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Barriers and policy challenges in developing circularity approaches in the EU battery sector: An assessment

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ABSTRACT

Using a qualitative case-study approach, we assess the barriers and policy challenges that companies in the EU battery sector face in implementing circularity. The study involves a sample of 20 companies drawn from a combination of purposeful and snowball sampling methods. Empirical data were collected through in-depth interviews. The results show that the EU's revised policy framework for batteries, high-level strategies and financial support for research projects can be enabling factors for adopting circularity approaches. At the same time, interviews reveal uncertainties about the requirements of the EU Batteries Regulation on data sharing, responsibility for end-of-life (EoL) battery management and carbon footprint. Other key concerns identified are the complex cross-border movement of EoL batteries, the lack of ecodesign requirements and inconsistent waste classification frameworks. Our results suggest that the EU policy mix affecting battery circularity extends to various domains, which highlights the importance of ensuring coherence between instruments and objectives.

1. Introduction

The role of lithium-ion batteries (LIBs) as energy storage systems is becoming increasingly important in the context of the ongoing transition to electric mobility. Owing to decreasing production costs, improvements in energy density and strong government support, LIBs are driving the decarbonisation of the transportation sector, which is among the major contributors to global greenhouse gas emissions (Olabi et al., 2023; Ziegler et al., 2021). The global vehicle fleet is expected to be transformed in the coming years, with millions of new electric vehicles (EVs) powered by LIBs hitting the roads (Rajaeifar et al., 2022; International Energy Agency, 2021).

While transitioning to electric mobility is estimated to significantly mitigate climate change (Requia et al., 2018; Moro and Lonza, 2018), the large-scale adoption of EVs presents challenges (Albertsen et al., 2021), primarily at the battery production stage (Stampatori et al., 2020). Key battery materials like lithium, cobalt and natural graphite are sourced from a few countries, raising supply concerns (Righetti and Rizos, 2023; Dunn et al., 2022). Their extraction requires high energy and water consumption (Engels et al., 2022) and can entail environmental impacts such as eutrophication and soil contamination (Farjana et al., 2019). Moreover, sourcing materials from developing countries with unstable political environments poses worrying social risks (Mancini et al., 2021; Rajaeifar et al., 2022). At the end-of-life (EoL) stage of batteries, improper treatment and recycling can lead to further environmental and health risks (Nie et al., 2023). These factors warrant action to reduce primary material extraction and waste generation (Sheth et al., 2023; Chirumalla et al., 2024).

Applying circular economy processes in the battery sector can support a more sustainable transition path for the industry (Sopha et al., 2022; Albertsen et al., 2021). For example, recycling EoL batteries can reduce demand for primary resources and mitigate extraction impacts, while offering a domestic source of critical materials facing supply risks (Baars et al., 2021; Drabik and Rizos, 2018). Reusing batteries with remaining energy storage capacities for stationary applications can help extend their life and value for longer (Wrålsen et al., 2021; Helander and Ljunggren, 2023). In fact, previous research has shown that transitioning to net-zero electric mobility relies on implementing a circular economy (Demartini et al., 2023).

To support a circular economy for batteries, the EU has put forward a new regulatory framework for batteries. The Batteries Regulation introduces EU-wide mandatory sustainability and information requirements for all batteries placed on the European market, targeting the entire battery life cycle. Important provisions include minimum

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recycled content targets for lithium, nickel, cobalt and lead, carbon footprint declarations, rules on due diligence and minimum recycling and material recovery efficiencies (European Parliament and Council, 2023).

The requirement for a digital battery passport is a novel contribution of the Batteries Regulation (Halleux, 2023; Berger et al., 2022). It will represent the first application of the digital product passport (DPP) that will gradually be introduced for different product groups through the Ecodesign for Sustainable Products Regulation (European Commission, 2022). The DPP will act as an electronic record of products throughout their life cycle, aiming to increase transparency, sustainability and circularity (Adisorn et al., 2021). Digital battery passports will need to contain information on battery composition, state of health and battery use, to facilitate the safe dismantling of batteries and support EoL operations (European Parliament and Council, 2023).

Besides EU legislation, a number of high-level initiatives, such as the Global Battery Alliance (GBA, 2024) and the European Battery Alliance (EBA, 2023) have set out to improve the sustainability of battery value chains, while a growing number of EU-funded research projects are developing different approaches for increasing battery circularity (Battery Pass Consortium, 2023).

Although the body of literature on batteries has grown over recent years (Li et al., 2018; Rojaee and Shahbazian-Yassar, 2020), the bulk of published academic articles in the field provide technical and economic assessments (Wrålsen et al., 2021; Azadnia et al., 2021; Albertsen et al., 2021). There has been limited empirical work investigating critical barriers and enablers to implementing circularity in the battery sector (Rajaeifar et al., 2022; Wrålsen et al., 2021; Albertsen et al., 2021). In order to design effective policy responses, it is important to develop a thorough understanding of these factors which can be of policy, technical and economic nature (Sopha et al., 2022). Those studies that do assess barriers or enablers concentrate on one category of actors (e.g., auto or battery manufacturers, see Albertsen et al., 2021 and Parviziomran and Elliot, 2024), one specific circularity process (e.g. recycling, see Tripathy et al., 2023, second-life, see Chirumalla et al., 2024, data sharing for recycling and reuse, see da Silva et al., 2023), one country in the EU (i.e. Finland, see Rönkkö et al., 2021) or outside it (i.e. India, see Kumar et al., 2021), or collect evidence from experts around the globe (Wrålsen et al., 2021).

Previous studies have called for more in-depth assessments of various circularity processes for the battery sector (Albertsen et al., 2021), gathering evidence from experts across the battery supply chain (Kumar et al., 2021) and conducting relevant research with EU coverage (Azadnia et al., 2021). Authors have also highlighted the role of policy in driving circularity for the sector (Rajaeifar et al., 2022; Baars et al., 2021) and a need for studies that delve deeper into policy and regulatory aspects (Kumar et al., 2021).

To fill this gap, we provide an in-depth assessment of barriers and enablers to batteries' circularity in the EU, consulting experts from the entire battery value chain. We ask the following research question: *What barriers and enablers do companies across the EU face in developing and implementing circular economy models for batteries?* Our analysis is based on companies implementing processes that support circularity in the EU battery sector. We focus on the EU as it has identified batteries as a vital part of its green industrial transition and related policies (European Commission, 2021; 2023).

To the best of our knowledge, this is the first study of its kind to focus on the EU and to cover the full spectrum of actors involved in circularity processes, including battery producers, collectors, recyclers, second-life application developers and auto manufacturers.

2. Literature review

This section reviews the existing literature on battery circularity, identifying crucial barriers and enablers. These are grouped under six different categories (see Appendix A).

2.1. Barriers

Many barriers stem from existing **policies and regulations**. Legal uncertainties and unclear rules (Curtis et al., 2021; Giosuè et al., 2021; Parviziomran and Elliot, 2024) as well as a lack of common standards, e.g. for safety and evaluating battery status, can impede EoL strategies (Ma et al., 2021; Rallo et al., 2022). Difficulties in achieving recycling targets may arise from low availability of secondary materials (Helander and Ljunggren, 2023). Moreover, the waste status of batteries can make them subject to high safety requirements and prior notification, creating legal challenges in shipping and transporting batteries (Albertsen et al., 2021; National Board of Trade Sweden, 2023).

Financial and economic factors can also constrain battery circularity. Developing a business case for second-life battery applications is often difficult due to much uncertainty about their economic viability and a lack of investment incentives (Mayyas et al., 2019; Wrålsen et al., 2021). While prices of first life LIBs, for instance, are expected to decrease, there are high costs for circular approaches due to storage, handling, transportation and recovery processes (Rönkkö et al., 2021; Sopha et al., 2022).

Supply chain barriers to battery circularity can arise from difficulties in cooperation among supply chain actors (Azadnia et al., 2021; Sopha et al., 2022) and reluctance to share data and information on EoL processes (Giosuè et al., 2021; Serna-Guerrero et al., 2022). The resulting lack of transparency contributes to uncertainties regarding the optimal format for data sharing to facilitate circularity (Serna-Guerrero et al., 2022) and the quantity of secondary material flows (Harper et al., 2019). Furthermore, there are hindrances in collection, storage and transportation stemming from a lack of facilities for EoL management for LIBs, making it hard to optimise material flows (Rajaeifar et al., 2022; Rallo et al., 2022). The low availability of secondary materials may also impede recycling processes (Helander and Ljunggren, 2023; Mayyas et al., 2019).

Technological factors can affect battery circularity, e.g. through insufficient infrastructure for disposing, collecting, sorting, dismantling, remanufacturing and recycling LIBs (Kumar et al., 2021; Rallo et al., 2022). Continuous evolution of battery chemistry creates uncertainties (Curtis et al., 2021; Rajaeifar et al., 2022) that lead to inconsistent battery assessments, e.g. regarding their state of health and remaining useful life (Albertsen et al., 2021; Haram et al., 2021). Variability in battery chemistry and composition (Mayyas et al., 2019; Murdock et al., 2021) and designs ill-prepared for EoL management (Azadnia et al., 2021; Sopha et al., 2022) also cause technical problems for (automated) disassembly and recycling.

Specialised personnel and tools required for EoL handling are often missing, exacerbating health and safety risks from dismantling, discharging, reassembly, etc. (Rajaeifar et al., 2022). Insufficient data render accurate assessments of environmental impacts difficult (Curtis et al., 2021; Haram et al., 2021), while impeding the implementation of circular tools such as the DPPs (Götz et al., 2022).

Demand network barriers relate to the business-to-business (B2B) and the business-to-consumer (B2C) environment. In both, there is often a lack of trust in circular solutions and misconceptions around secondary battery applications, as quality is often perceived as low (Ma et al., 2021; Rajaeifar et al., 2022). A general lack of awareness among business customers leads to confusion around the safe handling of secondary batteries (Parviziomran and Elliot, 2024), while missing consumer awareness may lead to low return rates of LIBs at EoL (Murdock et al., 2021; Sopha et al., 2022). The costly and often inaccessible nature of reuse and recycling options incentivises consumers to opt for disposal instead (Curtis et al., 2021; Rönkkö et al., 2021).

Factors related to **company organisation** can also hinder circular approaches. Specifically, companies may lack circular economy knowledge, referring not only to technological knowledge required for new processes (Parviziomran and Elliot, 2024) but also to awareness of the benefits of circularity for EV batteries and of suitable circular business models (Chirumalla et al., 2024). They may also lack the time and internal resources required for novel practices (Azadnia et al., 2021).

2.2. Enablers

Policies and regulations have the potential to encourage businesses and consumers to adopt circularity processes (Azadnia et al., 2021; Wrålsen et al., 2021). Clear legal requirements can decrease investment risks and uncertainties (Curtis et al., 2021), while harmonised data requirements and standards can support competitiveness and consumer confidence in secondary products (Haram et al., 2021). Funding schemes enable private investment and support the competitiveness of circularity processes (Curtis et al., 2021; Sopha et al., 2022). EU laws like the Batteries Regulation (Albertsen et al., 2021) and policy tools like Extended Producer Responsibility (Baars et al., 2021; Giosuè et al., 2021) and recycled content targets (Koppelaar et al., 2023) could strengthen the market for secondary raw materials and spur collection and recycling of EV batteries. DPPs have the potential to enhance transparency and data reliability, while supporting carbon reduction and circularity strategies (Götz et al., 2022; Koppelaar et al., 2023).

Among **economic enablers**, circular processes for batteries can provide revenue opportunities while also supporting the adoption of innovations (Haram et al., 2021; Wrålsen et al., 2021). A key **supply chain** enabler is establishing partnerships, i.e. for collaboration and alignment of interests, among supply chain stakeholders (Baars et al., 2021; Giosuè et al., 2021). Increased information sharing could reduce costs, market uncertainty and related risks (Curtis et al., 2021). Furthermore, decentralised geographical location of second-life infrastructure could reduce transport costs and logistical complexity (Rallo et al., 2022).

Technological enablers, such as battery design for automated disassembly and optimisation of material use, as well as standardisation of cell material, design and processing, could increase the economic viability of second-life processes (Giosuè et al., 2021; Rajaeifar et al., 2022). Greater flexibility in recycling processes and enhanced screening, monitoring and sorting methods can also act as enablers (Murdock et al., 2021). Improvements in digital technologies, e.g., regarding data availability and traceability, can support optimising strategies at the end of (first) life (Baars et al., 2021; da Silva et al., 2023).

In the **demand network** category, in a B2B environment, increased company awareness of environmental issues may drive demand for more circular approaches (Parviziomran and Elliot, 2024). This can also be observed in the B2C environment where higher public awareness and engagement in sustainability issues can be an important enabler (Sopha et al., 2022). Battery passports can act as drivers for more informed and sustainable consumer choices (Götz et al., 2022).

Company organisation can drive battery circularity through various factors related to the organisational set-up and company culture. Crucially, internal commitment and motivated employees, better communication and knowledge transfer, and a clear strategy have been identified as enablers in the literature (Albertsen et al., 2021). Internal innovation and circularity implementation, such as through innovative business models (Sopha et al., 2022; Chirumalla et al., 2024), and a dedicated circularity team can be an additional advantage (Albertsen et al., 2021).

3. Methodology

The study is exploratory in scope and adopts a qualitative case-study approach to address the research question. The explanatory nature of the study is deemed appropriate for answering the 'what' questions posed and building new knowledge (Yin, 1994). Defining the types of cases for the analysis and boundaries for the research are important steps (Ragin, 2000; Miles and Huberman, 1994). To this end, the assessment draws from several cases of companies that have developed models for achieving circularity or resource efficiency for batteries. This includes recycling and second-life applications that seek to extend the lifetime of batteries. Through a bottom-up approach relying on data collected from multiple company cases impacted by the EU policy mix on batteries we aim to develop a deeper understanding of the real-life barriers companies face and the existing policy gaps and inconsistencies (Lune and Berg, 2017; Voss et al., 2002; Ossenbrink et al., 2019). The empirical component of the study relies on in-depth interviews with senior company representatives for collecting rich qualitative data (Saunders et al., 2009; Yin, 2009).

In order to develop the sample this study, we used the purposive sampling strategy complemented by the snowball sampling method. In line with the purposeful sampling approach, we utilised our ''special knowledge or expertise about some group to select subjects who represent this population'' (Lune and Berg, 2017, p. 39). We specifically utilised as a starting point a group of industrial partners in the EU-funded project BATRAW,[1] which develops circularity approaches for EV batteries. Using the snowball sampling method (see Saunders et al., 2009; Lune and Berg, 2017), we then extended the sample by asking the interview participants to identify and propose other experts ''who possess the same relevant attributes they do'' (Lune and Berg, 2017, p. 39).

We applied the following criteria for selecting the companies to be included in the study. First, the company should be engaged in a processes supporting recycling or second-life applications (Vermunt et al., 2019). Second and in line with the scope of the study, the companies should either operate in the EU or place their products on EU market to be impacted by EU legislation in this field (Albertsen et al., 2021). Third, we aimed to feature in the sample companies across all stages of the battery value chain that implement circularity approaches (Serna-Guerrero et al., 2022), namely battery producers, collectors, companies offering reuse services, dismantlers, recyclers and end users. In total, we compiled a sample of 20 companies for interviews (see Table B1, Appendix B) including a mix of industrial partners involved in BATRAW and other companies in the battery value chain. We decided that a sample of this size would allow us to collect rich information from each case study while ensuring that data can be analysed with a reasonable amount of effort (Marshall et al., 2013; Saunders et al., 2009).

Empirical data were collected from interviews that took place between August 2022 and April 2023. All interviews lasted at least 60 min, with some extending up to 75. Their content was structured around a questionnaire that used the categories of barriers and enablers established through the literature review presented in Section 2. This supported the later grouping of data with codes and their comparison across the different company cases (Miles and Huberman, 1994; Lune and Berg, 2017). In addition to the questions on barriers and enablers, the interviewees were also asked to identify potential policy inconsistencies (see Appendix C). Questions were asked in an open format, allowing the experts to elaborate on the barriers and enablers they face as well as to make suggestions (Yin, 2009). All interviews were held with the participation of at least two members of the research team; this enabled one interviewer to focus on managing the discussion and directly interact with the interviewee(s), while another took notes of the viewpoints expressed in a neutral way (Eisenhardt, 1989).

Detailed transcripts were subsequently prepared by the research team for all interviews. This exercise resulted in 141 pages of transcripts

[1] BATRAW receives funding through the European Union's Horizon Europe research and innovation programme (https://batraw.eu/). It aims to pioneer and showcase circular methodologies for managing end-of-life EV battery packs. The project will implement two pilot programmes: the first will utilise a semi-automatic disassembly process for reusing battery components, and the second will employ pre-treatment and hydrometallurgical techniques for recycling battery cells and modules. The 17 project partners include research institutions and companies from different stages of the battery value chain.

in total. To manage the large amount of data and identify common insights across the different case studies, data in the transcripts were coded (Lune and Berg, 2017). The different codes presented, in a short phrase, the relevant barrier or enabler (Saldaña, 2013). We used 36 codes in total which were compiled in two phases. During the first phase, we used the barriers and enablers identified through the literature review (see Table A1). These were complemented with 21 additional codes that were prepared by the authors. Data were then imported into an Excel document under the various codes. The codes were used as filters which allowed determining the frequency a barrier or enabler was raised and the identification of cross-case study insights. An overview of the methodology is shown in Fig. 1.

4. Results and discussion

4.1. Barriers

The first category of barriers emanating from the empirical analysis relate to the **policy and legislative framework**. A cluster of barriers were associated with the battery passport requirements of the EU Batteries Regulation. According to nine sampled companies, as observed in pilots, implementing the battery passport requirements will be a challenging task. This was attributed to the lack of common standards in place for consolidating all the required battery-related data from each actor across the value chain. One interviewee (Principal Policy Officer, supply chain traceability) stressed that for the effective implementation of the battery passport ''regulators should provide clear requirements for all data mandated in the passport and access guidelines for stakeholders''.

Concerns were also raised about the reliability of collected data from different actors and how it will be ensured in practice. Similar hurdles linked to the varied data formats across the battery supply chain were reported by Serna-Guerrero et al. (2022), which highlights the importance of developing standardised data collection processes to support transparency and circularity. A related issue pertains to the electronic exchange system of the battery passport, with five companies expressing concerns about how the confidentiality of sensitive data will be ensured and how only actors with legitimate interest will have access to this data. Moreover, in four cases companies held that there are uncertainties as to how data interoperability across the battery value chain will be achieved.

A pressing issue mentioned by companies involved in recycling but also auto manufacturers and providers of traceability solutions (seven in total) concerned the rules surrounding responsibility for handling the batteries used for second-life applications. In the experts' view, the rules in the Batteries Regulation leave room for interpretation about how in practice these responsibilities for managing the batteries will be transferred from one economic operator to another when batteries reach the end of their first life. As batteries are used in different automotive and stationary applications, it can be unclear which actor is responsible throughout the value chain. This also applies to the battery passport requirements and how they will be practically transferred for batteries that can be repurposed.

The implication of this vague framework is that some companies may be discouraged from investing in second-life business models. Five companies reported difficulties in implementing the requirements of the new EU Batteries Regulation. These included problems in enforcing the requirements for imported batteries and establishing a proper market surveillance system, a lack of clarity on how the battery management system will incorporate all metrics and a cumbersome mix of regulatory articles that need to be managed by both small and large companies.

In five other cases, the uncertainty surrounding the life-cycle assessment (LCA) and carbon footprint calculations for batteries was identified as an issue. One company carrying out a pilot reported that the complexity of the battery product makes it very hard to apply the life-cycle approach to the product's environmental footprint and to ensure that the results for batteries coming from different parts of the world are comparable. As stated by an expert from a company involved in battery material production and battery recycling (Senior Manager, recycling), ''harmonization is crucial when it comes to reporting data, such as CO_2 footprints, and we need a consistent methodology for calculating them''.

The complex legal rules for the cross-border movement of batteries were a common barrier in four interviews. The experts explained that the whole process of preparing the necessary documentation and getting approval from the authorities to ship batteries for recycling or repurposing can be quite burdensome. This challenge is often perpetuated by discordant requirements and waste-classification frameworks across different countries. Other studies have identified similar burdens associated with the shipment of waste and the divergent rules across EU Member States (see Van Buren et al., 2016; Rizos and Bryhn, 2022). This highlights the importance of policy coherence when implementing the EU policy framework on circularity at the Member State level (Lee et al., 2017; Wilts et al., 2016).

Four companies (two auto manufacturers and two recyclers) thought that various targets in the EU Batteries Regulation – namely on recycled content in new batteries, recycling efficiency and recovery rates for certain materials – are over-ambitious given the current state of the EU recycling chain. Making the battery packs more modular and easier to dismantle through forward-looking ecodesign policies, which are currently lacking, would support both recycling and second-life applications according to two auto manufacturers and two recyclers. In three cases, companies suggested that as the global competition for leadership in new battery technologies increases, the financial support provided to EU industry should be enhanced. Finally, a barrier noted by three companies was the lack of guidance in national legislation on the safe storage of EoL batteries.

Two major barriers of an **economic/financial nature** were identified during the interviews. The economic case for recycling LIBs was the first of these, pointed to by seven companies. The experts elaborated that

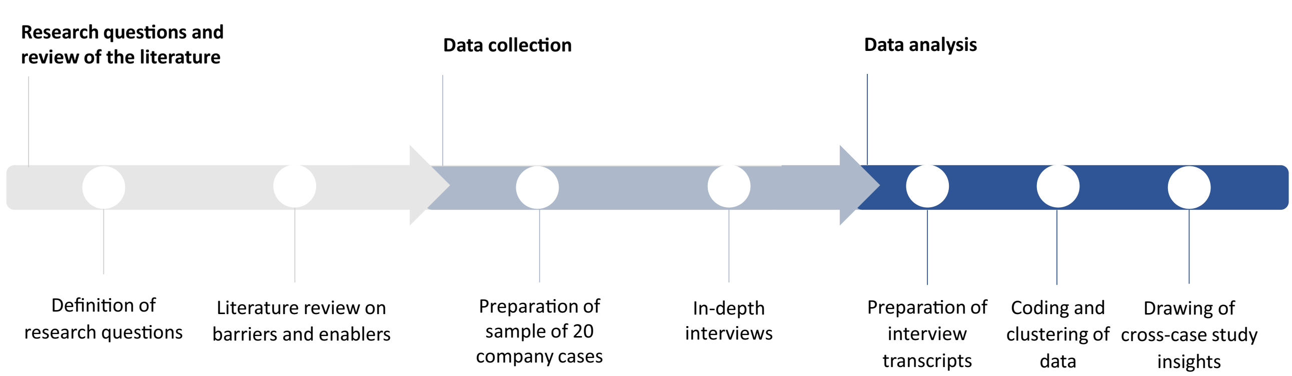

Fig. 1. Overview of research methodology.

raising the large funds required for large-scale recycling plants can be challenging, especially given that many recycling operations are not profitable during the early years of operation. Besides the high operating costs of the plant, the fluctuating prices of the recovered materials pose risks to the viability of the complex business case. This mirrors the findings by Mayyas et al. (2019) about the still uncertain economics of battery recycling.

The second key barrier, also mentioned by seven companies, was the difficulty of developing a viable business case for second-life battery applications. Two key factors that can hinder the competitiveness of such applications are the high costs of spare parts that may be required for repurposing the battery and the complicated disassembly process, especially for small battery packs. The latter factor corroborates the above-mentioned lack of ecodesign policies to support circular processes for LIBs. One expert from a company developing second-life applications stressed that in the absence of economic incentives it will be hard for reused batteries to compete in the market with new batteries that have higher energy capacity.

Another group of barriers emerge from the **supply chain**. Seven companies reported obstacles in collection, including insufficient collection schemes for portable LIBs, low volumes of large LIBs currently available for recycling and difficulties in collecting batteries from multiple sources and then sorting them according to their different chemistries.

During seven interviews, companies discussed the limited transparency across the battery supply chains, which hinders battery extraction, dismantling, recycling and reuse services. Among the types of information that are hard to get from suppliers are detailed mineral composition, chemical substances, the share of recycled content and original sources of materials. According to two companies (a provider of traceability solutions and a dismantler), it is particularly important for circularity processes to have information on the battery management system, the battery's state of health and charging history. In five cases, there was reference to a general reluctance among companies across different segments of the battery value chain to share data. This was attributed to confidentiality concerns and the fact that companies are only used to providing data on the basis of non-disclosure agreements.

While the battery passport of the new EU Batteries Regulation aims to address the above transparency-related issues, experts noted that the legal framework would need to provide assurance to companies that data are shared in a way that benefits the whole supply chain and does not entail confidentiality risks. These suggestions, citing the need to provide assurance to supply chain actors for data-powered circularity processes, are in line with published research in the field (Gupta et al. 2019).

Some barriers of a **technical nature** were also disclosed. In three cases, the companies offering collection, recycling and vehicle dismantling services reported that product design choices do not support the easy extraction of LIBs for recycling or using in second-life applications. As discussed by the experts, extracting the various components from the batteries is often a laborious and time-consuming process due to the glues used. Lack of battery pack standardisation was an important issue mentioned by three companies. The experts suggested that the multiplicity of different battery packs, geometries and shapes, coupled with the frequent lack of information about their previous usage, adds to the complexity of establishing standardised processes for recycling and reusing LIBs. Furthermore, two companies involved in recycling held that discharging some types of batteries to prepare them for safe recycling can be a complicated process.

A number of impediments were attributed to the **demand network**, including both consumers and clients in the B2B environment. The lack of consumer awareness about the benefits of recycling and reuse processes was a common barrier in four interviews. In particular, the experts noted that there is still large scope for improving consumers' knowledge about the impacts of their consumption choices and the importance of proper collection of products with LIBs, especially smaller consumer electronics.

The same point also applies to companies in the B2B environment, which often have low awareness of their environmental footprint. In three cases, it was suggested that for a segment of consumers and clients there is lack of interest in circular solutions, especially if they come at a higher cost. A given example was second-life batteries, which according to the experts, are not easily prioritised over new batteries due to the increased costs involved. Finally, two companies providing second-life applications mentioned misconceptions in the market about the quality and performance of reused batteries.

On the **company organisation** front, the difficulties of adapting to the evolving market were deemed a barrier during four interviews. As noted by the interviewees, in some cases it can be challenging for companies wishing to expand their recycling and reuse business to integrate new equipment and technologies into existing operations, as well as train employees on new processes. Lack of time and capacity constraints was another barrier identified by two companies. The experts explained that for companies, and especially SMEs, obtaining all the necessary permits and licenses to comply with the regulatory requirements can require significant internal resources.

4.2. Enablers

A key category of enablers emerging from the interviews relates to **policies and regulations**. Experts from all battery value chain segments covered by this paper highlighted the potential of the EU Batteries Regulation to drive circularity within companies and along supply chains by creating binding requirements, such as recycling targets and carbon footprint declarations. These findings are in line with the literature, where many authors argue for the potential of clear legal requirements (Curtis et a., 2021), recycled content targets (Koppelaar et al., 2023) and the Batteries Regulation in particular (Albertsen et al., 2021).

Moreover, the EU battery passport emerged as a crucial enabler (ten interviews in total) for increasing supply chain transparency and standardisation, and for closing information gaps. With regard to the latter, one interviewee (Head of R&D, recycling) mentioned that ''the core information that would be useful for recyclers would be the chemistry inside and the percentages of the different components […] to improve the sorting process''. As also emphasised in the literature (Götz et al., 2022; Koppelaar et al., 2023), making this information available can help optimise recycling and second-life processes. However, an aspect uncovered in the interviews that is not extensively discussed in the present literature relates to the battery passport's potential to educate consumers on circularity and thereby encourage a change in consumption behaviour.

EU high-level strategies such as the EU Green Deal were argued by five interviewees from the manufacturing, second-life and traceability sectors to provide necessary signals to the automotive sector to transition towards EVs. An interviewee (Lead Engineer, reuse) said that ''actors in the market are discussing the objectives set up by the EU and are pushing the market towards electric vehicles''. Interestingly, the literature does not often discuss the potential of such high-level strategies, instead focusing on legal obligations and standards (Curtis et al., 2021; Götz et al., 2022; Haram et al., 2021), indicating that there may be more to explore in this context. Four experts engaged in different EoL operations pointed to the relevance of EU-funded projects in helping to finance circularity frameworks and creating demand for recycling and second-life applications. Furthermore, experts maintained that such projects generated the opportunity for stakeholder cooperation and mutual learning. The role of funding schemes in spurring private investment in battery circularity was also found in the literature (Curtis et al., 2021; Götz et al., 2022; Sopha et al., 2022), although their potential for stakeholder cooperation was not discussed there.

The second category of enablers stems from **financial and economic factors**. Revenue and cost-saving opportunities from the circular economy were highlighted as enablers by four firms (an auto manufacturer and different EoL operators), as confirmed by the literature (Haram et al., 2021; Wrålsen et al., 2021). Specifically, an interview from the auto manufacturing sector highlighted that ''[e]nabling to sell batteries as a second-life application would generate additional revenue streams''. Two firms engaged in second-life processes noted the high raw material and energy prices at the time as financial enablers of circular batteries, increasing the competitiveness of secondary batteries.

On **supply chain** enablers, seven experts, mainly from EoL and second life sectors, mentioned the establishment of partnerships, which is also an important enabler in the literature (Baars et al., 2021; Curtis et al., 2021; Giosuè et al., 2021; Wrålsen et al., 2021). According to the experts, partnerships are instrumental in building relationships of trust that, in turn, are key for increased information sharing and improved awareness of circularity processes. One expert (Co-Founder, traceability solutions) stated that ''if you can establish relationships between companies that trust each other […], more people get used to [sharing data] and it becomes easier for them''.

Within the **technology** category of enablers, digital technology, such as blockchain, was highlighted as facilitator of information sharing while increasing supply chain visibility and traceability. This is in line with findings by da Silva et al. (2023) and Júnior et al. (2023). Innovation in dismantling and recycling technology was pointed out by two firms from the recycling and refining sector as an enabler of EoL processes. New technologies for LIB recycling could increase the flexibility of recycling and improve the recovery of valuable materials, and the use of robotics was brought up as a way to improve the cost efficiency of recycling processes while reducing risks to human health.

Increasing public awareness of sustainability issues was mentioned as a major **demand network** enabler by nine firms (involved in auto manufacturing, supply chain traceability and EoL management/second-life), pushing companies to improve their public image and move to more circular solutions. One interviewee (Founder, recycling innovations) explained that in addition to environmental considerations ''extraction of cobalt and concerns about use of child labour have made people aware of the existence of supply chains for batteries''. This awareness can also lead to a change in consumer behaviour, e.g. regarding battery disposal. More sustainable consumer choices and demand for circular solutions were highlighted as overarching reasons for transitioning towards circular business models in the first place. This was largely not discussed in the existing literature.

The final group of enablers relates to **company organisation**. Here, internal commitment, motivated employees and environmental culture were emphasised by seven experts from across the battery value chain. A strong commitment to environmental values, including from upper management, leads to alignment of internal structures with circularity and sustainability objectives. Three companies (an auto manufacturer and producer of battery cell, a dismantler and a developer of battery recycling machinery) highlighted the potential of internal innovation to unlock financial benefits, anticipate market needs and encourage the transition towards more circular infrastructure.

Table 1 provides an overview of the key barriers and enablers identified through the interviews.

Table 1
Barriers and enablers emerging from the empirical analysis.

Category	Type	Barrier/Enabler	Number of sampled companies
Policies and regulations	Barrier	Challenges in implementing the battery passport requirements	9
		Lack of clear rules for second-life applications	7
		Uncertainties regarding the data exchange system	5
		Difficulties in implementing the requirements of the Batteries Regulation	5
		Lack of guidance on LCAs and carbon footprint calculations	5
		Uncertainties about data interoperability	4
		Legal challenges in shipping and transporting	4
		Difficulty in achieving recycling targets	4
		Lack of ambitious ecodesign policies	4
		Lack of financial support	3
		Lack of guidance on storing of batteries	3
	Enabler	Digital product passports	10
		EU Batteries Regulation	9
		EU high-level strategies	5
		EU-funded projects	4
Economic factors	Barrier	Challenging economic case for battery recycling	7
		Difficulties in developing a business case for second-life applications	7
	Enabler	Revenue opportunities	4
		High energy and primary raw material prices	2
Supply chain	Barrier	Collection issues	7
		Lack of transparency across supply chains	7
		Reluctance to share data	5
	Enabler	Establishing partnerships	7
Technology	Barrier	Battery design not supporting recycling and reuse	3
		Discharging process challenges	2
	Enabler	Digital technology	3
		Dismantling and recycling technology	2
Demand network	Barrier	Lack of consumer awareness	4
		Lack of interest in circular solutions	3
		Misconceptions about secondary battery applications	2
	Enabler	Increased public awareness of sustainability issues	9
		Increasing demand for circular/sustainable products	4
Company organisation	Barrier	Difficulties in adapting to the evolving market	4
		Lack of time and internal resources	2
	Enabler	Internal commitment and motivated employees	7
		Internal innovation	3

4.3. Inconsistencies in the policy mix

During the interviews, companies were also asked to identify potential inconsistencies in the existing policy mix affecting circularity for LIBs. For four companies involved in the recycling or dismantling of batteries, there are inconsistent objectives in the circularity and chemicals policy domains. The interviewees explicitly argued that while circular economy processes for batteries have a strong affinity with retaining their value for as long as possible and reusing their components, these objectives are complicated by the strict rules in place for the management of batteries and the resulting administrative burden.

In four other cases, the interviewees held that developing a viable recycling value chain for LIBs can be constrained by conflicting priorities and legal rules globally. Two specific examples given were the inconsistent frameworks for promoting the development of battery recycling plants in the EU and US, and the different classifications worldwide for waste batteries. On the former, companies argued that the uneven financial support opportunities in the EU and US affect the level playing field and may slow investments in Europe. One expert (Founder, recycling innovations) specifically emphasised that ''the US Inflation Reduction Act and the pace by which the US is currently driving investments create an uneven playing field and will have implications for the battery sector and battery production globally''. On the latter, it was suggested that the transboundary movement of EoL batteries is governed by varied and inconsistent classification approaches and control procedures for waste batteries. Inconsistent rules across the EU was a further challenge noted by two companies. A specific example provided by a recycling company referred to the diverse requirements across EU member states for managing plastic components included in batteries which can create confusion and an unfavourable investment environment for companies in the sector.

5. Conclusions

In assessing the barriers, enablers and inconsistencies in today's EU policy mix that affect the implementation of circularity processes for LIBs, we used qualitative empirical evidence gathered through in-depth interviews with companies across the battery value chain.

Our results suggest that the revised EU policy framework for batteries underpinned by a new regulation is perceived to be a major enabler in the adoption of circular economy business models and innovations. The upcoming binding requirements on recycling targets and carbon footprint as well as the second-life provisions are awakening interest in circular business models among companies in the value chain. In addition, the requirement for a battery passport and the new rules on data sharing may have a transformational impact on battery supply chains and address the lack of transparency. Beyond the new regulatory requirements, EU high-level strategies and financial support for research projects are two further important enablers emerging from the sample. The former signals a new level of ambition in EU sustainability policies, which in turn can influence changes in markets, while the latter can stimulate innovation and support knowledge sharing.

However, interview findings reveal several hurdles that need overcoming to create fertile ground for circularity processes and innovation in the battery value chain. One set of barriers are the new demands of the Batteries Regulation for data collection, sharing and availability. While the potential of the battery passport is acknowledged, effective implementation would require addressing issues such as data reliability and confidentiality, as well as the lack of common standards for data sharing. Given the novelty of the instrument and the lack of know-how, dedicated initiatives and projects bringing together different actors in the battery supply chain could help alleviate concerns about data sharing.

Two additional areas of the regulation that need further clarity, possibly through additional legislative acts, concern the responsibilities for managing batteries at the end of their first life and implementing the rules on carbon footprint. The findings also highlight other policy-related challenges, including the difficulty of transboundary movements of EoL batteries and the lack of ambitious ecodesign rules. Furthermore, the empirical evidence indicates that implementing circular processes in the battery value chain can be hindered by divergent requirements from different EU policy domains and global rules on batteries.

The above results imply that the overall EU policy mix for sustainability in the battery value chain has been broadened, with traditional waste management instruments now interlinked with others in areas such as digital and competition policies. As the portfolio of relevant policy instruments expands, it will be ever more important to ensure coherence and coordination between their objectives and to avoid inconsistencies with counterproductive results for companies wishing to adopt circularity approaches.

Ex-ante and ex-post assessments should therefore not view barriers and enablers in isolation, but rather as effects of a policy mix that transcends the boundaries of traditional policy domains. Given the global nature of the battery supply chains and the rapid growth of the sector, there is also a need to accelerate international coordination efforts on standards, waste definitions, classification frameworks and carbon footprint calculations.

Potential avenues for future research emerge from our results. One such path concerns the implementation of the EU battery passport. As explained above, our study identified a number of issues linked to growing data demands that would benefit from in-depth analysis with samples covering the entire battery value chain. The present inconsistencies in the overall policy mix affecting the adoption of circularity approaches in the battery value chain would also require further research. While our study represents a first attempt to identify such inconsistencies, there is a need for a more detailed mapping of conflicting rules stemming from EU and national policy frameworks to inform policy-makers. Following on from our results, a comparative analysis of the regulatory support frameworks for batteries in the EU and the US could furthermore deepen insights into inconsistent classification frameworks and standards affecting global value chains.

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CRediT authorship contribution statement

Vasileios Rizos: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Patricia Urban:** Writing – review & editing, Writing – original draft, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data availability

The authors do not have permission to share data.

Appendix A

Table A1
Framework of barriers and enablers in the implementation of circularity approaches for batteries.

Category	Type	Barrier/Enabler	References
Policies and regulations	Barrier	Legal uncertainties and unclear rules	(Curtis et al., 2021; Giosuè et al., 2021; Parviziomran and Elliot, 2024; Sopha et al., 2022)
		Lack of common standards	(Ma et al., 2021; Parviziomran and Elliot, 2024; Rallo et al., 2022; Sopha et al., 2022)
		Difficulties in achieving recycling targets	(Albertsen et al., 2021; Helander and Ljunggren, 2023)
		Waste status of batteries	(Albertsen et al., 2021; Rajaeifar et al., 2022)
		Legal challenges in shipping and transporting	(Albertsen et al., 2021; National Board of Trade Sweden, 2023; Rajaeifar et al., 2022)
	Enabler	Clear legal requirements	(Curtis et al., 2021)
		Harmonised data requirements and standards	(Curtis et al., 2021; Götz et al., 2022; Haram et al., 2021)
		Funding schemes	(Curtis et al., 2021; Götz et al., 2022; Sopha et al., 2022)
		EU Batteries Regulation	(Albertsen et al., 2021)
		Digital product passports	(Götz et al., 2022; Koppelaar et al., 2023)
Economic factors	Barrier	Difficulties in developing a business case for second-life battery applications	(Curtis et al., 2021; Haram et al., 2021; Mayyas et al., 2019; Wrålsen et al., 2021).
		High costs for circular approaches	(Albertsen et al., 2021; Rajaeifar et al., 2022; Rönkkö et al., 2021; Sopha et al., 2022)
	Enabler	Revenue opportunities	(Haram et al., 2021; Wrålsen et al., 2021)
Supply chain	Barrier	Difficulties in cooperation	(Azadnia et al., 2021; Sopha et al., 2022)
		Reluctance to share data	(Giosuè et al., 2021; Serna-Guerrero et al., 2022; Sopha et al., 2022)
		Supply chain uncertainties	(Serna-Guerrero et al., 2022; Azadnia et al., 2021; Harper et al., 2019;)
		Challenges in collection, storage and transportation	(Rajaeifar et al., 2022; Rallo et al., 2022)
		Low availability of secondary materials	(Albertsen et al., 2021; Helander and Ljunggren, 2023; Mayyas et al., 2019)
	Enabler	Establishing partnerships	(Baars et al., 2021; Curtis et al., 2021; Giosuè et al., 2021; Wrålsen et al., 2021)
		Increased information sharing	(Curtis et al., 2021)
		Geographical location	(Rallo et al., 2022)
Technology	Barrier	Insufficient infrastructure	(Kumar et al., 2021; Ma et al., 2021; Rallo et al., 2022; Sopha et al., 2022)
		Continuous evolution of battery chemistry	(Albertsen et al., 2021; Curtis et al., 2021; Haram et al., 2021; Rajaeifar et al., 2022, 2022; Sopha et al., 2022)
		Technical problems for (automated) disassembly and recycling	(Azadnia et al., 2021; Curtis et al., 2021; Harper et al., 2019; Mayyas et al., 2019; Murdock et al., 2021; Rajaeifar et al., 2022; Sopha et al., 2022)
		Health and safety risks	(Rajaeifar et al., 2022)
		Insufficient data	(Curtis et al., 2021; Götz et al., 2022; Haram et al., 2021; Rajaeifar et al., 2022)
	Enabler	Battery design	(Curtis et al., 2021; Giosuè et al., 2021; Murdock et al., 2021; Rajaeifar et al., 2022)
		Flexibility in recycling technologies	(Murdock et al., 2021)
		Digital technology	(Albertsen et al., 2021; Baars et al., 2021; da Silva et al., 2023; Júnior et al., 2023)
Demand network	Barrier	Lack of trust in circular solutions	(Curtis et al., 2021; Ma et al., 2021; Rajaeifar et al., 2022; Rönkkö et al., 2021)
		Misconceptions around secondary battery applications	(Curtis et al., 2021; Ma et al., 2021; Murdock et al., 2021; Sopha et al., 2022; Parviziomran and Elliot, 2024; Rajaeifar et al., 2022; Rönkkö et al., 2021)
		Inaccessible reuse and recycling options	(Curtis et al., 2021; Rönkkö et al., 2021)
	Enabler	Increased public awareness of sustainability issues	(Parviziomran and Elliot, 2024; Sopha et al., 2022)
		Sustainable consumer choices	(Götz et al., 2022)
Company organisation	Barrier	Lack of circular economy knowledge	(Azadnia et al., 2021; Chirumalla et al., 2024; Parviziomran and Elliot, 2024)
		Lack of time and internal resources	(Azadnia et al., 2021)
	Enabler	Internal commitment and motivated employees	(Albertsen et al., 2021)
		Internal innovation	(Albertsen et al., 2021; Chirumalla et al., 2024; Sopha et al., 2022)

Appendix B

Table B1
List of interviewed experts.

Number	Sector	Circular Process	Experts' role
Firm 1	Battery evaluation, disassembly and second-life applications	Reuse	1. Lead Engineer 2. Strategic Business Analyst
Firm 2	Auto manufacturer	Recycling & reuse	Developer of Innovation
Firm 3	Auto manufacturer	Recycling & reuse	1. Product Sustainability Leader 2. Product Development Engineer
Firm 4	End-of-life management & recycling of batteries	Recycling	1. Head of R&D 2. Innovation Researcher 3. Researcher – R&D
Firm 5	Collection of batteries	Collection	Manager
Firm 6	Supply chain traceability and circularity services	Traceability solutions supporting recycling and reuse	1.Co-Founder 2. Project Lead
Firm 7	Supply chain traceability and circularity services	Traceability solutions supporting recycling and reuse	Director of Business Development
Firm 8	Battery innovation service provider	Recycling innovations	1. Chief of Staff 2. Founder
Firm 9	Recycling & refining	Recycling	Director of Government Affairs
Firm 10	Battery material production & battery recycling	Recycling	Senior Manager

(continued on next page)

Table B1 (*continued*)

Number	Sector	Circular Process	Experts' role
Firm 11	Manufacturer of automotive parts & e-bike batteries	Recycling & reuse	1. Head of Office 2. Head of Battery Development
Firm 12	Recycling & refining	Recycling	Director of Public Affairs
Firm 13	Environmental services	Services supporting recycling	Project Lead
Firm 14	Standards & supply chain traceability	Traceability solutions supporting recycling and reuse	1. Principal Policy Officer 2. Senior Manager 3. Manager of Sustainability
Firm 15	Battery recycling	Recycling	CEO
Firm 16	End-of-life management & second-life applications	Reuse	1. Head of Environmental Management 2. Business Development Coordinator
Firm 17	Auto manufacturer & battery cell production	Recycling	1. Group Project Manager 2. Corporate External and Government Relations
Firm 18	Dismantling of vehicles & extraction of batteries	Dismantling for reuse and recycling	Head of Innovation
Firm 19	Second-life applications	Reuse	Co-Founder & CEO
Firm 20	Development of battery recycling machinery	Recycling	Recycling Engineer

Appendix C

Interview questions

I. Description of the company's business model and circular approach

Please provide the following information: (i) your position and role in the company, (ii) size of company, and (iii) description of the company's activities and processes supporting circularity in the battery sector.

II. Barriers

Which factors stemming from the existing EU policy framework, economics, supply chains, demand network and company organisation acted as barriers for your company in implementing a process supporting circularity in the battery sector?

II. Enablers

Which factors (i.e. enablers) stemming from the existing EU policy framework, economics, supply chains, demand network and company organisation acted as enablers for your company in implementing a process supporting circularity in the battery sector?

III. Inconsistencies in the policy mix

In your view, what are the key inconsistencies in the current policy mix for batteries? Are there any policies that contradict each other and pose challenges for businesses in this sector?

Appendix D

Table D1
Selected quotes from the interviews.

Category	Type	Quote	Interviewee role
Policies and regulations	Barrier	"Regulators should provide clear data requirements for all data mandated in the passport and access guidelines for stakeholders."	Principal Policy Officer, Traceability solutions
		"There are many attempts by different organizations to do track and trace data and implement due diligence, but the standards landscape is fragmented."	Director of Public Affairs, Recycling
		"Interoperability is a key challenge in relation to digital product passports. All the decentralized systems - which could be hundreds or even thousands – would need to communicate with each another through a smart technology adapter."	Director of Public Affairs, Recycling
		"It is unclear how the responsibility for implementing the battery passport requirements is transferred after the battery reaches the end of its first life and needs to be repurposed or recycled. The regulation uses the term "economic actor that places the battery on the market" as the responsible party, but there is room for interpretation."	Senior Manager, Recycling
		"Harmonization is crucial when it comes to reporting data, such as CO2 footprints, and we need a consistent methodology for calculating them. This is important so that everyone can report their data in a comparable and standardized manner."	Senior Manager, Recycling
		"Transportation policies and the classification of the battery as a dangerous waste are among the most important things that affect our business model. They make our work difficult since for every step we take we must inform our local and national governments."	Head of Environmental Management, Reuse
		"The text of national legislation is not very clear on battery storage requirements. It only mentions that hazardous waste must be stored in a closed container, but no further guidelines are provided regarding the types of containers and insulation materials."	Head of R&D, Recycling
	Enabler	"I believe the biggest enabler for us will be the Battery Regulation. It'll give us a good push for adopting circularity practices."	Head of Battery Development, Recycling & Reuse
		"The core information that would be useful for recyclers would be the chemistry inside and the percentages of the different components within the applications in order to improve the sorting process. This would be useful for the whole value chain, knowing the risk associated with the composition of the device."	Head of R&D, Recycling
		"Actors in the market are discussing the objectives set up by the EU and are pushing the market towards electric vehicles. There is a signal to the automotive sector that the transition away from fossil fuels is needed."	Lead Engineer, Reuse

(*continued on next page*)

Table D1 (*continued*)

Category	Type	Quote	Interviewee role
		"EU-funded projects help improve company development and incentivise expansion of recycling operations. They also raise public awareness for companies working in this field."	Innovation Researcher, Recycling
Economic factors	Barrier	"At the early stages, many recycling operations are not profitable. It takes years to develop a process and set up collection schemes. If there are no legal obligations in place, many recycling routes will simply not take off".	Director of Government Affairs, Recycling
		"Repurposing smaller battery packs requires a significant amount of time and effort, resulting in a high cost per kWh. This factor has complicated the launch of an own-initiated project that aimed to repurpose battery packs."	Head of Office, Recycling & Reuse
	Enabler	"Even if not yet well defined, there is high economic value in EoL batteries. Enabling to sell batteries as a second-life application would generate additional revenue streams and support the business model."	Product Sustainability Leader, Recycling and Reuse
		"The price increase of materials works in our favor. It makes new batteries more expensive, but it doesn't affect second-life batteries. Therefore, it actually serves as a driver for us."	Co-Founder & CEO, Reuse
Supply chain	Barrier	"While we sometimes find basic chemical composition details, we usually lack information on the proportion of different metals, such as cobalt and nickel, in the battery".	Head of Innovation, Dismantling
		"Companies are often reluctant to share more data than they are obliged to. It is essential for them to be told when this is a requirement for the project or by the industry, or due to a standard or a law already in place."	Co-Founder, Traceability solutions
	Enabler	"If you can establish relationships between companies that trust each other […], more people get used to [sharing data] and it becomes easier for them, especially when they trust that the information they share is in trusted hands."	Co-Founder, Traceability solutions
Technology	Barrier	"During the manufacturing stage batteries are designed with little consideration for their end-of-life disposal. As a result, when the time comes to dismantle them, it proves to be a laborious and time-consuming process. For instance, the cover is excessively glued all around its perimeter, making it particularly challenging to remove."	Head of Innovation, Dismantling
	Enabler	"Using robots is less risky for human health since they can discharge the batteries. The robotic arms can even be reprogrammed remotely under strict agreements with the recycler. This way, the arms can take the batteries apart, allowing for better access to the cells, cathode and anode plates, and the casings, which can be reused."	CEO, Recycling
Demand network	Barrier	"Consumers often lack knowledge about the contents of the products they use and their recycling opportunities at the end of life. More communication of recycling opportunities, campaigns and guidelines are necessary."	Head of R&D, Recycling
		"Currently, even environmentally conscious companies and startups prioritize cheaper options over the environmental benefits of second-life batteries. This pattern discourages the widespread adoption of second-life batteries. Customers often question why our batteries are not cheaper than new batteries with a higher environmental footprint."	Co-Founder & CEO, Reuse
	Enabler	"Extraction of cobalt and concerns about use of child labour have made people aware of the existence of supply chains for batteries. Environmental concerns […] are also impactful."	Founder, Recycling innovations
		"There is an increasing number of companies interested in buying remanufactured batteries. Another incentive for companies is to reduce their carbon footprint, as remanufactured and refurbished batteries have lower carbon footprint compared to new ones."	Product Sustainability Leader, Recycling & Reuse
Company organisation	Barrier	"A key challenge is that SMEs may find it more difficult to comply with the rules of EU regulations compared to larger organizations. […] It is important to find solutions that can be implemented by all types of organisations, regardless of their size."	Project Lead, Recycling
	Enabler	"A strong commitment to environmental values and the development of partnerships allows us to improve the company organisation and the products."	Strategic Business Analyst, Reuse
Inconsistency		"An inconsistency exists in existing regulations. On the one hand, they promote the second-life and reuse of lithium-ion batteries. However, these used lithium-ion batteries are classified as hazardous waste. This poses a problem because if these batteries still retain some value, they should not be classified as dangerous waste."	Head of Innovation, Dismantling
		"The US Inflation Reduction Act and the pace by which the US is currently driving investments create an uneven playing field and will have implications for the battery sector and battery production globally."	Founder, Recycling innovations

References

Adisorn, T., Tholen, L., Götz, T., 2021. Towards a digital product passport fit for contributing to a circular economy. Energies. (Basel) 14 (8), 2289.

Albertsen, L., Richter, J.L., Peck, P., Dalhammar, C., 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. Resour. Conserv. Recycl. 172, 105658.

Azadnia, A.H., Onofrei, G., Ghadimi, P., 2021. Electric vehicles lithium-ion batteries reverse logistics implementation barriers analysis: a TISM-MICMAC approach. Resour. Conserv. Recycl. 174, 105751.

Battery Pass consortium, 2023. Battery passport content guidance: achieving compliance with the EU Battery Regulation and increasing sustainability and circularity. Version 1.0. April 2023.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H.E., Heidrich, O., 2021. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat. Sustain. 4, 71–79.

Berger, K., Schoggl, J.P., Baumgartner, R.J., 2022. Digital battery passports to enable circular and sustainable value chains: conceptualization and use cases. J. Clean. Prod. 353 (15), 131492.

Chirumalla, K., Kulkov, I., Parida, V., Dahlquist, E., Johansson, G., Stefan, I., 2024. Enabling battery circularity: unlocking circular business model archetypes and collaboration forms in the electric vehicle battery ecosystem. Technol. Forecast. Soc. Change 199, 123044.

Curtis, T.L., Smith, L., Buchanan, H., 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. National Renewable Energy Laboratory, Golden, CO. NREL/TP-6A20-77035.

da Silva, E.R., Lohmer, J., Rohla, M., Angelis, J., 2023. Unleashing the circular economy in the electric vehicle battery supply chain: a case study on data sharing and blockchain potential. Resour. Conserv. Recycl 193, 106969.

Demartini, Ferrari, M., Govindan, K., Tonelli, F., 2023. The transition to electric vehicles and a net zero economy: a model based on circular economy, stakeholder theory, and system thinking approach. J. Clean. Prod. 410, 137031, 2023.

Drabik, E., V. Rizos, V., 2018. Prospects for electric vehicle batteries in a circular economy. CEPS Research Report No 2018/05.

Dunn, J., Kendall, A., Slattery, M., 2022. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. Resour. Conserv. Recycl. 185, 106488.

EBA, 2023 European Battery Alliance. Accessed 17/04/2024 at https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-battery-alliance_en.

Eisenhardt, K.M., 1989. Building theories from case study research. Acad Manage Rev 14 (4), 532–550.

Engels, P., Cerdas, F., Dettmer, T., Frey, C., Hentschel, J., Herrmann, C., Mirfabrikikar, T., Schueler, M., 2022. Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data. J. Clean. Prod. 336, 130474.

European Commission, 2021. Updating the 2020 new industrial strategy: building a stronger single market for Europe's recovery. COM(2021) 350 final.

European Commission, 2022. Proposal for a regulation of the european parliament and of the council establishing a framework for setting ecodesign requirements for sustainable products and repealing directive 2009/125/EC. COM(2022) 142 final.
European Commission, 2023. A green deal industrial plan for the net-zero age. COM (2023) 62 final.
European Parliament and Council, 2023. Regulation (EU) 2023/1542 of the European Parliament and of the council of 12 july 2023 concerning batteries and waste batteries, amending directive 2008/98/EC and regulation (EU) 2019/1020 and repealing directive 2006/66/EC.
Farjana, S.H., Huda, N., Mahmud, M.A., 2019. Life cycle assessment of cobalt extraction process. J. Sustain. Min. 18 (3), 150–161.
GBA, 2024. Global battery alliance. Accessed 17/04/2024 at https://www.globalbattery.org/.
Giosuè, C., Marchese, D., Cavalletti, M., Isidori, R., Conti, M., Orcioni, S., Ruello, M.L., 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. 13 (20), 11154.
Götz, T., Berg, H., Jansen, M., Adisorn, T., Cembrero, D., Markkanen, S., Chowdhury, T., 2022. Digital Product passport: The ticket to Achieving a Climate Neutral and Circular European economy? Wuppertal Institute for Climate, Environment and Energy.
Gupta, S., Chen, H., Hazen, B.T., Kaur, S., Gonzalez, E.D.R.S., 2019. Circular economy and big data analytics: a stakeholder perspective. Technol. Forecast. Soc. Change. 144, 466–474.
Halleux, V. 2023. New EU regulatory framework for batteries. EPRS - European parliamentary research service. PE 747.922.
Haram, M.H.S.M., Lee, J.W., Ramasamy, G., Ngu, E.E., Thiagarajah, S.P., Lee, Y.H., 2021. Feasibility of utilising second life EV batteries: applications, lifespan, economics, environmental impact, assessment, and challenges. Alex. Eng. J. 60 (5), 4517–4536.
Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., 2019. Recycling lithium-ion batteries from electric vehicles. Nature 575, 75–86.
Helander, H., Ljunggren, M., 2023. Battery as a service: analysing multiple reuse and recycling loops. Resour. Conserv. Recycl. 197, 107091.
International Energy Agency, 2021. Annual electric car sales in the sustainable development scenario, 2020-2040 [WWW Document]. URL. https://www.iea.org/data-and-statistics/charts/annual-electric-car-sales-in-the-sustainable-development-scenario-2020-2040. accessed 22.08.23.
Júnior, C.A.R., Sanseverino, E.R., Gallo, P., Koch, D., Kotak, Y., Schweiger, H.G., Zanin, H., 2023. Towards a business model for second-life batteries: barriers, opportunities, uncertainties, and technologies. J. Energy Chem. 78, 507–525.
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., Fontana, A., 2023. A digital product passport for critical raw materials reuse and recycling. Sustainability. 15 (2), 1405.
Kumar, P., Singh, R.K., Paul, J., Sinha, O., 2021. Analyzing challenges for sustainable supply chain of electric vehicle batteries using a hybrid approach of Delphi and Best-Worst Method. Resour. Conserv. Recycl. 175, 105879.
Lee, P., Sims, E., Bertham, O., Symington, H., Bell, N., Pfaltzgraff, L., Sjögren, P., Wilts, H., O'Brien, M., Benke, J., 2017. Towards a circular economy – Waste management in the EU. Study IP/G/STOA/FWC/2013-001/LOT 3/C3. 10.2861/978568.
Li, M., Lu, J., Chen, Z., Amine, K., 2018. 30 Years of lithium-ion batteries. Adv. Mater. 30 (3), 1800561.
Lune, H., Berg, B.C., 2017. Qualitative Research Methods For the Social Sciences, 9th edition. Pearson Education Limited, Harlow.
Ma, X., Azhari, L., Wang, Y., 2021. Li-ion battery recycling challenges. Chem. 7 (11), 2843–2847.
Mancini, L., Eslava, N.A., Traverso, M., Mathieux, F., 2021. Assessing impacts of responsible sourcing initiatives for cobalt: insights from a case study. Resour. Policy. 71, 102015.
Marshall, B., Cardon, P., Poddar, A., Fontenot, R., 2013. Does sample size matter in qualitative research?: a review of qualitative interviews in is research. J. Comput. Inf. Syst. 54 (1), 11–22.
Mayyas, A., Steward, D., Mann, M., 2019. The case for recycling: overview and challenges in the material supply chain for automotive li-ion batteries. Sustainable Mater. Technol. 19, e00087.
Miles, M.B., Huberman, A.M., 1994. Qualitative Data Analysis: An Expanded Sourcebook, 2nd edition. Sage Publications, Thousand Oaks.
Moro, A., Lonza, L., 2018. Electricity carbon intensity in European Member States: impacts on GHG emissions of electric vehicles. Transp. Res. D: Transp. Environ. 64, 5–14.
Murdock, B.E., Toghill, K.E., Tapia-Ruiz, N., 2021. A perspective on the sustainability of cathode materials used in lithium-ion batteries. Adv. Energy Mater. 11 (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.
Nie, Y., Wang, Y., Li, L., Liao, H., 2023. Literature review on power battery echelon reuse and recycling from a circular economy perspective. Int. J. Environ. Res. Public Health. 20, 4346.
Olabi, A.G., Abbas, Q., Shinde, P.A., Abdelkareem, M.A., 2023. Rechargeable batteries: technological advancement, challenges, current and emerging applications. Energy 266 (1), 126408.
Ossenbrink, J., Finnsson, S., Bening, C.R., Hoffman, V.H., 2019. Delineating policy mixes: contrasting top-down and bottom-up approaches to the case of energy-storage policy in California. Res. Policy. 48, 103582.
Parviziomran, E., Elliot, V., 2024. Barriers to circular economy: insights from a small electric vehicle battery manufacturer. J. Purch. Supply Manag., 100905
Ragin, C.C., 2000. Fuzzy-Set Social Science. The University of Chicago Press, Chicago.
Rajaeifar, M.A., Ghadimi, P., Raugei, M., Wu, Y., Heidrich, O., 2022. Challenges and recent developments in supply and value chains of electric vehicle batteries: a sustainability perspective. Resour. Conserv. Recycl. 180, 106144.
Rallo, H., Sánchez, A., Canals, Ll., Amante, B., 2022. Battery dismantling centre in Europe: a centralized vs decentralized analysis. RCR Advances 15, 200087.
Requia, W.J., Mohamed, M., Higgins, C.D., Arain, A., Ferguson, M., 2018. How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health. Atmos. Environ. 185, 64–77.
Righetti, E., Rizos, V., 2023. The EU's Quest for strategic raw materials: what role for mining and recycling? Intereconomics 58 (2), 69–73.
Rizos, V., Bryhn, J., 2022. Implementation of circular economy approaches in the electrical and electronic equipment (EEE) sector: barriers, enablers and policy insights. J. Clean. Prod. 338, 130617.
Rojaee, R., Shahbazian-Yassar, R., 2020. Two-dimensional materials to address the lithium battery challenges. ACS Nano 14 (3), 2628–2658.
Rönkkö, P., Ayati, S.M., Majava, J., 2021. Remanufacturing in the heavy vehicle industry—case study of a finnish machine manufacturer. Sustainability. 13, 11120.
Saldaña, J., 2013. The Coding Manual For Qualitative Researchers, 2nd edition. Sage Publications, London.
Saunders, M., Lewis, P., Thornhill, A., 2009. Research Methods for Business Students, 5th edition. Pearson Education Limited, Harlow.
Serna-Guerrero, R., Ikonen, S., Kallela, O., Hakanen, E., 2022. Overcoming data gaps for an efficient circular economy: a case study on the battery materials ecosystem. J. Clean. Prod. 374, 133984.
Sheth, R.P., Ranawat, N.S., Chakraborty, A., Mishra, R.P., Khandelwal, M., 2023. The lithium-ion battery recycling process from a circular economy perspective—a review and future directions. Energies. (Basel) 16 (7), 3228.
Sopha, B.M., Purnamasari, D.M., Ma'mun, S., 2022. Barriers and Enablers of circular economy implementation for electric-vehicle batteries: from systematic literature review to conceptual framework. Sustainability. 14 (10), 6359.
Stampatori, D., Raimondi, P.P., Noussan, M., 2020. Li-Ion batteries: a review of a key technology for transport decarbonization. Energies. (Basel) 13 (10), 2638.
Tripathy, A., Bhuyan, A., Padhy, R.K., Mangla, S.K., Roopak, R., 2023. Drivers of lithium-ion batteries recycling industry toward circular economy in industry 4.0. Comput. Ind. Eng. 179, 109157.
Van Buren, N., Demmers, M., van der Heijden, R., Witlox, F., 2016. Towards a circular economy: the role of Dutch logistics industries and governments. Sustainability 8 (7), 647.
Vermunt, D.A., Negro, S.O., Verweij, P.A., Kuppens, D.V., Hekkert, M.P., 2019. Exploring barriers to implementing different circular business models. J. Clean. Prod. 222, 891–902.
Voss, C., Tsikriktsis, N., Frohlich, M., 2002. Case research in operations management. Int. J. Oper. Prod. Manag. 22, 195–219.
Wilts, H., von Gries, N., Bahn-Walkowiak, B., 2016. From waste management to resource efficiency—the need for policy mixes. Sustainability. 8 (7), 622.
Wrålsen, B., Prieto-Sandoval, V., Mejia-Villa, A., O'Born, R., Hellstrom, M., Faessler, B., 2021. Circular business models for lithium-ion batteries - Stakeholders, barriers, and drivers. J. Clean. Prod. 317, 128393.
Yin, R.K., 1994. Case Study Research and Methods: Design and Methods, 2nd edition. Sage Publications, Thousand Oaks.
Yin, R.K., 2009. Case Study Research and Methods: Design and Methods, 4th edition. Sage Publications, Thousand Oaks.
Ziegler, M.S., Song, J., Trancik, J.E., 2021. Determinants of lithium-ion battery technology cost decline. Energy Environ. Sci. 14, 6074–6098.