97 % of disassembly costs (Gu et al., 2024).

Shen (2024) estimates repurposing costs between 11 EUR/kWh and 47 EUR/kWh – highlighting the substantial price reductions that second-life battery packs could achieve if these costs were minimised or avoided. Such reductions would support the economic competitiveness of repurposed batteries.

²⁴ Access to complete battery operational data improves the accuracy and precision for battery state assessments. In cases where such data are not available, testing decommissioning parameters can be required as part of the repurposing process, incurring additional processing times and costs, which can increase the final retail price (Shen, 2024).

CONCLUSIONS AND ENABLING CONDITIONS

As policy, technological and economic factors converge to drive EVs into the mainstream, implementing circular applications for battery packs that have reached the end of their first operating life emerges as a necessary foundation for managing the environmental impacts of batteries. Circular applications and particularly recycling are becoming increasingly important due to geopolitical considerations and the critical economic value of materials contained in LIBs, the dominant battery technology in current applications. The EU has been at the forefront of international regulatory efforts to promote circularity applications for batteries and has provided financial support to various demonstration projects, including BATRAW.

From a scaling-up perspective, both principal circularity applications – namely recycling and second-life use – are still in the early stages of development in the EU. Regarding recycling, the three primary routes – pre-treatment, pyrometallurgical and hydrometallurgical recycling – which are often used in combination, exhibit varying levels of technological readiness. The announced battery material recovery and recycling projects that we have attempted to document in this report indicate an expansion trend, although these activities remain concentrated in a limited number of EU countries. At the same time, our interviews with companies across the full battery circularity value chain reveal several policy, economic and market-related challenges that will need to be addressed in the coming years.

A cluster of these challenges relates to the evolving EU policy landscape, with the EU Batteries Regulation serving as a key cornerstone. While companies generally view the Regulation as an important tool for promoting circularity in the sector, it also presents several implementation challenges, with the rules and requirements related to the battery passport being one example. Delays in introducing secondary legislation to clarify certain provisions only add to this challenge.

The economics of battery recycling also remain difficult. For recycling to be viable in the long term, revenues obtained from selling recovered metals must exceed the costs incurred during the recycling process. Factors such as volatility in metal commodity prices and the shift towards cheaper LFP batteries with lower recyclable value compared to NMC chemistries further complicate the economic case for battery recycling. Further cost reduction opportunities will therefore need to be sought in areas including labour costs (for example, through automated processes, as observed in BATRAW), battery standardisation and the application of design-for-recycling principles.

Second-life applications for batteries that have reached the end of their first operational life in EVs are also emerging in the EU. Such applications involve the repurposing of

battery packs or modules and their use as storage systems in residential, commercial or industrial settings. Our review indicates a growing interest in such applications, often supported by EU-funded projects, although EV repurposing remains less mature compared to recycling. Similar to recycling, second-life applications face policy, economic and market-related challenges that limit their widespread use.

In the policy realm, regulatory uncertainties such as the allocation of responsibilities and liabilities for second-life batteries often discourage companies from investing in second-life markets. Overall, however, the Batteries Regulation and the battery passport were perceived by companies as positive drivers for second-life use, especially if these ambiguities are addressed and when repurposing companies gain access to BMS data. The underdeveloped standardisation landscape for second-life applications was another key challenge identified in the interviews. One example concerns the lack of harmonised standards defining the parameters and methodologies for assessing a battery's SoH and other performance indicators across different applications.

Regarding the economic case for second-life battery use, batteries pursuing a second-life pathway must compete with first-life batteries and therefore need to be offered at a lower price than new batteries. To create a viable business environment for such applications, a sufficient price margin between repurposed and new batteries must also be sustained in the long term. Our analysis shows that this will be a difficult task in practice, especially since the retail prices of new LIB packs have declined significantly in recent years. As such, further cost reductions for second-life applications would need to be achieved through, for instance, greater automation of repurposing processes or by focusing on applications with lower repurposing costs, such as off-grid stationary energy storage.

Based on our analysis, we identify three key enabling conditions for scaling up circularity applications for EVBs in the EU:

Support effective implementation of the EU policy framework underpinned by the Batteries regulation: With the EU Batteries Regulation as a cornerstone, a revised and dedicated policy framework has been put in place to support circularity applications for EVBs. As shown by our interviews with companies spanning all battery circularity segments, the Regulation, with its various binding requirements, including those related to the battery passport, has the potential to act as a key driver of circularity in the sector. However, for the Regulation to fulfil its potential, further support will be needed to ensure its effective implementation. Key priorities include the timely adoption of secondary legislation and the provision of technical guidance to increase regulatory certainty regarding different provisions of the Regulation. Examples of areas requiring clarification include how data handling and sharing obligations will be managed as

batteries move through different life-cycle stages, how carbon footprint calculations will be performed, the methodology for calculating and verifying recycled content and the liability framework and procedures governing batteries transitioning to repurposing applications.

Strengthen financial support for the scaling up of battery circularity applications in the EU: Our research shows that the challenging economics of battery circularity and second-life applications constitute one of the key barriers to scaling up such solutions in the EU. Further cost reduction opportunities will need to be explored to improve the economic viability of these processes. Providing financial support to such projects—especially during the initial launch phase and until they reach sufficient scale—will be essential. This is especially important due to the intense global competition and the fact that the EU is currently falling behind in several segments of the battery circular value chain. In addition to programmes such as Horizon Europe and financing provided by the European Investment Bank, financial support mechanisms should be further reinforced to accelerate the development and deployment of battery circularity solutions. This will be especially relevant in the context of the next Multiannual Financial Framework for the 2028–2034 period, which will play a key role in supporting these efforts.

Harmonise standardisation landscape impacting EVBs' circularity: While standardisation efforts are ongoing at both the international and EU levels, our research points out that several gaps remain and will need to be addressed in the coming years to create a solid foundation for innovation in battery circularity. A primary area of focus is the standardisation framework underpinning the implementation of the battery passport, which will need to progress to clarify aspects such as data interoperability, data integration and verification. Establishing standards in these areas would also help increase confidence among supply chain actors when sharing relevant data. Another key area is the lack of harmonised standards for the SoH and other battery performance indicators, which hinders the assessment of battery condition and the identification of the most suitable next step – whether reuse, repurposing, or recycling – after their first life. Additionally, the limited standardisation of battery pack design makes dismantling processes more difficult.

ANNEXES

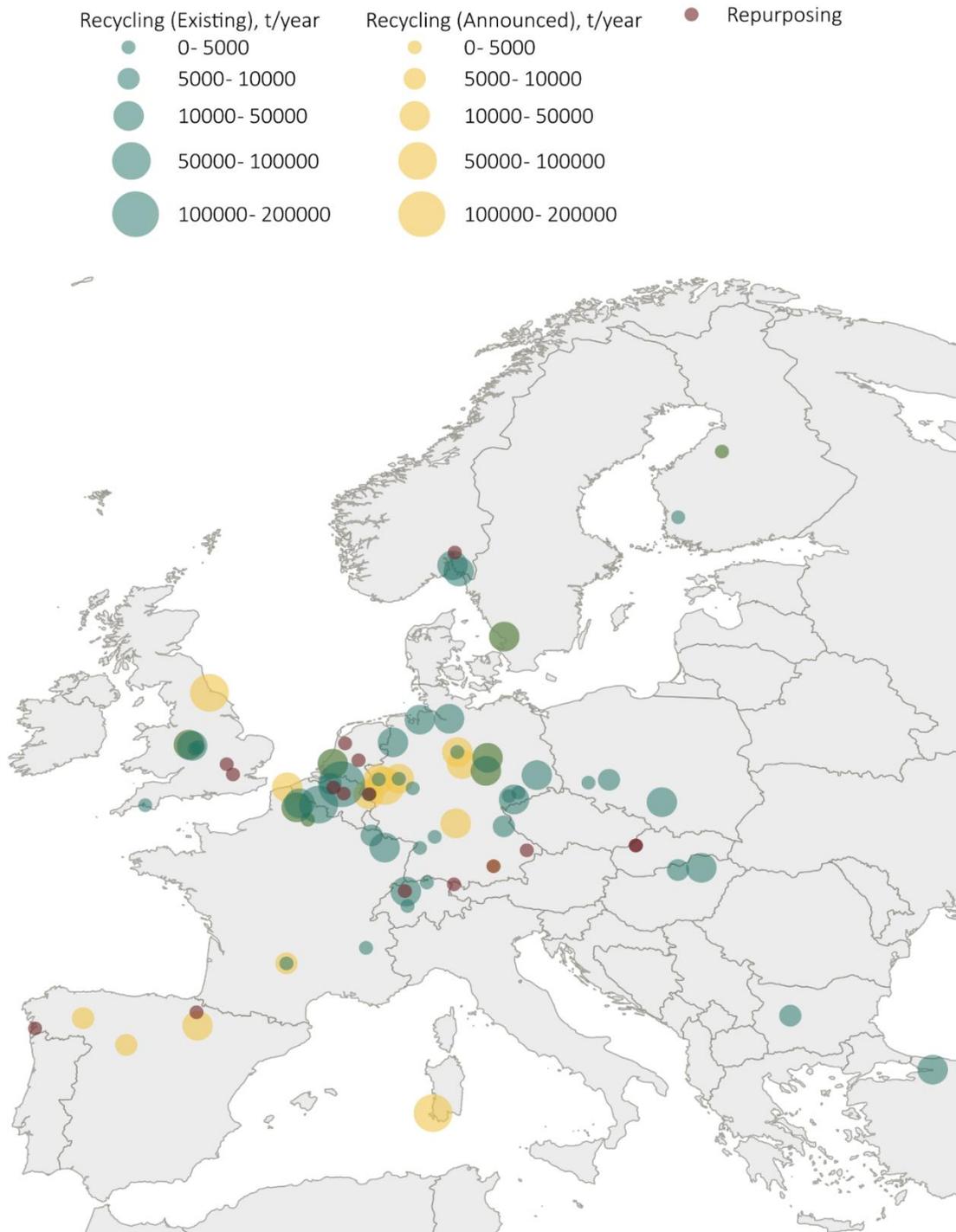
ANNEX A: LIST OF INTERVIEWEES

Number	Sector	Actor's Role
1	Battery evaluation, disassembly and second-life applications	1. Lead Engineer 2. Strategic Business Analyst 3. Process Engineer 4. Innovation Manager
2	Auto manufacturer	1. Developer of Innovation
3	Auto manufacturer	1. Product Sustainability Leader 2. Product Sustainability Engineer 3. Product Sustainability Engineer 4. Product Sustainability Team Member 5. Product Sustainability Team Member
4	End-of-life management & recycling of batteries	1. Head of R&D 2. Innovation Researcher 3. Researcher – R&D
5	Collection of batteries	1. Manager
6	Supply chain traceability and circularity services	1. Co-founder 2. Project Lead
7	Supply chain traceability and circularity services	1. Director of Business Development
8	Battery innovation service provider	1. Chief of Staff 2. Founder
9	Recycling & refining	1. Director of Government Affairs 2. Director of Public Affairs
10	Battery material production & battery recycling	1. Senior Manager
11	Manufacturer of automotive parts & e-bike batteries	1. Head of Office 2. Head of Battery Development
12	Environmental services	1. Project lead
13	Standards & supply chain traceability	1. Principal Policy Officer 2. Senior Manager 3. Manager of Sustainability
14	Battery recycling	1. Chief Executive Officer

15	End-of-life management & second-life applications	1. Head of Environmental Management 2. Business Development Coordinator
16	Auto manufacturer & battery cell production	1. Group Project Manager 2. Corporate External and Government Relations 3. Head of Environment and Technical Regulation 4. Responsible for Batteries Regulation and LCA of EV batteries
17	Dismantling of vehicles & extraction of batteries	1. Head of Innovation
18	Second-life applications	1. Co-founder & Chief Executive Officer
19	Development of battery recycling machinery	1. Recycling Engineer
20	Robotic disassembly of batteries	1. Project Manager
21	Robotic disassembly of batteries	1. Principal Lecturer 2. R&D specialist 3. R&D coordinator
22	Circular solutions for energy storage systems	1. Chief Technology Officer
23	Mining & recycling	1. Head of Financing Strategy
24	Non-profit association	1. Clean Vehicles Manager
25	Auto manufacturer	1. Batteries regulation specialist
26	Auto manufacturer	1. LCA Specialist
27	Industry association	1. Sustainability Manager 2. General Manager
28	Technological association	1. Senior Sustainability Researcher 2. Researcher
29	Research institute	1. Research Associate

ANNEX B: OVERVIEW OF BATTERY RECYCLING AND REPURPOSING FACILITIES IN EUROPE

Figure B1: Combined map with existing and announced recycling plants in Europe, along with existing repurposing facilities.



Source: Author's elaboration based on initial data compilation from [Battery-News \(2025\)](#) and [Fraunhofer \(2024\)](#), complemented by further desk research. Facilities lacking capacity specifications have been excluded.

Table B1: Existing EV Battery Recycling Plants

Country	Location	Plant Operator	Existing Capacity (t/year)
Belgium	Dour	BE VOLT (AVESTA)	70 000
	Hoboken	Umicore	7 000
	Olen	Aurubis	135 000
Bulgaria	Medet	Altium	8 000
Finland	Nivala	AkkuSer	800
	Harjavalta	Fortum	3 000
France	Harnes	Li-Cycle (Glencore)	10 000
	Saint Quentin	SNAM	1 900
	Grenoble	SK Tes	600
	Saint-Laurent-Blangy	Battri	15 000
	Viviez	SNAM	1 000
	Dieuze	Veolia	10 000
	Amneville	Cedilor (Veolia)	7 000
Germany	Krefeld	Accurec	4 500
	Schwarzheide	BASF	15 000
	Aachen	Cylib	120
	Wendeburg	Duesenfeld	3 000
	Hettstedt	Ecobat	10 000
	Hamburg	EMR	25 000
	Zwickau	Erlos	3 500
	Kirchartd	Fortum	3 000
	Chemnitz	Kyburz	2 000
	Magdeburg	Battery Lifecycle Company (BLC)	10 000
	Kuppenheim	Primobius (Mercedes-Benz)	2 500

	Aue	Nickelhutte Aue (NHA)	10 000
	Hilchenbach	Primobius (Mercedes-Benz)	3 650
	Hagen	Pure Battery Technologies	2 500
	Bremerhaven	Redux Recycling	10 000
	Meppen	Relion Bat	30 000
	Wernberg-Koblitz	ROTH	9 000
Hungary	Alsószolca	Andrada	10 000
	Bátonyterenye	SungEel Hitech	7 000
Netherlands	Rotterdam	SK Tes	10 000
Norway	Fredrikstad	Hydrovolt	12 000
	Moss	Li-Cycle (Glencore)/ECO STOR	10 000
Poland	Legnica	Royal Bees	3 600
	Zawiercie	AE Elemental	12 500
	Bukowice	POSCO	7 000
Sweden	Halmstad	STENA	10 000
Switzerland	Wimmis	Batrec	4 000
	Freienstein	Kyburz	200
	Biberist	Librec	12 000
Türkiye	Kocaeli	Exitcom	10 000
United Kingdom	Birmingham	EMR	2 000
	Plymouth	Altium	100
	Darlaston	Ecobat	15 000
	Wolverhampton	Recyclus Group	22 000
	Minworth	Veolia	5 000
Total Europe	-	-	528 970
Total EU-27	-	-	436 670

Source: Based on [Battery-News \(2025\)](#) and [Fraunhofer \(2024\)](#), complemented by the authors' desk research to verify and update information on facilities.

Table B2: Announced EV Battery Recycling Plants

Country	Location	Plant Operator	Announced New Capacity (t/year)
Finland	Nivala	AkkuSer	2 200
France	Saint Quentin	SNAM	3 100
	Saint-Laurent-Blangy	Battri	20 000
	Viviez	SNAM	5 000
	Dunquerque	Orano	20 000
Germany	Krefeld	Accurec	15 500
	Randersacker	CellCircle	25 000
	Aachen	Cylib	9 880
	Dormagen	Cylib	60 000
	Wendeburg	Duesenfeld	9 000
	Hettstedt	Ecobat	15 000
	Goslar	H.C. Starck Tungsten	20 000
	Aachen	Iondrive	3 000
	Magdeburg	Battery Lifecycle Company (BLC)	20 000
	Hagen	Pure Battery Technologies	12 500
	Munich	Tozero	1 500
Italy	Portovesme	Li-Cycle (Glencore)	50 000
Netherlands	Rotterdam	SK Tes	30 000
Spain	Cubillos del Sil	Novoltio (Endesa/Urbaser)	8 000
	Valladolid	Ilunion	6 000
	Caparroso	BeeCycle (SungEel Hitech)	10 000
Sweden	Halmstad	STENA	20 000
United Kingdom	Teesside	Altium	50 000
	Wolverhampton	Recyclus Group	19 500

Total Europe	-	-	422 180
Total EU-27	-	-	352 680

Source: author's elaboration based on initial data from [Battery-News \(2025\)](#) and [Fraunhofer \(2024\)](#), complemented by the authors' desk research to verify and update information on facilities.

Table B3: EV Battery Repurposing Facilities

Country	Location	Plant Operator
Austria	Woldfurt	E. Battery Systems
Belgium	Tienen	Watt4ever
	Mechelen	Octave
Germany	Munich	STABL
	Iggensbach	CarBatteryReFactory (Fenecon)
	Aachen	Voltfang
Netherlands	Zwaag	EccarACCU
	Ede	Spiers New Technologies
Norway	Oslo	ECO STOR
Slovakia	Dubnica nad Vahom	ZTS VV
	Trenčín	Eaq
Spain	Orcoyen	BeePlanet
	Vigo	Little Energy
Switzerland	Biberist	Libattion
United Kingdom	Luton	Lithium Battery Recycling Solutions (Cawleys Group)
	London	Zebobe

Source: Author's elaboration based on initial data in [Battery-News \(2025\)](#), complemented by the authors' desk research to verify and update information on facilities.

ANNEX C: RECYCLABLE VALUE ASSESSMENT OF LIB PACKS

Methodology

To determine and compare the ‘recyclable value’ of LIB packs, we calculated the ‘weighted value potential’ across both LFP and NMC battery chemistries. These calculations are based on the average lithium, cobalt and nickel concentrations contained within each of the battery types, as reported in IRENA (2024).

Our calculations consider specific lithium compound compositions, where the lithium carbonate commodity price is considered for LFP batteries and the lithium hydroxide commodity price is applied to the NMC chemistry.

Calculations use the most recent publicly available metal commodity prices, where the data for lithium hydroxide is representative of the November-December 2025 period, January-June 2025 for lithium carbonate, December 2025-January 2026 for cobalt, and January-December 2025 for nickel. Details on each of the datasets can be found in Table C1.

Table C1: Details of commodity price data used in calculations

Metal	Data Type	Source	Period
Lithium hydroxide	Month 2 closing price (day-delayed) as of 8 January 2026	LME (2026a)	November–December 2025
Lithium carbonate	CIF Asia prices	Provided by BMI	January–June 2025
Cobalt	3-month closing price (day-delayed) as of 27 January 2026	LME (2026b)	December 2025–January 2026
Nickel	2025 Annual Average	World Bank (2026)	January–December 2025

Although both LFP and NMC batteries contain additional metals and non-metallic materials, this analysis focuses solely on the metals listed above. As a result, our calculations are representative only of these materials and the specified time frames, and should not be interpreted as the total value of LFP and NMC LIB packs. Furthermore, calculations assume metals are recoverable at a 100 % rate.

Weighted value potential is calculated as the product of metal concentration (kg/kWh) and commodity price (EUR/kg), expressed in EUR/kWh. All values are expressed in 2025 EUR terms, converted using European Central Bank conversion rates.

Results

Table C2: Weighted Value of LFP and NMC batteries, calculated from metal concentrations and commodity prices

Metal	Commodity Price (EUR/kg)	Metal Concentration (kg/kWh)		Weighted Value of Metals (EUR/kWh)	
		<i>LFP</i>	<i>NMC</i>	<i>LFP</i>	<i>NMC</i>
Lithium hydroxide	9.18	-	0.63	-	5.78
Lithium carbonate	8.51	0.53	-	4.51	-
Cobalt	49.71	-	0.14	-	6.96
Nickel	13.39	-	0.58	-	7.76
Total	80.79	0.53	1.35	4.51	20.51

Source: Calculations based on data from IRENA (2024), LME (2026a), LME (2026b), World Bank (2026).

ANNEX D: METHODOLOGY AND DATA FOR EVB PRICE PROJECTIONS FOR NEW AND REPURPOSED EVBS

Methodology

As part of our assessment of the economic viability of repurposed batteries, we developed price scenarios through 2030 based on recorded prices of new LIB packs from 2020 to 2025. Complete (2015 to 2025) price data for new lithium battery packs were compiled from 23 sources, averaged on an annual basis, as shown in Table D1.

In parallel, 19 retail price data points were collected for repurposed battery packs from six sources in the literature. These values have been reported individually by reference year in Table D2, but have not been normalised by SoH, RUL or any other parameter. These involve a wide range of applications and therefore showcase the current range of retail prices that could be present in the market. Due to the limited and heterogeneous nature of the data, no clear price trend could be drawn.

Results

Table D1: Historical data for new LIB pack prices

Year	Historical average new battery pack retail prices (EUR/kWh)	Battery pack retail price scenarios					
		CEPS1		CEPS2		CEPS3	
		New (EUR/kWh)	Maximum repurposed requirement (EUR/kWh)	New (EUR/kWh)	Maximum repurposed requirement (EUR/kWh)	New (EUR/kWh)	Maximum repurposed requirement (EUR/kWh)
2015	410	-	-	-	-	-	-
2016	324	-	-	-	-	-	-
2017	253	-	-	-	-	-	-
2018	206	-	-	-	-	-	-
2019	176	-	-	-	-	-	-
2020	169	-	-	-	-	-	-
2021	140	-	-	-	-	-	-
2022	152	-	-	-	-	-	-
2023	136	-	-	-	-	-	-

2024	109	-	-	-	-	-	-
2025	102	-	-	-	-	-	-
2030	-	102	51	67	34	34	17

Source: Al-Alawi (2022), BloombergNEF (2021), BloombergNEF (2022), BloombergNEF (2023), BloombergNEF (2024), Burke et al. (2024), Dong et al. (2023), Ember (2025), Fraunhofer ISI (2025), Goldman Sachs (2023), Goldman Sachs (2024), IEA (2024b), Li et al. (2017), Mauler et al. (2021), Neubauer et al. (2015), NREL (2024), Nykvist and Nilsson (2015), Penisa et al. (2020), S&P Global (2022), S&P Global (2025b), US Department of Energy (2023).

Table D2: Historical data for repurposed LIB pack prices

Year	Repurposed Battery Retail Price (EUR/kWh)			
2015	194	47	23	-
2016	-	-	-	-
2017	82	44	150	-
2018	286	57	-	-
2019	-	-	-	-
2020	91	75	67	81
2021	91	-	-	-
2022	-	-	-	-
2023	125	286	19	18
2024	-	-	-	-
2025	51	257	-	-

Source: Dong et al. (2023), Li et al. (2017), Madlener and Kirmas (2017), Moreira et al. (2021), Negium and Wang (2024), Tankou et al. (2023).

According to our analysis, the average retail price of new battery packs in 2025 was 102 EUR/kWh. Our projections, under three scenarios – CEPS1, CEPS2, and CEPS3 – represent conservative, intermediate and base case scenarios, respectively, for new battery pack prices by 2030.

In the CEPS1 scenario, the retail price of new battery packs remains constant through 2030, with no further reductions relative to the 2025 level. The CEPS2 scenario assumes a reduced-price decline rate, equal to 50 % of the rate observed between 2020 and 2025 (i.e. 6.7 EUR/kWh/year). The CEPS3 scenario assumes that the price reduction rate observed between 2020 and 2025 continues, corresponding to a reduction of 13.4 EUR/kWh/year.

The economic viability of repurposed batteries depends on limiting their market price to approximately 50-60 % of new battery pack prices. We here adopted an assumption of a 50 % price margin. Based on this assumption, we estimated the maximum 2030 retail price at which repurposed EV battery packs would remain competitive relative to new battery packs: 51 EUR/kWh for CEPS1, 34 EUR/kWh for CEPS2, and 17 EUR/kWh for CEPS3.

All prices are expressed in 2025 EUR terms, converted using European Central Bank conversion rates.

REFERENCES

- Ahmed, S., Verhulst, E. and Boks, C. (2025), 'Second life of electric vehicle lithium-ion batteries from a sustainable business model perspective', in Fukushima, S., Nonaka, T., Kobayashi, H., Tokoro, C. and Yamasue, E. (eds), *EcoDesign for Circular Value Creation: Volume I*, Springer Nature Singapore, Singapore, pp. 229-243. https://doi.org/10.1007/978-981-97-9068-5_15
- Akram, M.N. and Abdul-Kader, W. (2024), 'Repurposing second-life EV batteries to advance sustainable development: A comprehensive review', *Batteries*, Vol. 10, No 12, 452. <https://doi.org/10.3390/batteries10120452>
- Al-Alawi, M.K., Cugley, J. and Hassanin, H. (2022), 'Techno-economic feasibility of retired electric-vehicle batteries repurpose/reuse in second-life applications: A systematic review', *Energy and Climate Change*, Vol. 3, 100086. <https://doi.org/10.1016/j.egycc.2022.100086>
- Albertsen, L., Richter, J.L., Peck, P., Dalhammar, C. and Plepys, A. (2021), 'Circular business models for electric vehicle lithium-ion batteries: An analysis of current practices of vehicle manufacturers and policies in the EU', *Resources, Conservation and Recycling*, Vol. 172, 105658. <https://doi.org/10.1016/j.resconrec.2021.105658>
- Ali, A., Shoaib, A., Tasbirul, I.M., Qadir, S.A. and Shahid, M. (2025), 'Sustainable recycling of end-of-life electric vehicle batteries: EV battery recycling frameworks in China and the USA', *Recycling*, Vol. 10, No. 2, p. 68.
- Baars, J., Domenech, T., Bleischwitz, R., Melin, H.E. and Heidrich, O. (2021), 'Circular economy strategies for electric vehicle batteries reduce reliance on raw materials', *Nature Sustainability*, Vol. 4, pp. 71-79.
- Bai, B., Xiong, S., Song, B., & Xiaoming, M. (2019), 'Economic analysis of distributed solar photovoltaics with reused electric vehicle batteries as energy storage systems in China', *Renew. Sustain. Energy Rev*, Vol. 109, pp.213–229. <https://doi.org/10.1016/j.rser.2019.03.048>.
- BloombergNEF (2021), 'Hitting the EV Inflection Point', Bloomberg Finance, https://tecdn.ams3.cdn.digitaloceanspaces.com/files/2021_05_05_Electric_vehicle_price_parity_and_adoption_in_Europe_Final.pdf
- BloombergNEF (2022), 'Lithium-ion battery pack prices rise for the first time to an average of \$151/kWh', *Bloomberg New Energy Finance*, <https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/>
- BloombergNEF (2023), 'Lithium ion battery pack prices hit record low of 139 kWh', Bloomberg New Energy Finance, <https://about.bnef.com/insights/clean-energy/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/>,
- BloombergNEF (2024), 'Lithium-ion battery pack prices see largest drop since 2017, falling to \$115 per kilowatt-hour: BloombergNEF', *Bloomberg New Energy Finance*, <https://about.bnef.com/insights/commodities/lithium-ion-battery-pack-prices-see-largest-drop-since-2017-falling-to-115-per-kilowatt-hour-bloombergnef/>
- Bobba, S., Latunussa, C., Manni, F.M. and Mathieux, F. (2025), *Deep dive on critical raw materials for batteries in the EU*, Publications Office of the European Union, Luxembourg.

Burke, A. F., Zhao, J., & Fulton, L. M. (2024), 'Projections of the cost of light-duty battery-electric and fuel cell vehicles (2020-2040) and related economic issues', *Research in Transportation Economics*. Vol. 105, 101440, <https://www.sciencedirect.com/science/article/abs/pii/S0739885924000350>

Caldini, S., Macchiarelli, I., Unger, B., & Olsen, V.(2024), *Second life: Maximizing lifecycle value of EV batteries*, Arthur D. Little, <https://www.adlittle.com/en/insights/viewpoints/second-life-maximizing-lifecycle-value-ev-batteries>

Cattani, N. S., Weinert, C., Mussehl, V., Frieges, M., & Kampker, A. (2025). Economic and structural challenges of lithium-ion battery recycling in Europe: A stakeholder-based assessment. *Waste Management*, 205, 114962.

Colarullo, L. and Thakur, J. (2022), 'Second-life EV batteries for stationary storage applications in Local Energy Communities', *Renewable and Sustainable Energy Reviews*, Vol. 169, 112913. <https://doi.org/10.1016/j.rser.2022.112913>

Crenna, E., Gauch, M., Widmer, R., Wäger, P. and Hischer, R. (2021), 'Towards more flexibility and transparency in life cycle inventories for lithium-ion batteries', *Resources, Conservation and Recycling*, Vol. 170, 105619.

Curtis, T.L., Smith, L., Buchanan, H. and Heath, G. (2021), *A circular economy for lithium-ion batteries used in mobile and stationary energy storage: Drivers, barriers, enablers, and U.S. policy considerations*, NREL/TP-6A20-77035, National Renewable Energy Laboratory, Golden, CO.

da Silva, E.R., Lohmer, J., Rohla, M. and Angelis, J. (2023), 'Unleashing the circular economy in the electric vehicle battery supply chain: A case study on data sharing and blockchain potential', *Resources, Conservation and Recycling*, Vol. 193, 106969.

Dietz, C., Righetti, E. and Egenhofer, C. (2025), *Navigating the EV transition: Barriers and tools for shifting Europe to low-carbon mobility*, CEPS In-Depth Analysis No 2025-08, July.

DNV (2023), 'Battery recycling in Europe', DNV, <https://www.dnv.com/energy-transition/battery-recycling-in-europe/>

Dong, Q., Liang, S., Li, J., Kim, H. C., Shen, W., & Wallington, T. J. (2023), 'Cost, energy, carbon footprint benefits of second-life electric vehicle battery use', *iScience*, Vol. 26, No. 7, 107195, <https://www.sciencedirect.com/science/article/pii/S2589004223012725>,

Dunn, J., Kendall, A. and Slattery, M. (2022), 'Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts', *Resources, Conservation and Recycling*, Vol. 185, 106488.

Egle, L., Pierri, E., García John, E., García-Gutiérrez, P. and Gaudillat, P. (2024), *Technical recommendations for the targeted amendment of the European List of Waste entries relevant to batteries: support for the new batteries regulatory framework – WP8*, Publications Office of the European Union, Luxembourg, <https://data.europa.eu/doi/10.2760/7560598>

Ellen MacArthur Foundation (2026), *Leading the charge: Turning risk into reward with a circular economy for EV batteries and critical minerals*.

Ember (2025), *Global Electricity Review 2025*, Ember, <https://ember-energy.org/latest-insights/global-electricity-review-2025/>

European Commission (2025), 'European Alternative Fuels Observatory', *European Commission*, <https://alternative-fuels-observatory.ec.europa.eu/transport-mode/road/european-union-eu27/vehicles-and-fleet>

Farmer, A. and Watkins, E. (2023), *Managing waste batteries from electric vehicles: The case of the European Union and Japan*, Institute for European Environmental Policy.

Feng, J., Liu, W. & Chen, F. (2025), 'Moving towards a circular economy: a systematic review of barriers to electric vehicle battery recycling', *Sustainable production and consumption*, Vol. 54, pp. 241-260, <https://www.sciencedirect.com/science/article/pii/S2352550925000053>

Fonseca Guimarães, L., Soares Tenório, J. A., Vaccari, M., Romano Espinosa, D. C. and Botelho Junior, A. B. (2024), 'Characterization of Lithium-Ion Batteries from Recycling Perspective towards Circular Economy', *Minerals*, Vol. 14, pp. 878, <https://doi.org/10.3390/min14090878>

Fraunhofer ISI (2025), *Batteries for Electric Cars: Fact Check and Need for Action – An Update*, Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, https://www.isi.fraunhofer.de/content/dam/isi/dokumente/policy-briefs/2025-05_policy_brief_batteries_electric_cars_update_fact_check_action.pdf

Fuinhas, J.A., Koengkan, M., Leitão, N.C., Nwani, C., Uzuner, G., Dehdar, F., Relva, S. and Peyerl, D. (2021), 'Effect of battery electric vehicles on greenhouse gas emissions in 29 European Union countries', *Sustainability*, Vol. 13, No. 24, 13611.

Geslin, A., Xu, L., Ganapathi, D., Moy, K., Chueh, W. C., & Onori, S. (2025), 'Dynamic cycling enhances battery lifetime', *Nature Energy*, Vol. 10, pp.172-180, <https://www.nature.com/articles/s41560-024-01675-8>

Giosuè, C., Marchese, D., Cavalletti, M., Isidori, R., Conti, M., Orcioni, S., Ruello, M.L. and Stipa, P. (2021), 'An exploratory study of the policies and legislative perspectives on the end-of-life of lithium-ion batteries from the perspective of producer obligation', *Sustainability*, Vol. 13, No 20, 11154.

Goldman Sachs (2023), 'Electric vehicle battery prices are falling faster than expected', *Goldman Sachs*, <https://www.goldmansachs.com/insights/articles/electric-vehicle-battery-prices-falling>

Goldman Sachs (2024), 'Electric vehicle battery prices are expected to fall almost 50% by 2026', *Goldman Sachs*, <https://www.goldmansachs.com/insights/articles/electric-vehicle-battery-prices-are-expected-to-fall-almost-50-percent-by-2025>

Götz, T., Berg, H., Jansen, M., Adisorn, T., Cembrero, D., Markkanen, S. and Chowdhury, T. (2022), *Digital product passport: The ticket to achieving a climate-neutral and circular European economy?*, Wuppertal Institute for Climate, Environment and Energy, Wuppertal.

Gu, X., Bai, H., Cui, X., Zhu, J., Zhuang, W., Li, Z., Hu, X. and Song, Z. (2024), 'Challenges and opportunities for second-life batteries: Key technologies and economy', *Renewable and Sustainable Energy Reviews*, Vol. 192, 114191. <https://doi.org/10.1016/j.rser.2023.114191>

Gutsch, M. and Leker J. (2024), 'Costs, carbon footprint, and environmental impacts of lithium-ion batteries – From cathode active material synthesis to cell manufacturing and recycling', *Applied Energy*, Vol. 353, Part B, 122132

Haram, M.H.S.M., Lee, J.W., Ramasamy, G., Ngu, E.E., Thiagarajah, S.P. and Lee, Y.H. (2021), 'Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges', *Alexandria Engineering Journal*, Vol. 60, No 5, pp. 4517-4536.

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkim, R., Allan, W., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L. & Anderson, P. (2019), 'Recycling lithium-ion batteries from electric vehicles', *Nature*, Vol. 575, pp.75-86, <https://www.nature.com/articles/s41586-019-1682-5>

Helander, H. and Ljunggren, M. (2023), 'Battery as a service: Analysing multiple reuse and recycling loops', *Resources, Conservation and Recycling*, Vol. 197, 107091.

Hellström, M. and Wrålsen, B. (2024), 'Towards a circular business ecosystem of used electric vehicle batteries – A modelling approach', *Sustainable Futures*, Vol. 8, 100325. <https://doi.org/10.1016/j.sftr.2024.100325>

Hertzke, P., Schaufuss, P., Kampshoff, P., Möller, T., Smith, A.-S. and Rupalla, F. (2025), *New twists in the electric-vehicle transition: A consumer perspective*, McKinsey Center for Future Mobility, April.

Hossain, E., Sami, N.M., Sunny, M.S.H., Murtaugh, D., Mody, J. and Faruque, H.M.R. (2019), 'A comprehensive review on second-life batteries: Current state, manufacturing considerations, applications, impacts, barriers and potential solutions, business strategies, and policies', *ResearchGate*. <https://doi.org/10.1109/ACCESS.2019.2917859>

IEA (2023), *Batteries and Secure Energy Transitions*, World Energy Outlook Special Report, International Energy Agency, Paris, <https://iea.blob.core.windows.net/assets/cb39c1bf-d2b3-446d-8c35-aae6b1f3a4a0/BatteriesandSecureEnergyTransitions.pdf>

IEA (2024a), *Global EV Outlook 2024*, International Energy Agency, Paris, <https://iea.blob.core.windows.net/assets/a9e3544b-0b12-4e15-b407-65f5c8ce1b5f/GlobalEVO Outlook2024.pdf>

IEA (2024b), 'Average electric vehicle battery price in the Net Zero Scenario, 2023 and 2030', *International Energy Agency*, <https://www.iea.org/data-and-statistics/charts/average-electric-vehicle-battery-price-in-the-net-zero-scenario-2023-and-2030>

IEA (International Energy Agency) (2025a), *What Next for the Global Car Industry? An Energy Technology Perspectives Special Report*, IEA Publications.

IEA (International Energy Agency) (2025b), *Global EV Outlook 2025*, IEA Publications, <https://www.iea.org/reports/global-ev-outlook-2025>.

IEA (International Energy Agency) (2025c), *Recycling of Critical Minerals – Strategies to scale up recycling and urban mining: A World Energy Outlook Special Report*, IEA Publications.

IEA (2025d), 'Share of electric vehicle sales by battery chemistry in selected regions, 2022-2024', *International Energy Agency*, <https://www.iea.org/data-and-statistics/charts/share-of-electric-vehicle-sales-by-battery-chemistry-in-selected-regions-2022-2024>

IEA (2025e), *Global Critical Minerals Outlook 2025*, International Energy Agency, Paris, <https://www.iea.org/reports/global-critical-minerals-outlook-2025>

International Trade Administration (2025), *South Korea electric vehicles (EV) market*, U.S. Department of Commerce, 21 July.

IRENA (2024). *Critical Materials: Batteries for electric vehicles*, International Renewable Energy Agency, Abu Dhabi, <https://www.irena.org/Publications/2024/Sep/Critical-materials-Batteries-for-electric-vehicles>

Júnior, R.C.A., Sanseverino, E., Gallo, P., Koch, D., Kotak, Y., Schweiger, H.-G. and Zanin, H. (2023), 'Towards a business model for second-life batteries: Barriers, opportunities, uncertainties, and technologies', *Journal of Energy Chemistry*, Vol. 78, pp. 507-525. <https://doi.org/10.1016/j.jechem.2022.12.019>

Kishita, Y., Boks, C., Proff, M., Uhlig, E., Ahmed, S., Pantelatos, L. and Grimmel, P. (2024), 'Towards sustainable circular EV battery value chains: A review and comparative analysis between Germany, Norway, and Japan', *2024 Electronics Goes Green 2024+ (EGG)*, pp. 1–9.

Koppelaar, R.H.E.M., Pamidi, S., Hajósi, E., Herreras, L., Leroy, P., Jung, H.-Y., Concheso, A., Daniel, R., Francisco, F.B., Parrado, C., Dell'Ambrogio, S., Guggiari, F., Leone, D. and Fontana, A. (2023), 'A digital product passport for critical raw materials reuse and recycling', *Sustainability*, Vol. 15, No 2, 1405.

Kostenko, G. and Zaporozhets, A. (2024), 'World experience of legislative regulation for lithium-ion electric vehicle batteries considering their second-life application in power sector', *System Research in Energy*, No. 2 (77), pp. 97–114.

Lander, L., Cleaver, T., Rajaeifar, M. A., Nguyen-Tien, C., Elliot, R. J. R, Heidrich, O., Kendrick, E., Edge, J. S., & Offer, G. (2021), 'Financial viability of electric vehicle lithium-ion battery recycling', *iScience*, Vol. 24, No. 7, 102787, <https://www.sciencedirect.com/science/article/pii/S2589004221007550>

Latini, D., Vaccari, M., Lagnoni, M., Orefice, M., Mathieux, F., Huisman, J., Tognotti, L. and Bertei, A. (2022), 'A comprehensive review and classification of unit operations with assessment of outputs quality in lithium-ion battery recycling', *Journal of Power Sources*, Vol. 546, 231979. <https://doi.org/10.1016/j.jpowsour.2022.231979>

Lehmusto, M. & Santasalo-Aarnio, A. (2025), 'Impact of first-life usage on second-life performance of lithium-ion batteries', *New Energy*. Vol 9., 100385, https://www.sciencedirect.com/science/article/pii/S2949821X25001486?ref=pdf_download&fr=RR-2&rr=9ace65e08d0383c6

Li, Y., Wang, X., Butler, D, Liu, J., & Qu, J. (2017), 'Second-use potential of retired EV batteries in the power system and associated cost analysis', *Energy Storage and Science Technology*, Vol. 7, pp. 243-249. <https://esst.cip.com.cn/EN/abstract/abstract461.shtml>

Liekowski, S., Tuuf, J., & Björklund-Sänkiaho, M. (2024), 'Techno-Economic Analysis of the Business Potential of Second-Life Batteries in Ostrobothnia, Finland', *Batteries*, Vol. 10, No. 1, 36, <https://www.mdpi.com/2313-0105/10/1/36>

LME (2026a). 'LME Lithium Hydroxide CIF (Fastmarkets MB)', *London Metals Exchange*, <https://www.lme.com/Metals/EV/LME-Lithium-Hydroxide-CIF-Fastmarkets-MB#Trading+day+summary>

LME (2026b). 'LME Cobalt. London Metals Exchange', *London Metals Exchange*, <https://www.lme.com/Metals/EV/LME-Cobalt#Overview>

Ma, X., Azhari, L. and Wang, Y. (2021), 'Li-ion battery recycling challenges', *Chem*, Vol. 7, No 11, pp. 2843-2847.

Madlener, R. & Kirmas, A. (2017), 'Economic Viability of Second Use Electric Vehicle Batteries for Energy Storage in Residential Applications', *Energy Procedia*, Vol. 105, pp. 3806-3815, <https://www.sciencedirect.com/science/article/pii/S187661021730989X>

Manaia, J.P., Pedreiro, G., Dias, J.P., Santos, J., Alves, A. and Pardal, A. (2025), 'Sustainable repurposing of EV batteries: A methodology for certification in the EU', *Future Batteries*, Article 100101.

Moreschi, M. & Rizos, V. (2026), *Overcoming challenges for second-life applications for battery packs: Lessons from pilot cases*, CEPS In-Depth Analysis, Brussels.

Mathews, I., Xu, B., He, W., Batteto, V., Buonassisi, T., & Peters, I. M. (2020), 'Technoeconomic Model of Second-Life Batteries for Utility-Scale Solar Considering Calendar and Cycle Aging', *Applied Energy*, Vol. 269, 115127, <https://www.sciencedirect.com/science/article/abs/pii/S0306261920306395>

Mauler, L., Duffner, F., Zeier, W. G., & Leker, J. (2021), Battery cost forecasting: a review of methods and results with an outlook to 2050, *Energy & Environmental Science*, Vol. 14, pp. 4712-4739, <https://pubs.rsc.org/en/content/articlelanding/2021/ee/d1ee01530c>

Mayyas, A., Steward, D. and Mann, M. (2019), 'The case for recycling: Overview and challenges in the material supply chain for automotive Li-ion batteries', *Sustainable Materials and Technologies*, Vol. 19, e00087.

McKinsey (2023), *Second-life EV batteries: the newest value pool in energy storage*, McKinsey & Company, <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-evbatteries-the-newest-value-pool-in-energystorage>.

McKinsey (2024), *The battery chemistries powering the future of electric vehicles*, McKinsey & Company, <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-battery-chemistries-powering-the-future-of-electric-vehicles#/>

Meyer, D., Schauensteiner, N. and Riquel, J. (2024), 'Business models and ecosystems in the circular economy using the example of battery second use storage systems', *Sustainability*, Vol. 16, No 5, 1906. <https://doi.org/10.3390/su16051906>

Ministry of Economy, Trade and Industry (2022), *Battery industry strategy: Interim summary*, 22 April.

Omrani, M. and Jannesari, H. (2019), 'Economic and environmental assessment of reusing electric vehicle lithium-ion batteries for load leveling in the residential, industrial and photovoltaic power plants sectors', *Renewable and Sustainable Energy Reviews*, Vol. 116, 109413. <https://doi.org/10.1016/j.rser.2019.109413>

Moreira, A. C., Pinto, D. R., Rosalem, M. D. F. N. C., Rolim, L. A. G., Medrano, M. S. & Junior, E. (2021). 'A Comprehensive Second-Life Review of Electric Vehicle Batteries - A Brazilian Study Case', *IEEE*, <https://ieeexplore.ieee.org/document/9543057>

Mulder, G., De Craemer, K. and Lemaire, E. (2022), 'Labelling and certification protocols for second life batteries', *Zenodo*. <https://doi.org/10.5281/zenodo.6674934>

Murdock, B.E., Toghil, K.E. and Tapia-Ruiz, N. (2021), 'A perspective on the sustainability of cathode materials used in lithium-ion batteries', *Advanced Energy Materials*, Vol. 11, No 39, 2102028.

National Board of Trade Sweden (2023), *Trade rules for a circular economy: The case of used lithium-ion batteries*, National Board of Trade Sweden, Stockholm.

Neigum, K. & Wang, Z. (2024), 'Technology, economic, and environmental analysis of second-life batteries as stationary energy storage: A review', *Journal of Energy Storage*, Vol. 103, 114393, <https://www.sciencedirect.com/science/article/pii/S2352152X24039793>

Neubauer, J., Smith, K., Wood, E., Pesaran, A. (2015), *Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries*, NREL Technical Report, National Renewable Energy Laboratory, Golden, CO, <https://www.nrel.gov/docs/fy15osti/63332.pdf>

NREL (2024), 'Battery Electric Vehicle Assumptions', *National Renewable Energy Laboratory*, https://atb.nrel.gov/transportation/2024/battery_electric_vehicle_assumptions

Nykvist, B. & Nilsson, M. (2015), 'Rapidly falling costs of battery packs for electric vehicles', *Nature Climate Change*, Vol. 5, pp. 329-332, <https://www.nature.com/articles/nclimate2564>

Open Battery Passport (2025), *Global battery passport regulations: Requirements and future outlook*, 7 January.

Parvizioman, E. and Elliot, V. (2024), 'Barriers to circular economy: Insights from a small electric vehicle battery manufacturer', *Journal of Purchasing and Supply Management*, 100905.

Patel, A. N., Lander, L., Ahuja, J., Bulman, J., Lum, J. K. H., Pople, J. O. D., Hales, A., Patel, Y., & Edge, J. S. (2024), 'Lithium-ion battery second life: pathways, challenges and outlook', *Frontiers in Chemistry*, Vol 12, 1358417, <https://pubmed.ncbi.nlm.nih.gov/38650673/>

Peiseler, L., Wood, V. and Schmidt, T.S. (2023), 'Reducing the carbon footprint of lithium-ion batteries, what's next?', *Next Energy*, Vol. 1, No. 2, 100017.

Peixoto, T., Di Persio, F., & Agostini, A. (2025). Lithium-ion battery recycling routes: an environmental assessment in the context of the European battery regulation. *Sustainable Chemistry for the Environment*, 100306.

Penisa, X., N., Castro, M. T., Pascacio, J. D. A., Esparcia, E. A., Schmidt, O., & Ocon, J. D. (2020), 'Projecting the price of lithium-ion NMC battery packs using a multifactor learning curve model', *Energies*, Vol. 13, No. 20, 5276, https://www.mdpi.com/1996-1073/13/20/5276#Appendix_C

Perocillo, Y.K., Pirard, E. and Léonard, A. (2025), 'Process simulation-based LCA: Li-ion battery recycling case study', *The International Journal of Life Cycle Assessment*, Vol. 30, No. 11, 2494–2518. <https://link.springer.com/article/10.1007/s11367-025-02478-z>

Petersen, I., Gode, P., Walker, A., Debrabander, F., Dubois, M., Neubauer, N., Melodia, B. and De Jager, S. (2024), *Navigating the unknowns: Drivers and projections for EV battery recycling*, Global Battery Alliance and Deloitte Belgium, Brussels.

Pipitone, E., Caltabellotta, S. and Occhipinti, L. (2021), 'A life cycle environmental impact comparison between traditional, hybrid, and electric vehicles in the European context', *Sustainability*, Vol. 13, No. 19, 10992.

Podias, A., Pfrang, A., Di Persio, F., Kriston, A., Bobba, S., Mathieux, F., Messagie, M. and Boon-Brett, L. (2018), 'Sustainability assessment of second use applications of automotive batteries: Ageing of Li-ion battery cells in automotive and grid-scale applications', *World Electric Vehicle Journal*, Vol. 9, No 2, 24. <https://doi.org/10.3390/wevj9020024>

Prenner, S., Part, F., Jandric, A., Bordes, A., Leonhardt, R., Jung-Waclik, S. and Huber-Humer, M. (2024b), 'Enabling circular business models: Preconditions and key performance indicators for the market launch of repurposed second-life lithium-ion batteries from electric vehicles', *International Journal of Energy Research*, Vol. 2024, No 1, 8331870. <https://doi.org/10.1155/er/8331870>

Prenner, S., Part, F., Jung-Waclik, S., Bordes, A., Leonhardt, R., Jandric, A., Schmidt, A. and Huber-Humer, M. (2024a), 'Barriers and framework conditions for the market entry of second-life lithium-ion batteries from electric vehicles', *Heliyon*, Vol. 10, No 18, e37423. <https://doi.org/10.1016/j.heliyon.2024.e37423>

Racu, A. and Poliscanova, J. (2024a), *An industrial blueprint for batteries in Europe: How Europe can successfully build a sustainable battery value chain*, Transport & Environment, Brussels.

Racu, A. and Poliscanova, J. (2024b), *From waste to value: Why battery recycling is Europe's chance for resource sufficiency and a low-impact supply chain*, Transport & Environment, Brussels. https://www.transportenvironment.org/uploads/files/2024_12_Battery_recycling_report.pdf

Rajaeifar, M.A., Ghadimi, P., Raugei, M., Wu, Y. and Heidrich, O. (2022), 'Challenges and recent developments in supply and value chains of electric vehicle batteries: A sustainability perspective', *Resources, Conservation and Recycling*, Vol. 180, 106144.

Rallo, H., Sánchez, A., Canals, L., & Amante, B. (2022), 'Battery Dismantling Centre in Europe: A Centralized vs Decentralized Analysis', *Resources, Conservation & Recycling Advances*, Vol. 15, 200087, <https://www.sciencedirect.com/science/article/pii/S2667378922000256>

Righetti, E. and Rizos, V. (2024), *Reducing supply risks for critical raw materials: Evidence and policy options*, CEPS In-Depth Analysis No. 2024-01, CEPS, Brussels.

Rizos, V. and Urban, P. (2024a), *Implementing the EU Digital Battery Passport: Opportunities and challenges for battery circularity*, CEPS In-Depth Analysis No. 2024-05, CEPS, Brussels.

Rizos, V. and Urban, P. (2024b), 'Barriers and policy challenges in developing circularity approaches in the EU battery sector: An assessment', *Resources, Conservation and Recycling*, Vol. 209, 107800.

Rizos, V. and Vu, H. (2024), *Compliance with the EU's carbon footprint requirements for electric vehicle batteries: An overview of challenges*, CEPS In-Depth Analysis No 2024-15, CEPS, Brussels.

Rönkkö, P. and Ayati, S.M. (2021), 'Remanufacturing in the heavy vehicle industry—case study of a Finnish machine manufacturer', *Sustainability*, Vol. 13, 11120.

Rufino Júnior, C.A., Riva Sanseverino, E., Gallo, P., Koch, D., Diel, S., Walter, G. and Zanin, H. (2024), 'Towards to battery digital passport: Reviewing regulations and standards for second-life batteries', *Batteries*, Vol. 10, No. 4, p. 115.

S&P Global (2022), *Battery Pack Costs Rise for Battery Electric Vehicles*. *Battery Pack Costs Rise for Battery Electric Vehicles*, S&P Global Mobility, <https://www.spglobal.com/mobility/en/info/0822/ev-battery-pack-costs-whitepaper.html>

S&P Global (2025a), 'LFP battery market share to grow in Europe, but recycling challenges remain: panelists', *S&P Global*, <https://www.spglobal.com/energy/en/news-research/latest-news/metals/022625-lfp-battery-market-share-to-grow-in-europe-but-recycling-challenges-remain-panelists>

S&P Global (2025b), 'Where are EV battery prices headed in 2025 and beyond?', *S&P Global*, <https://www.spglobal.com/automotive-insights/en/blogs/2025/01/where-are-ev-battery-prices-headed-in-2025-and-beyond#link3>

Saleem, U., Joshi, B., & Bandyopadhyay, S. (2023), 'Hydrometallurgical Routes to Close the Loop of Electric Vehicle (EV) Lithium-Ion Batteries (LIBs) Value Chain: A Review', *Journal of Sustainable Metallurgy*, Vol. 9, pp. 950-971, <https://link.springer.com/article/10.1007/s40831-023-00718-w?utm>

Salek, F., Resalati, S., Babaie, M., Henshall, P., Morrey, D. and Yao, L. (2024), 'A review of the technical challenges and solutions in maximising the potential use of second life batteries from electric vehicles', *Batteries*, Vol. 10, No 3, 79. <https://doi.org/10.3390/batteries10030079>

Sattar, A., Greenwood, D., Dowson, M., & Unadkat, P. (2020), 'Automotive lithium-ion battery recycling in the UK', *WMG The University of Warwick*, Coventry, <https://hvm.catapult.org.uk/wp-content/uploads/2022/06/22350m-WMG-Battery-Recycling-report-v7.pdf>

Schlott, L., Gutsch, M., & Leker, J. (2025), 'Cost modelling and key drivers in lithium-ion battery recycling', *Nature Reviews Clean Technology*, Vol. 1, pp. 656-770, <https://www.nature.com/articles/s44359-025-00095-5>

Schulz-Mönnighoff, M. and Evans, S. (2023), 'Key tasks for ensuring economic viability of circular projects: Learnings from a real-world project on repurposing electric vehicle batteries', *Sustainable Production and Consumption*, Vol. 35, pp. 559-575. <https://doi.org/10.1016/j.spc.2022.11.025>

Seika, J. and Kubli, M. (2024), 'Repurpose or recycle? Simulating end-of-life scenarios for electric vehicle batteries under the EU battery regulation', *Sustainable Production and Consumption*, Vol. 51, pp. 644-656. <https://doi.org/10.1016/j.spc.2024.09.023>

Serna-Guerrero, R., Ikonen, S., Kallela, O. and Hakanen, E. (2022), 'Overcoming data gaps for an efficient circular economy: A case study on the battery materials ecosystem', *Journal of Cleaner Production*, Vol. 374, 133984.

Shahjalal, M., Roy, P.K., Shams, T., Fly, A., Chowdhury, J.I., Ahmed, M.R. and Liu, K. (2022), 'A review on second-life of Li-ion batteries: Prospects, challenges, and issues', *Energy*, Vol. 241, 122881. <https://doi.org/10.1016/j.energy.2021.122881>

Shen, W. (2024), 'Feasibility and economic analysis of electric vehicle battery secondary utilization to reduce wind and photovoltaic abandonment', *International Journal of Low-Carbon Technologies*, Vol. 19, pp. 324-329, <https://academic.oup.com/ijlct/article/doi/10.1093/ijlct/ctad133/7612225>

Song, H., Chen, H., Wang, Y. and Sun, X.-E. (2024), 'An overview about second-life battery utilization for energy storage: Key challenges and solutions', *Energies*, Vol. 17, No 23, 6163. <https://doi.org/10.3390/en17236163>

Sopha, B.M., Purnamasari, D.M. and Ma'mun, S. (2022), 'Barriers and enablers of circular economy implementation for electric-vehicle batteries: From systematic literature review to conceptual framework', *Sustainability*, Vol. 14, No. 10, 6359.

Steckel, T., Kendall, A., & Ambrose, H. (2021), 'Applying levelized cost of storage' methodology to utility-scale second-life lithium-ion battery energy storage systems', *Applied Energy*, Vol. 300, 117309, <https://www.sciencedirect.com/science/article/abs/pii/S0306261921007212>

Strupeit, L. and Tojo, N. (2023), *Circular business models for the solar power industry—Guide for policy makers*, Lund University, Lund.

Su, D., Mei, Y., Liu, T. and Amine, K. (2025), 'Global regulations for sustainable battery recycling: Challenges and opportunities', *Sustainability*, Vol. 17, No. 7, p. 3045.

Tankou, A., Bieker, G., & Hall, D. (2023), Scaling up reuse and recycling of electric vehicle batteries: assessing challenges and policy approaches, Washington DC, *ICCT International Council on Clean Transportation*, <https://theicct.org/publication/recycling-electric-vehicle-batteries-feb-23/>

Tawonezvi, T., Nomnga, M., Petrik, M., & Bladergroen, B. J. (2023), 'Recovery and Recycling of Valuable Metals from Spent Lithium-Ion Batteries: A Comprehensive Review and Analysis', *Energies*, Vol. 16, No. 3, 1365, <https://www.mdpi.com/1996-1073/16/3/1365>

Terkeş, M., Demirci, A., Gökalp, E. and Cali, U. (2024), 'Battery passport for second-life batteries: Potential applications and challenges', *IEEE Access*, Vol. PP, pp. 1-1. <https://doi.org/10.1109/ACCESS.2024.3450790>

Tian, X., Peng, F., Chen, X., Wei, G., Gan, Y., Zhang, Z. and Liu, Y. (2025), 'Management of spent power batteries in China: Progress, policies, and challenges', *Renewable and Sustainable Energy Reviews*, Vol. 219, p. 115797.

Toorajipour, R., Chirumalla, K., Johansson, G., Dahlquist, E. and Wallin, F. (2024), 'Implementing circular business models for the second-life battery of electric vehicles: Challenges and enablers from an ecosystem perspective', *Business Strategy and the Environment*, Vol. 33, No 8, pp. 8637-8655. <https://doi.org/10.1002/bse.3941>

Toro, L., Moscardini, E., Baldassari, L., Forte, F., Falcone, I., Coletta, J., & Toro, L. (2023). A systematic review of battery recycling technologies: advances, challenges, and future prospects. *Energies*, 16(18), 6571.

T&E (2025), *From Waste to Value: Driving Circularity in Europe*, Transport & Environment, <https://www.transportenvironment.org/articles/from-waste-to-value-driving-circularity-in-europe>

Upadhyay, A., Dalal, M., Sanghvi, N., Singh, V., Nair, S., Scurtu, I.C. and Dragan, C. (2021), 'Electric vehicles over contemporary combustion engines', *IOP Conference Series: Earth and Environmental Science*, Vol. 635, 012004.

US Department of Energy (2022), *Bipartisan Infrastructure Law: Battery recycling and second life applications selections*, Vehicle Technologies Office, 16 November.

US Department of Energy (2023), 'Electric Vehicle Battery Pack Costs for a Light-Duty Vehicle in 2023 Are 90% Lower than in 2008, according to DOE Estimates', *US Department of Energy*, <https://www.energy.gov/eere/vehicles/articles/fotw-1354-august-5-2024-electric-vehicle-battery-pack-costs-light-duty>

Van Hoof, G., Robertz, B. and Verrecht, B. (2023), 'Towards sustainable battery recycling: A carbon footprint comparison between pyrometallurgical and hydrometallurgical battery recycling flowsheets', *Metals*, Vol. 13, 1915. <https://doi.org/10.3390/met13121915>

VDE Renewables (2022), *2nd life battery storage projects in Europe*. <https://www.vde.com/resource/blob/2212746/23eabc6fc64bb8bae16a13e6c19e847f/emilas-2nd-life-projekt-data.pdf>

Vullum-Bruer, F., Galteland, O., Gouis, M., McDougall, N. and Tenhunen-Lunkka, A. (2024), 'Existing and upcoming challenges for extending electric vehicle battery lifetime through second-life applications', *Journal of Circular Economy*, Vol. 2, No. 2.

Wesselkämper, J. & Von Delft, S. (2024), 'Current status and future research on circular business models for electric vehicle battery recycling', *Resources, Conservation & Recycling*. Vol. 26, 107596, <https://eprints.gla.ac.uk/323698/>

Widiawati, K., Sopha, B.M., Tjahjono, B. and Rakoto, N. (2025), 'Circularity potentials, influential factors, modeling approach and policy interventions of circular supply chain for electric vehicles', *Cleaner Engineering and Technology*, Vol. 27, 101013

World Bank (2026). *World Bank Commodities Price Data (The Pink Sheet)*, World Bank, Washington DC, <https://thedocs.worldbank.org/en/doc/18675f1d1639c7a34d463f59263ba0a2-0050012025/related/CMO-Pink-Sheet-January-2026.pdf>

Wrålsén, B., Prieto-Sandoval, V., Mejia-Villa, A., O'Born, R., Hellstrom, M. and Faessler, B. (2021), 'Circular business models for lithium-ion batteries: Stakeholders, barriers, and drivers', *Journal of Cleaner Production*, Vol. 317, 128393.

Yang, J., Jiang, Q. and Zhang, J. (2025), 'Bridging the regulatory gap: A policy review of extended producer responsibility for power battery recycling in China', *Energy for Sustainable Development*, Vol. 86, p. 101697.

Zapico, E., Pérez, S., Hernández, J.C. and López, P. (2024), Report on EV repairing and battery module replacing batteries and/or modules on EV.

Zhao, Y. & Kaur, G. (2025), 'The future of recycling for critical materials: the example of EV batteries', *Geosystems and Geoenvironmental*, Vol. 4, No. 2, 100376, <https://www.sciencedirect.com/science/article/pii/S2772883825000263>

Zhao, Y., Pohl, O., Bhatt, A., Collis, G., Mahon, P., Rüter, T. and Hollenkamp, A. (2021), 'A review on battery market trends, second-life reuse, and recycling', *Sustainable Chemistry*, Vol. 2, pp. 167-205. <https://doi.org/10.3390/suschem2010011>

Zheng, X. Zhu, Z., Lin, X., Zhang, Y., He, Y., Cao, H., and Sun., Z. (2018), 'A Mini-Review on Metal Recycling from Spent Lithium Ion Batteries', *Engineering*, Vol. 4, No. 3., pp. 361-370, <https://www.sciencedirect.com/science/article/pii/S2095809917308226>

ABOUT THE BATRAW PROJECT



BATRAW's main objective is to develop and demonstrate two innovative pilot processes for electric vehicle batteries: i) a semi-automated processes for the handling of the batteries to separate their components, including cells and modules suitable for reuse and ii) a mechanical pre-treatment and hydrometallurgical recycling process to improve the separation of the materials contained in the so-called black mass (a substance composed of non-ferrous metals resulting from the shredding of the batteries). The project will also create a prototype battery from the recovered raw materials and a digital battery passport to capture and communicate key information throughout the battery life-cycle, including the sourcing, processing, (re-)use and recycling of components. As part of the project, eco-design guidelines for the repair and dismantling of batteries, as well as best practices for the safe handling and transport of batteries will be developed. For more information about the project, see: <https://batraw.eu>



Funded by the European Union. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the granting authority can be held responsible for them.

PARTNERS



**Renault
Group**



FORD OTOSAN



LEITAT
managing technologies

POSCO
HOLDINGS



MINESPIDER





**CEPS
PLACE DU CONGRES 1
B-1000 BRUSSELS**
