Global Circular Economy Status of Retired Traction Lithium-ion Batteries: Market, Policy, and Technological Gaps and Causes

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Executive Summary

This research examines the global circular economy (CE) status of retired traction lithium-ion batteries (LIBs), focusing on market trends, policy frameworks, and technological advancements. It begins by highlighting the uneven adoption of circular practices across key regions, noting that while countries like China have achieved large-scale battery recycling, others struggle with minimal collection rates and limited infrastructure. We identified economic disincentives, including higher costs for recycled materials relative to virgin-sourced alternatives, as a fundamental barrier to broad-based recycling adoption.

On the policy front, strict mandates and regulatory consistency correlate strongly with improved battery recovery rates. Nevertheless, many regions lack cohesive policies and robust enforcement mechanisms, undermining the economic incentives needed to scale up recycling. Technologically, advanced methods capable of efficiently recovering lithium, cobalt, and nickel do exist but often remain confined to laboratory settings. The limited commercial adoption stems from both high capital costs and an industry preference for established processes, which typically focus on extracting only the most valuable metals.

Despite constraints in data availability, we found clear opportunities for stakeholders to optimize battery lifecycles. Formalizing informal recycling channels, strengthening extended producer responsibility, and expanding second-life applications hold particular promise in emerging economies. The report concludes that closing the gap between academic breakthroughs and industrial practice will require sustained coordination among governments, industry, and research institutions. By adopting robust policy measures, embracing cost-effective technologies, and prioritizing workforce training, a truly CE for traction LIBs becomes a credible pathway toward sustainability and resource efficiency.

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1 Introduction

As electric vehicles (EVs) have become a consumer-preferred mainstream product within the automotive industry, the negative environmental externalities associated with retired traction lithium-ion batteries (LIBs) are often overlooked. Is our society adequately prepared to handle the massive volume of EV batteries that reaches end-of-life (EoL) in the near future? The global shift towards sustainable energy has accelerated the deployment of EVs, positioning LIBs as a dominant energy storage technology due to their superior energy density, long cycle life, and rechargeability (Philippot et al., 2019). As electric mobility gains traction, the demand for LIBs has surged, underscoring their role in modern energy systems. Traction batteries, a specific category of LIBs, are designed for high-demand applications in electric trucks, buses, and passenger cars, essential for the decarbonization of the transportation sector. These batteries are engineered to provide high power output, long-range capabilities, and reliable performance under diverse conditions, making them crucial to decreasing fossil fuel dependency and alleviating greenhouse gas emissions (Bouter & Guichet, 2022).

China has emerged as the largest global market for EVs and traction batteries, propelled by robust policy support, technological innovation, and strong market demand. Government initiatives, including subsidies, infrastructure investments, and stringent regulations to curb air pollution, have positioned China as a leader in the electric mobility sector. Since 2020, China has accounted for more than half of global EV sales, underscoring the country’s central role in driving electric mobility globally. Moreover, the Chinese government has made significant investments in R&D, focusing on enhancing battery energy density, cost efficiency, and safety features (Velázquez-Martínez et al., 2019a). These efforts have led to innovations such as improved cathode and anode materials, advancements in battery management systems, and the exploration of new recycling technologies. However, despite these advancements, challenges persist, including recycling complexities, supply chain vulnerabilities, and the need for further improvements in performance and sustainability. Addressing these issues will require continuous innovation, enhanced infrastructure, and effective policies to build a more resilient and sustainable LIBs market in China (Islam & Iyer-Raniga, 2022a).

Given China's leading role in the EV market, the adoption of a circular economy (CE) model is crucial for achieving sustainable development goals. The CE's focus on resource reuse and recycling aligns with the need to address the environmental challenges imposed by retired traction LIBs. The CE model presents an alternative economic system that aims to minimize waste and maximize resource utilization by promoting reuse, recycling, and regeneration (Gutsch & Leker, 2022). The concept of a CE emphasizes the reusability and recycling of resources, aiming to reduce waste and create closed-loop systems (Kara et al., 2022). In the context of traction batteries, the CE approach can potentially mitigate the environmental impacts by enhancing the sustainability of battery production, use, and disposal processes (Bouter & Guichet, 2022).

With the projected growth in EVs and the subsequent increase in LIBs demand, the need for a sustainable approach to battery production, use, and disposal becomes evident. The CE model encourages the extension of battery life through repair and refurbishment, the use of second-life applications, and ultimately, the recycling of batteries to recover valuable materials such as lithium, cobalt, and nickel. This not only mitigates environmental impact of mining new resources but also creates economic value by closing the loop on material use.

Moreover, the CE in battery management is essential for mitigating the environmental and social impacts associated with the linear economy's waste generation. It promotes the development of industrial systems that are restorative by design, which is particularly important as the global demand for batteries is projected to reach over 5.5 TWh by 2030, with LIBs accounting for more than 90% of this demand (Systemiq, 2023). The CE approach can help in reducing the greenhouse gas intensity of batteries while creating additional economic value, making it a critical component in the journey towards sustainable battery management and a just transition in the battery industry (Fleischmann et al., 2023).

The rapid expansion of EV market has significantly increased the demand for traction LIBs, presenting considerable environmental and resource management challenges. The existing linear economy (LE) model, characterized by resource extraction, use, and disposal, dominates the industry, leading to concerns over resource depletion, waste accumulation, and adverse environmental impacts. This model exacerbates sustainability issues, undermining global efforts to combat climate change and conserve resources (Neves & Marques, 2022). Shifting towards a CE model offers a viable solution by promoting closed-loop systems that emphasize reuse, recycling, and regeneration of materials, reducing environmental harm and conserving valuable resources (Gutsch & Leker, 2022).

However, despite the clear benefits, the transition to a CE in the traction battery sector has been inconsistent, with significant disparities across different regions. Policy frameworks, technological capabilities, and design constraints vary, resulting in uneven adoption of CE practices (Malik, 2023). Current recycling practices face numerous inefficiencies, and regulatory barriers often limit the effective recovery of valuable materials from EoL batteries. For instance, the economic viability of recycling is impeded by the high costs of material recovery, and technological challenges persist in efficiently processing different battery chemistries. Furthermore, existing practices continue to contribute to environmental problems, including GHG emissions, hazardous waste generation, and excessive water use, underscoring the need for comprehensive CE measures (Helbig & Hillenbrand, 2024). Life-cycle assessments (LCA) have demonstrated that the externalities associated with traction batteries, from production to disposal, are inadequately addressed by existing systems. Sustainable future development in this sector requires the widespread adoption of CE principles, reinforced by robust policies, technological innovation, and increased investment in recycling infrastructure (Malik, 2023; Philippot et al., 2019).

Hence, the research objectives and scope of this consultancy report are delineated to ascertain the divergence between the prevailing state of the retired traction LIBs industry and the envisioned CE paradigm, with a focus on identifying the underlying causes. The overarching research question seeks to elucidate the CE status of the LIBs industry in China and globally, from 3 vantage points of market dynamics, policy frameworks, and technological advancements, thereby aiming to uncover the reasons for any discrepancies. The market survey endeavors to ascertain whether the current LIBs industry adheres to a LE or CE model, and to quantify the extent of this adherence on a country-by-country basis. The policy review will identify and situate discrepancies between the CE market practices and existing policies, followed by a discussion on the potential reasons for these incongruities. Lastly, the technology analysis will investigate the existence of a gap between academic research and industrial practices in LIBs recycling technology, and to explore the scientific rationale behind any prevailing technical bottlenecks.

By examining the alignment of the industry with CE principles, we will offer a global perspective on the sustainability of battery production and management practices, identifying regional differences and potential areas for improvement. It will provide a clear and explicit statement of its objectives, ensuring transparency and replicability in its approach. The importance of this consultancy report for the field of environmental science and the automotive industry will be emphasized, highlighting its potential impact on policy development, industry practices, and future technological innovations.

In this consulting report, the market, policy, and technological aspects of the CE for retired traction LIBs are examined. Literature reviews assess the status and identify research gaps in market practices, policy frameworks, and technological advancements. The overview highlights the methodology and objectives of the study, setting the stage for a comprehensive analysis of the global LIBs management ecosystem.

2 Background

2.1 Market Survey

2.1.1 Global LIBs Market and CE Challenges

To understand the current state of LIBs recycling, it is essential to examine global market dynamics and the future directions of the industry. The global LIBs market has experienced significant growth due to the rising adoption of electric vehicles (EVs) and the increasing demand for energy storage solutions. Despite this expansion, sustainability challenges persist, primarily concerning the lifecycle management of batteries. The current industry practices often align with a LE model, characterized by extraction, use, and disposal, leading to issues such as resource depletion and environmental degradation.

One research highlighted that most regions still operate within this LE framework, with limited efforts towards recycling and reuse (Velázquez-Martínez et al., 2019b). The CE model, which promotes closed-loop systems by encouraging recycling and regeneration, presents a promising alternative. However, the transition to CE has been uneven across regions. Europe has led the way, driven by regulatory frameworks such as the EU Battery Directive, which mandates the collection, recycling, and management of EoL batteries (Harper et al., 2023a). Germany, France, and Netherlands have particularly mature recycling infrastructures, supported by strong policies and investments in technology. The emphasis on sustainable practices in Europe has facilitated the development of efficient material recovery systems, positioning the region as a leader in circular models for LIBs.

In contrast, Asia, particularly China, remains the largest producer of LIBs but continues to face substantial challenges in fully implementing CE practices. Despite government efforts to promote recycling through policies and incentives, the infrastructure is still developing, and technological limitations persist. A study pointed out that while China has the potential to become a leader in CE, consistent implementation and investment in recycling technologies are needed to realize this potential fully (Islam & Iyer-Raniga, 2022b). The market remains heavily focused on production, with less emphasis on EoL management.

The United States has also struggled to adopt CE practices, largely due to fragmented policies at the federal and state levels. Private sector initiatives have driven some progress, but a lack of cohesive national policy has hindered broader adoption (Baum et al., 2022). Economic factors, such as the high cost of recycling compared to manufacturing new batteries, also play a significant role in limiting CE practices in the U.S. Without robust incentives and consistent standards, recycling efforts remain less economically attractive for companies, deterring significant investments in recycling infrastructure (Mossali et al., 2020).

The market dynamics indicate that while some countries have made strides towards adopting CE practices, broader global adoption requires overcoming substantial policy, technological, and economic barriers. Understanding these regional differences is essential for advancing sustainable practices and achieving global sustainability goals within the LIBs industry. Collaboration between nations, particularly in sharing best practices and aligning regulations, could accelerate the global shift towards a CE for LIBs (Harper et al., 2023a).

2.1.2 Key Research Gaps in Market Practices

Despite regional advancements, several gaps remain in the current research. There is a noticeable lack of cross-regional comparative studies, making it challenging to evaluate the effectiveness of policies on CE adoption across different markets (Ranta et al., 2018). Additionally, more research is needed to develop cost-efficient recycling technologies that can compete with traditional manufacturing processes, especially in markets with underdeveloped infrastructures (Wrålsen et al., 2021). Existing literature also falls short in establishing standardized guidelines for reusing LIBs, which are critical for fostering broader adoption of circular models (Islam & Iyer-Raniga, 2022b). Addressing these gaps is essential for facilitating a more cohesive and effective transition towards a CE in the global LIBs market.

2.2 Policy Review

2.2.1 Gap Between CE Market and Policies in Recycling Technology

The transition to a CE for retired traction LIBs is hindered by a significant gap between market practices and existing policies. While policies are often formulated with ambitious goals to promote the CE of batteries, academic research has not fully caught up in providing detailed implementation strategies. For example, policies may target high recycling rates, but academic studies lack in-depth exploration of the economic and logistical feasibilities within the market context.

In 2021, case study research focused on several countries' battery recycling initiatives (Rizos & Urban, 2024). They determined that one potential reason for the gap is the misalignment of incentives. Policies may have good intentions, such as reducing environmental impacts, but the implementation fails as market actors do not have sufficient economic incentives to comply. For instance, the high cost of setting up advanced battery recycling facilities is not offset by the current policy incentives, leading to a slow adoption rate in the market.

Another research utilized a survey of industry and academic stakeholders. Their key finding was that a lack of communication and collaboration between academia and the market is a major contributor to the gap. Academic research often occurs in isolation, not fully understanding the real-time challenges and opportunities in the market. As a result, policies are based on incomplete or inaccurate academic insights, and market actors do not have access to the latest research findings to inform their operations. And they applied a data analytics method to analyze policy trends and academic research outputs. They discovered that the rigidity of policy frameworks is another issue. Policies are sometimes slow to adapt to the dynamic nature of the market and the rapid advancements in battery technology. Academic research may propose innovative solutions, but policies do not have the flexibility to incorporate them quickly, leading to a widening gap.

Furthermore, one research found that the complexity of the battery supply chain is a factor. Policies may not consider the full scope of the supply chain, from battery production to EoL recycling, and academic research may focus only on specific segments. This lack of holistic understanding results in gaps between what is envisioned in policy and what can be achieved in the market (Albertsen et al., 2021).

2.2.2 Justifications for Existing Policy Approaches

The existing policies on LIBs recycling are shaped by several scientific and technological factors. Firstly, the complexity and variability of battery chemistries pose significant challenges for recycling. Different types of LIBs, such as lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP), require distinct recycling processes due to their unique chemical compositions. This complexity is highlighted in a study demonstrating that the state of health (SOH) of batteries significantly influences the efficiency and profitability of recycling technologies (Calisto Friant et al., 2021). The study's cradle-to-grave analysis reveals that higher SOH levels result in better economic and environmental outcomes, thereby necessitating policies that account for these variations.

Secondly, the economic viability of recycling technologies is a critical factor influencing policy decisions. A study discusses the economic challenges associated with implementing advanced recycling technologies, such as direct recycling (Chenavaz & Dimitrov, 2024). The study uses bibliometric analysis to identify major research trends and gaps, concluding that the high initial costs and technological complexities deter widespread adoption. Consequently, policies tend to favor more established, albeit less efficient, recycling methods.

In addition, the lack of standardized methodologies for assessing the environmental impacts of recycling technologies complicates policy formulation. Conventional recycling methods, such as pyrometallurgy and hydrometallurgy, focus on specific metals and often overlook the broader environmental implications (Hayagan et al., 2024). The study advocates for the development of unified assessment methodologies that can provide a comprehensive evaluation of different recycling scenarios, thereby informing more effective policy decisions.

Lastly, the regulatory landscape is influenced by the need to optimize the trade-off between economic performance and environmental sustainability. The joint position paper by NGOs (2021) argues that current policies are often shaped by short-term economic interests rather than long-term sustainability goals (EU, 2021). The paper recommends the introduction of economic incentives and regulatory measures to promote the adoption of advanced recycling technologies and the integration of second-life applications.

2.2.3 Policy Research Gap Identification

The literature on the CE status of retired traction LIBs reveals several controversies and limitations. One significant controversy lies in the effectiveness of different recycling technologies. While Ma et al. (2024) advocate for direct recycling due to its high recovery rates and environmental benefits, this method is not widely adopted due to economic and technological barriers (Ma et al., 2024a). Additionally, the lack of standardized methodologies for assessing the environmental impacts of recycling technologies complicates policy formulation (Hayagan et al., 2024). Furthermore, the economic viability of recycling technologies remains a critical issue, as high initial costs and technological complexities deter widespread adoption (Chenavaz & Dimitrov, 2024). Lastly, there is a shortage of quantitative research supporting the implications of CE policies, calling for more empirical studies to inform policy decisions (Calisto Friant et al., 2021).

2.3 Technological Analysis

2.3.1 Gap of Academic Research and Industry in Recycling Technology

A notable gap exists between academic research and industrial practices in the recycling technology of retired traction LIBs. This gap is evident from the disparity in technological advancements and their practical applications. While academic research has made considerable progress in developing advanced recycling methods such as hydrometallurgical and direct recycling techniques, these methods have not been widely adopted by the industry due to economic and logistical challenges (Ma et al., 2024b). The study employed a LCA approach to evaluate the environmental and economic impacts of different recycling methods, highlighting that although advanced methods are more environmentally friendly, they are often cost-prohibitive for large-scale industrial applications.

Moreover, a review indicated that the global recycling rate for materials, including LIBs, remains around 45%, despite significant technological advancements (Giglio et al., 2024). This review utilized a bibliometric analysis of academic publications and industry reports to map the technological progress and challenges in recycling. The findings suggest that the slow adoption of advanced recycling technologies in the industry is partly due to the high initial investment costs and the lack of a robust infrastructure for material collection and processing.

The U.S. Department of Energy's National Blueprint for Lithium Batteries (2021-2030) also underscores this gap by outlining the need for a coordinated effort to bridge the divide between research and industrial application (FCAB, 2021). The blueprint emphasizes the importance of developing a domestic supply chain for LIBs that includes advanced recycling technologies. However, it acknowledges that current industrial practices are lagging behind academic research due to economic constraints and regulatory restrictions.

2.3.2 Potential Scientific Reasons for Current Technical Bottlenecks

Several scientific reasons contribute to the current technical bottlenecks in the recycling of retired traction LIBs. One primary issue is the complexity of LIBs composition, which includes a variety of materials such as lithium, cobalt, nickel, and manganese. They require different extraction and processing techniques, making the recycling process technically challenging and economically unviable in some cases. The heterogeneous nature of LIBs complicates the recycling process, as different battery chemistries require tailored recycling approaches (Tembo et al., 2024). This review analyzed various recycling methods and their effectiveness, highlighting that the lack of standardized processes for different battery types is a significant bottleneck.

Another critical bottleneck is the state of health (SOH) of retired batteries, which affects the efficiency and profitability of recycling methods. SOH of batteries significantly impacts the outcomes of different recycling technologies (Ma et al., 2024b). For instance, batteries with higher SOH are more suitable for direct recycling methods, which are more efficient but less commonly used due to their technical complexity and high costs.

Furthermore, the economic viability of recycling technologies is influenced by the volatile prices of raw materials. The National Blueprint for Lithium Batteries (2021-2030) notes that the cost of recycling is often higher than the value of the recovered materials, particularly when the prices of critical materials like cobalt and nickel are low (FCAB, 2021). This economic challenge discourages the adoption of advanced recycling technologies that are otherwise environmentally beneficial.

In summary, the gap between academic research and industrial practices in LIBs recycling is driven by economic and logistical challenges, despite significant technological advancements. The scientific reasons for the current technical bottlenecks include the complex composition of LIBs, the varying SOH of retired batteries, and the economic viability of recycling methods. Addressing these challenges requires coordinated efforts between academia, industry, and government to develop cost-effective and efficient recycling technologies.

2.3.3 Technology Research Gap Identification

Several controversies and limitations in the current literature revolve around the economic feasibility of advanced recycling technologies. Despite academic research advocating methods like hydrometallurgical and direct recycling due to their higher material recovery rates (Gaines, 2018), these are often hindered from widespread industrial adoption due to high operational costs and technological complexities. The heterogeneity of battery chemistries, such as NMC and LFP, also presents a significant challenge as they require specific recycling processes, complicating the development of universal solutions and increasing the complexity and cost of sorting and processing (Ma et al., 2024b). A notable research gap is the lack of standardized protocols for battery recycling, leading to inconsistent practices and inefficiencies across different facilities (Chen et al., 2019a). Moreover, the impact of battery degradation on recycling efficiency is often overlooked, with batteries of lower states of health yielding fewer valuable materials and diminishing the economic viability of the recycling process.

3 Analytical Strategy

3.1 Research Design: Mixed Methods Approach

Our research applies a mixed methods approach, combining field and desktop research to comprehensively assess the global circular economy status of retired traction LIBs. The field research consists of a questionnaire interview followed by a stakeholder analysis and mapping process. The questionnaire is designed to determine the roles, priorities, and influence of stakeholders lying within the EV battery value chain, exploring their altitude and capturing their insights about traction LIBs CE adoption. Responses are analyzed using a stakeholder power-interest grid overlayed with strategy matrix (Freeman, 2010), which classifies stakeholders based on their ability to influence and their interest in traction LIBs CE development.

The desktop research is represented by benchmarking analysis, systematically comparing the LIB recycling industry's performance across different countries. This analysis follows a structured framework that includes key indicators such as recycling rates, economic profitability, material recovery efficiency, regulatory stringency, and technological maturity. The selection of these metrics is justified by their ability to capture essential industry dynamics and policy effectiveness. For example, recycling rates reflect the efficiency of existing collection and recovery systems, while regulatory stringency indicates the strength of legal frameworks promoting CE principles (Bongers & Casas, 2022). The study draws on official reports, peer-reviewed literature, and industry reports to ensure robust comparative insights. By integrating both qualitative and quantitative data, this research enhances its empirical depth and practical relevance, providing a holistic assessment of the CE landscape for retired traction LIBs.

3.1.1 Field Research Procedure: Stakeholder Engagement & Analysis

The stakeholder analysis and mapping process follows a structured approach to systematically identify, categorize, and assess the influence of various stakeholders involved in the CE of retired traction LIBs. This process begins with stakeholder identification, where key actors within the LIBs value chain are recognized. These include EV consumers, LIBs producers, EV manufacturers, LIBs recyclers, automotive manufacturers, government agencies, non-governmental organizations (NGOs), and academia. Each stakeholder group is identified based on their roles in different stages of the battery lifecycle, including supply chain, battery production, battery consumption, reuse and recycling, and second-life applications.

Once stakeholders are identified, the next step involves collecting qualitative insights through stakeholder interviews using a standardized survey instrument. This survey is designed to gather data on stakeholders' interests, priorities, level of influence, and perceived challenges in implementing circular economy initiatives (Appx. A). Respondents indicate their main concerns, including economic profitability, compliance with environmental regulations, technological barriers, and market expansion opportunities. They will also need to provide information on their willingness to collaborate with other stakeholders and the mechanisms they prefer for cooperation, such as research and development partnerships, supply chain collaboration, or industry association initiatives. The survey results will be summarized in the stakeholder analysis table (Table 1).

Table 1. Stakeholder analysis summary table for traction LIBs industry

Stakeholder Identity	CE Stage(s) Involved	Key Interests	Influence Power	Alignment with CE Goals	Support/ Opposition Rationale	Strategic Actions
…						

Columns Legend:

Stakeholder Identity	Group classification (e.g., Manufacturer, Government, Recycler, NGO, Academia).
CE Stages Involved	What value chain stages do they involve (e.g. Production, Consumption, Recycling).
Key Interests	Primary objectives (e.g., Profitability, Compliance, *Market Expansion*).
Level of Influence	Degree of impact on CE outcomes (High/Medium/Low).
Alignment with CE Goals	Supportive/Neutral/Resistant
Support/Opposition Rationale	This stakeholder favors or disfavors CE practices due to: obstacles faced (e.g., High Costs, Regulatory Gaps, Technical Limitations), or opportunities (e.g., *Seeks cost savings via recycling*).
Strategic Actions	Recommendations to engage/influence (e.g., *Subsidies for recyclers*, *R&D partnerships*).

After gathering responses, the collected data will be mapped into a power-interest grid, which categorizes stakeholders based on their ability to influence traction LIBs CE outcomes and their level of interest in such initiatives. High-power, high-interest stakeholders, such as government agencies and major LIBs producers with lobbying capacity, are identified as key decision-makers, while high-power, low-interest stakeholders, such as certain policymakers, may require strategic engagement to increase their involvement. Stakeholders with low power but high interest, such as NGOs and consumer advocacy groups, may play an important role in lobbying and awareness campaigns. The final step is overlaying the stakeholders power interest-grid with a strategy matrix (Fig. 1), which determines the optimal engagement approach for each category. This structured approach ensures that the analysis leads to actionable insights, guiding policy recommendations and collaborative strategies that enhance CE adoption in the LIBs industry.

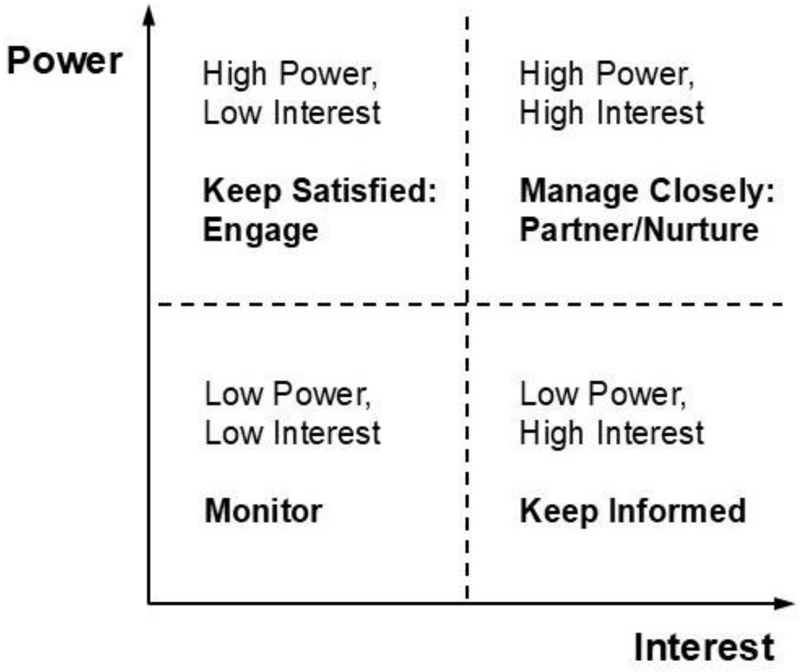

Fig. 1 The power-interest grid for matching stakeholders with targeted management strategies.

3.1.2 Desktop Research: Benchmarking Analysis Procedure

The benchmarking analysis follows a structured approach to assess the global CE status of traction LIBs by systematically comparing key performance indicators across nations, providing insights into economic feasibility, policy effectiveness, and technological development. Each research sub-question has been carefully chosen to capture essential industry dynamics, while the selection of representative metrics and literature strands ensures that findings are grounded in empirical data and comparative assessments (Table 2).

Table 2. The benchmarking analysis roadmap for surveying the traction LIBs industry landscape

Research Framework	Benchmarking Analysis		
Aspects	Market	Policy	Technology
Research Sub-questions	Is the current LIBs battery industry following a linear or circular economy, and to what extent in which country?	Identify discrepancies between CE market and policies. Discuss potential reasons.	Is there a gap between academic research and industries in recycling technology?
Scope	Production, Reuse, Recycle, Disposal, Economic Cost	Policy gap analysis, geopolitical trends (e.g., national regulations)	Technological gap analysis, recycling efficiency, R&D focus

Type of Metrics or Area of Interest	1. Shipment volumes by traction LIBs 2. Market size & market shares by traction LIBs producer & recycler 3. Linear vs. circular cost comparison: virgin vs. recycled materials. 4. Reuse and recycling rates 5. EoL disposal volumes	1. Global regulatory frameworks for traction LIBs production, reuse, recycling, disposal 2. Policy alignment with CE goals 3. Compliance rate 4. Incentive mechanisms (e.g. Economic incentives like subsidies or tax credits) 5. Geopolitical trends (e.g., EU Green Deal)	1. Global traction LIBs recycling R&D investment trends 2. Academic vs. industry recycling patents topic trend 3. Material recovery rates of the recycling process 4. Technology readiness levels (e.g. Safety concerns for LIBs disassembly.)

3.1.2.1 Global Market Status of Circular Economy for Traction LIBs

The market status evaluation examines the entire lifecycle of traction LIBs within the CE framework, from production to disposal. The scope of this research sub-question is to determine how LIBs are manufactured, repurposed, and processed at the end of their life, enabling a cross-regional comparison of CE adoption levels. The rationale for this choice is that understanding industry-wide practices helps identify best-case scenarios and areas requiring intervention. To ensure robust comparisons, metrics such as production volumes, reuse rates, recycling efficiency, and landfill diversion rates are assessed. These indicators reflect the overall effectiveness of a region's CE implementation. The chosen literature strands include market reports, industry white papers, and academic studies that detail LIBs lifecycle performance, sustainability trends, and economic feasibility assessments.

3.1.2.2 Global Policy Status of Circular Economy for Traction LIBs

The policy benchmarking assesses the regulatory frameworks governing LIBs production, reuse, recycling, and disposal in various countries worldwide, aiming to compare the efficacy of different policy approaches in promoting CE practices. Policies play a critical role in shaping industry behavior, influencing compliance levels, and fostering sustainability initiatives. Key factors to consider includes policy alignment, compliance rate, and incentives mechanisms. These indicators help determine the extent to which regulatory framework facilitates CE adoption. The selected literature strands consist of government regulations, international policy comparison studies, legal analyses, and regulatory compliance reports that provide data on LIB-related environmental legislation.

3.1.2.3 Global Research and Technological Status of Circular Economy for Traction LIBs

The technological assessment evaluates the maturity of LIBs recycling and repurposing technologies. The scope of this sub-question is to identify gaps between academic research and industrial application, as well as to assess the commercial (Gürel, 2017)scalability of emerging technologies. Technological innovation is a key enabler of LIBs CE practices, and benchmarking regional differences allows for the identification of best practices. The chosen metrics include the efficiency of LIBs recycling processes, the rate of second-life battery adoption, the number of industry patents, and the funding allocated to battery technology research. These indicators provide insight into the technological readiness of different regions. Relevant literature includes scientific publications on LIBs recycling advancements, technology patents, and industry reports on research funding.

3.2 SWOT-TOWS Analysis for Deriving Recommendations

Once the results are gathered, we will apply the SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis to synthesize findings from stakeholders and benchmarking analysis. The rationale for using SWOT is its ability to categorize industry conditions into clear strategic insights (Gürel, 2017). The internal environment is defined as the traction LIBs industry, whereas the external environment includes economic, or policy forces exerted on the industry. This framework categorizes internal factors such as technological capabilities and market readiness, and external factors such as policy environment and capital investment that accelerate or hinder traction LIBs CE adoption.

Building upon SWOT, the TOWS matrix is applied to develop actionable strategies. Unlike SWOT, which merely identifies factors, TOWS structures them into strategic responses. For instance, if a major threat is weak policy enforcement, TOWS formulates industry-led initiatives to mitigate regulatory gaps (Weihrich, 1982). This structured approach ensures that conclusions are evidence-based, data-driven and strategically sound.

Our analytical strategy provides a structured framework for assessing the global CE of traction LIBs. The integration of benchmarking analysis and stakeholder analysis ensures a balanced evaluation of market trends, policy effectiveness, and technological advancements. By applying the SWOT-TOWS framework to evaluate the status, empirical findings can be translated into strategic recommendations, which is intended to inform policymakers, industry leaders, and researchers in optimizing CE practices for LIBs.

4 Result

4.1 Market Survey

4.1.1 Shipment Volumes of Traction LIBs

Global LIBs shipments totaled 1,501.9 GWh in 2024, reflecting a 22.0% year-over-year (YoY) increase, with EV traction LIBs accounting for 1,036 GWh, an 18.6% annual rise (Chico, 2025). China led global shipments, reaching 1,175 GWh, a 32.6% increase from 2023. Of this, EV traction batteries comprised over 780 GWh, while energy storage batteries exceeded 335 GWh, growing 23% and 64% YoY, respectively (China Economic Net, 2025). China's EV market expansion with 12.87 million units sold in 2024, which is a 35.5% increase from the prior year, further solidified its dominance, increasing its global EV market share from 64.8% in 2023 to 70.5% in 2024 . In contrast, Europe's EV sales declined by 2.0% to 2.89 million units, while the U.S. market grew by 7.2% to 1.57 million units (EVTank, 2025). The traction LIBs industry remains highly concentrated, with CATL maintaining global leadership, shipping 339.3 GWh. BYD, leveraging vertical integration, ranked second, while South Korea's LG Energy Solution (LGES) followed at 120 GWh. Notably, China's CALB surpassed Japan's Panasonic, reinforcing China's increasing influence in the global battery sector (SNE Research, 2025).

4.1.2 Market Size & Market Shares by Traction LIBs Producer & Recycler

The global traction LIBs market expanded significantly in 2024 (Vega-Muratalla et al., 2024), driven by rising EV adoption and increased production capacity (Popien et al., 2023). Market valuation is projected to increase from $34.2 billion in 2020 to $87.5 billion by 2027, with production capacity estimated between 2–3.5 TWh by 2030 (Li & Jin, 2023). China dominates production, benefiting from resource availability, economies of scale, and policy support, with CATL alone accounting for 37.9% of the global market in 2024 (SNE Research, 2025). While Europe and North America are scaling up production, supported by EU decarbonization policies and U.S. incentives under the Inflation Reduction Act, Asia-Pacific remains the global leader in LIBs manufacturing (Degen, 2023).

Table 3. Regional market trends and key players in traction LIBs production

Region	Key Players	Market Share Trends	Sources
Asia-Pacific	CATL, BYD, Tesla	Dominance in global LIBs production, with China leading in raw material supply and exports	(Peng et al., 2024) (Martínez-Hernando et al., 2023) (Midler & Alochet, 2023)
Europe	Volkswagen, BMW	Rapid growth in LIBs production, driven by EU's decarbonization goals and EBA initiatives	(Degen, 2023) (Wilson, 2022) (Mutta & S. Soumya, 2024)
North America	Tesla, General Motors	Focus on innovation and sustainability, with significant investments in LIBs production	(Midler & Alochet, 2023) (Berckmans et al., 2017) (Mutta & S. Soumya, 2024)
Africa/S. America	Emerging players	Leveraging abundant natural resources to establish themselves in the global supply chain	(Peng et al., 2024) (Martínez-Hernando et al., 2023)

The LIBs recycling sector is also expanding, with a global market valuation of $5.41 billion in 2024, projected to reach $24.15 billion by 2032(*Lithium Ion Battery Recycling Market Size Global Report, 2025*). Asia-Pacific leads with a 90.77% share, driven by CATL, GEM, and Ganfeng Lithium, while U.S. firms including Redwood Materials and Li-Cycle are increasing capacity. Europe is investing in circular supply chains, with Northvolt and SNAM spearheading regional recycling initiatives (Wilson, 2022). As LIBs demand grows, recycling will play a pivotal role in reducing raw material dependency and strengthening supply chain resilience(Peng et al., 2024).

4.1.3 Linear vs. Circular Cost Comparison: Virgin vs. Recycled Materials

The economic viability of virgin-mined versus recycled LIBs materials remains a decisive market factor. Recycled lithium currently costs five times more than lithium extracted from brine mining, largely due to high energy consumption and processing inefficiencies(Kbaker, 2022). Recycling facilities impose processing fees, increasing short-term costs compared to direct extraction(He et al., 2024). However, technological advancements and economies of scale are expected to reduce recycling costs by 17%, and revenue by 9.9% by 2040, improving cost competitiveness (Nguyen-Tien et al., 2022). Despite the current cost gap, recycled LIBs materials demonstrate performance parity with virgin-mined counterparts, exhibiting identical cycle-life, discharge capacity, and Coulombic efficiency, reinforcing their long-term viability (Redwood Materials, 2024). While virgin material extraction remains more cost-effective in the short term, regulatory pressures and resource scarcity will likely accelerate the shift toward recycling. As recycling infrastructure matures and costs decline, market forces will increasingly align with CE principles.

4.1.4 Reuse and Recycling Rates

As EV adoption accelerates, reuse and recycling rates of traction LIBs are becoming critical market factors. By 2040, LIBs production for EVs is projected to exceed 4 million tons, generating an estimated 63 GWh of EoL batteries annually by 2030, necessitating scalable recycling solutions (Kampker et al., 2023; Richa et al., 2014). China leads global LIBs recycling, with 500,000 metric tons of processing capacity as of 2023, significantly surpassing the U.S. and Europe, each at 200,000 metric tons (Statista ,2023). China also achieves 70% collection rates, enabled by government mandates and an established infrastructure (Bhar et al., 2023; Harper et al., 2023b). In contrast, the U.S. and EU face collection rates below 10%, constrained by fragmented networks, weak consumer participation, and financial barriers (Jorges et al., 2023). Europe's LIBs recycling capacity is growing, with Umicore processing 7,000 metric tons annually, yet high costs and limited financial support hinder expansion, potentially preventing the recovery of sufficient materials for two million EVs by 2030 (Blenkinsop, 2024; *EV Batteries*, 2024). The U.S. lags behind, largely due to weak regulatory mandates and an underdeveloped recycling framework (Jorges et al., 2023). India explores second-life applications for LIBs, repurposing them for backup power in small businesses, yet lacks structured policies and financial incentives for large-scale recycling (AP News, 2024).

4.1.5 EoL Disposal Volumes

By 2030, an estimated 100–120 GWh of EV batteries will reach EoL annually, necessitating efficient disposal and recycling strategies (Chung, 2021). China, as the largest EV market, is experiencing surging EoL LIBs volumes, prompting government-led recycling and reuse policies (Chung & Cheng, 2019). Europe, despite over 30 announced recovery projects, faces high energy costs and limited financial support, restricting its ability to recycle sufficient battery material for future EV production (Reuters, 2024). In the United States, companies like Redwood Materials recover over 95% of nickel, cobalt, lithium, and copper, yet national recycling capacity remains insufficient (Electrek, 2023). India's EoL LIBs volumes are rising, with initiatives exploring battery repurposing for backup power. However, a lack of structured policies and financial incentives impedes large-scale recycling (AP News, 2024). The disparity in global disposal readiness underscores the urgent need for enhanced infrastructure and policy measures.

4.1.6 Key Gaps and Drivers Identification in Global Traction LIBs CE Market Adoption

Despite advancements in the LIBs market, significant gaps persist in the transition to a CE, particularly in cost competitiveness, recycling efficiency, and disposal readiness. Recycled lithium remains five times more expensive than virgin lithium, discouraging market adoption despite projections of a 36% cost reduction by 2040 (Kbaker, 2022; Sagner & Artola, n.d.). China dominates LIBs recycling, processing 500,000 metric tons in 2023, while Europe and the U.S. lag at 200,000 metric tons each, with collection rates below 10% due to fragmented networks (Harper et al., 2023b). EoL battery disposal remains inadequate, with 100–120 GWh projected to reach disposal annually by 2030, yet Europe faces high energy costs, and the U.S. lacks large-scale infrastructure (Chung, 2021). Key drivers include cost asymmetry, regional market fragmentation, and limited short-term profitability, as recyclers prioritize cobalt and nickel recovery over lithium extraction (Redwood Materials, 2024). While China leads in scalability, Europe and the U.S. must enhance infrastructure and reduce cost barriers to align with CE objectives. Without immediate market-driven interventions, LIBs recycling will remain economically constrained.

4.2 Policy Review

4.2.1 Global Regulatory Frameworks for LIBs Production, Reuse, Recycling, Disposal

The regulatory landscape for traction LIBs varies significantly between the EU's CE market and other regions. The EU's Battery Regulation (European Commission, 2025), effective from February 2024, sets a global benchmark by mandating full lifecycle sustainability rules, including carbon footprint declarations, recycled material quotas (e.g., 70% lithium recovery by 2030), and digital "battery passports" to enhance supply chain transparency (European Commission, 2023). In contrast, the United States lacks a federal framework specifically addressing LIBs recycling. Existing policies, such as the Resource Conservation and Recovery Act (RCRA), treat LIBs as universal waste but fail to mandate recycling or set recovery targets. However, the U.S. Department of Energy (DOE) recently appropriated $70 million funding to improve recycling technologies under the Bipartisan Infrastructure Law (DOE, 2025.). Meanwhile, China's policies, such as its 2025 target for 65% battery recycling rates, lack binding carbon footprint requirements and rely heavily on informal recycling channels (Huang et al., 2023). Indonesia's approach prioritizes raw material nationalism (e.g., nickel export bans) over circularity, focusing on attracting foreign investment for refining rather than closed loop systems (Rizos & Urban, 2024).

4.2.2 Policy Alignment with CE Goals

While these regulatory frameworks aim to mitigate environmental impacts, their alignment with CE principles varies. The EU's framework is among the most aligned with CE goals. It explicitly promotes material recovery and reuse to reduce reliance on raw material imports (European Commission, 2023a). However, in markets like the U.S., policy fragmentation undermines CE objectives. For example, state-level initiatives often conflict with federal guidelines, creating barriers for nationwide recycling programs (Curtis et al., 2021). In emerging economies such as India and South Korea, CE alignment is hindered by limited infrastructure for battery collection and recycling. While these countries have introduced policies to encourage LIBs recycling, such as India's draft Battery Waste Management Rules, implementation remains inconsistent due to weak enforcement mechanisms (Arora & Chopra, 2024).

4.2.3 Regulatory Stringency and Recycling Disparities: A Global Perspective

Compliance disparities highlight systemic gaps, revealing the complex interplay between regulatory stringency, economic feasibility, and recycling outcomes. The EU’s stringent policies continue to drive high compliance rates, reinforced by strict enforcement mechanisms and ambitious targets, such as the mandated collection rate of up to 73% for portable batteries by 2030 (European Commission, 2023b). However, these measures face resistance due to significant compliance costs, with European battery production expenses nearly double those in China. The policy stringency rating for each country is recorded in Appx. B. Fig. 2 illustrates a clear positive correlation between policy strictness and recycling rates, with the EU leading in regulatory enforcement (policy score: 9.0), while China, despite a moderate policy rating (7.5), achieves the highest recycling volumes, driven by a mix of formal and informal recovery channels. Conversely, compliance in countries like the U.S., where a relatively high policy score (8.5) fails to translate into robust recycling performance, is hampered by voluntary guidelines and a lack of penalties for non-compliance (Goldberg, 2023.). A similar situation has arisen in India, where regulatory enforcement is weak (policy score: 3.0). Japan, for instance, demonstrates a balanced yet unremarkable performance, with both policy stringency and recycling rates remaining at mid-range levels (5.5). In developing economies, low compliance rates stem from inadequate infrastructure and informal recycling sectors that dominate waste management systems. In China, despite 0.65 million tons official recycling volume, informal sectors dominate, with limited oversight of hazardous waste handling (EVTank, 2025). These informal networks often prioritize cost-efficiency over environmental standards, undermining formal CE initiatives. The assessment criteria for each country’s policy and recycling performance are detailed in Table 4, providing a comprehensive foundation for evaluating the effectiveness of different regulatory approaches across diverse economic and institutional landscapes. These countries were selected because they represent major economies with varying levels of policy development, industrial capacity, and market maturity in lithium-ion battery recycling.

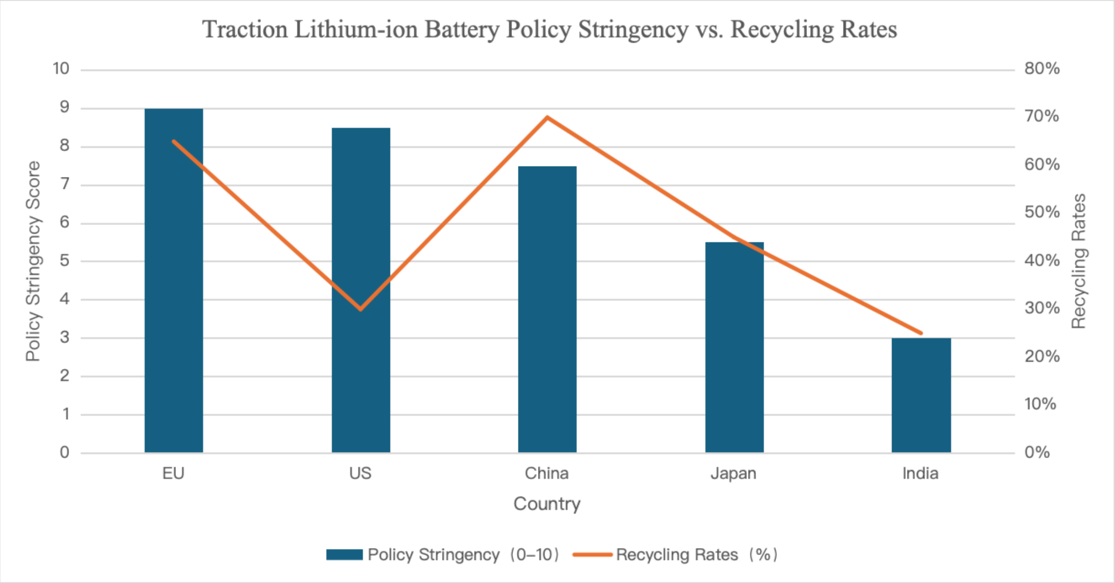

Fig. 2 Traction lithium-ion battery policy stringency scores vs. recycling rates.

Table 4. Criteria for policy stringency score

Dimension	Key Indicators	Weight
Regulatory Hierarchy	Legal binding force (e.g., national law vs. voluntary guidelines).	20%
Target Bindingness	Mandatory targets.	25%
Sector Coverage	Scope across the battery lifecycle (mining, production, recycling, trade).	20%
Enforcement Mechanisms	Penalties (fines, market bans), monitoring systems (e.g., battery passports).	25%
Transparency	Public reporting requirements and third-party audits.	10%

4.2.4 Economic Incentives and Policy Strategies in Battery Recycling

Economic incentives play a critical role in bridging market-policy gaps. The EU offers subsidies for research into sustainable battery technologies and recycling processes under programs including Horizon Europe (Holland High Tech, 2024), like allocating €200 million through its Innovation Fund and state aid to subsidize green battery production (Brussels, 2024). Similarly, the U.S. DOE's funding initiatives aim to reduce recycling costs and improve material recovery rates. The government has allocated over $3 billion in grants to enhance domestic production of advanced batteries and materials for electric vehicles across 14 states (MESC, 2025). However, these incentives are often insufficient to address high initial costs associated with LIBs recycling technologies. China has adopted a more aggressive approach by mandating EPR systems that hold manufacturers financially accountable for EoL battery management (Jiang & Zhang, 2023). This model incentivizes companies to invest in recycling infrastructure but may not be easily replicable in regions with less centralized governance structures.

4.2.5 Geopolitical Challenges and Policy Dynamics in LIBs Recycling

Geopolitical factors significantly influence LIBs markets and policies. The EU's Green Deal emphasizes strategic autonomy by reducing reliance on imported raw materials through domestic recycling initiatives (European Commission, 2021). However, China's dominance in lithium processing poses challenges for global supply chains. Despite efforts by Western nations to diversify sources of critical materials, China's integrated supply chain offers cost advantages that are difficult to match (Karin Michalikova, 2023). Additionally, trade barriers hinder international collaboration on LIBs recycling. For example, inconsistent definitions of LIBs waste complicate cross-border transportation for recycling purposes (Evdokia Moïsé, & Stela Rubínová, 2023). Harmonizing international standards could facilitate trade in recyclable materials but requires significant political coordination.

4.2.6 Key Gaps and Drivers Identification in Global Traction LIBs CE Policies

Globally, traction LIBs policies reveal critical gaps in aligning with circular economy (CE) principles. While the EU enforces stringent lifecycle regulations (e.g., mandatory carbon reporting, 95% cobalt recovery by 2030), many regions lack binding sustainability frameworks. For instance, parts of Asia and Africa prioritize resource extraction or industrial growth over recycling infrastructure, with informal sectors handling up to 70% of retired batteries in countries like India and Nigeria. Even in advanced economies like the U.S., federal policies lag state-level initiatives, creating fragmented compliance. Economic incentives further misalign nations such as South Korea and Japan invest heavily in R&D but lack cohesive recycling mandates, while resource-rich countries like Chile focus on lithium exports without circularity strategies.

These disparities stem from competing priorities, which are environmental integrity versus economic growth, and uneven technological capabilities. Developed economies leverage regulations to curb reliance on imports (e.g., EU's Battery Passport), whereas emerging markets often prioritize rapid industrialization or resource nationalism (e.g., Congo's cobalt export controls) (Battery Pass, 2021; SFA, 2025). Geopolitical tensions, such as U.S.-China competition over battery tech dominance, deepen fragmentation by discouraging standardized policies. Additionally, cost barriers hinder compliance, as seen in Southeast Asia, where high recycling expenses push informal practices (Thomas Luedi et al., 2025). Ultimately, the lack of global coordination, coupled with divergent national interests and resource dependencies, perpetuates a fractured approach to achieving a circular LIBs ecosystem.

Table 5. Traction lithium-ion battery policy vs. circular economy market practice gaps

Country	Policy Framework	Market Practices	Key Gaps	Source
European Union	Comprehensive Batteries Regulation (2023): Requires 70% recycling rate by 2025; Recycled content mandates, collection targets, digital passports by 2027.	High compliance rates but challenges in scaling recycling infrastructure and meeting ambitious targets. BMW, VW piloting energy storage with reused batteries.	Limited recycling capacity; high costs of compliance for manufacturers; overcapacity in recycling infrastructure vs. low volume of end-of-life (EoL) batteries.	(European Commission, 2023b)
United States	Inflation Reduction Act allocates $14 million for 1,000 recycling centers; voluntary guidelines under Resource Conservation and Recovery Act; Producer-led recycling mandates.	ABI forecasts recycling capacity for 1.3M batteries by 2030, but only 340K retired batteries will be available. ReCell Center develops closed-loop recycling, yet commercialization lags.	Policy fragmentation and absence of nationwide infrastructure for LIBs recycling.	(Curtis et al., 2021; Rajat Rajbhandari, PhD, MOBI et al., 2023)

China	Updated 2024 regulations require 3% R&D investment by LIBs companies; Management Measures for Recycling and Utilization of New Energy Vehicle Batteries mandates automakers to establish recycling channels (Ni/Co/Mn recovery ≥98%, Li ≥85%); Basically national recycling network	Brunp Recycling achieves 99.6% Ni/Co/Mn recovery, 91% Li recovery. GEM and Guoxuan High-Tech lead full-chain recycling. Dominates global LIBs production but faces structural overcapacity; informal recycling sector prevalent.	Insufficient high-quality recycling capacity. informal practices undermine formal CE initiatives.	(Cheng Yu, 2024; China Chemical Reporter, 2024)
India	2025 Budget removed customs duties on key materials; National Manufacturing Mission supports domestic production to reach the ambitious goal of having EV sales coverage of 70% of commercial vehicles, 30% of private cars, and 40% of buses by 2030	Reliance, Tata exploring domestic recycling with foreign tech partnerships.	Weak enforcement of recycling policies; limited market incentives for repurposing retired batteries.	(Aqueouss, 2025)
Japan	Extended Producer Responsibility (EPR) led by automakers. ≥80% rare metal recovery (e.g., Honda's closed-loop tech).	Toyota, Nissan achieve Ni recycling; 4R Energy commercializes reused batteries.	Lack of large-scale infrastructure, reliant on hydrometallurgy.	(Mordor Intelligence, 2025)

4.3 Technology Analysis

4.3.1 Global Traction LIBs Recycling R&D Investment Trends

While academic research has surged in LIBs recycling innovation, industrial adoption lags due to mismatched funding priorities. Governments and private sectors are funneling substantial resources into recycling R&D. For example, the U.S. Department of Energy allocated $15 million to its ReCell Center in 2019 to advance cost-effective recycling technologies (Umicore N.V. et al., 2022). Similarly, the UK's ReLiB project unites academia and industry to optimize recycling efficiency (Umicore N.V. et al., 2022). However, a 2023 review highlights that over 70% of global R&D funding targets *early-stage* laboratory innovations, such as novel hydrometallurgical processes, while less than 30% supports scaling these technologies for industrial use (Bae & Kim, 2021). Private companies like Li-Cycle and Redwood Materials prioritize profitability, focusing on cobalt and nickel recovery rather than emerging academic breakthroughs in lithium extraction, which currently recovers only 1–3% of lithium globally due to high costs (Green, 2024). This funding asymmetry perpetuates a “valley of death” where promising academic solutions fail to transition to commercial viability.

4.3.2 Academic vs. Industry Recycling Patent Trends

Patent analysis reveals divergent priorities between academia and industry. Academic institutions dominate patents related to environmentally friendly methods, such as direct recycling (repairing electrode materials) and bioleaching, which accounted for 45% of LIBs recycling patents published between 2020 and 2024 (Ji et al., 2023). In contrast, industry patents focus on process optimization (e.g., automated dismantling) and high-value material recovery (e.g., cobalt refining), driven by immediate economic returns. For instance, a 2024 study found that 80% of industry patents target cobalt recovery, whereas academic patents emphasize lithium and graphite recycling, materials with lower market value but higher environmental urgency (Priore et al., 2024; Zanoletti et al., 2024). Besides, when comparing academic and industry recycling patent trends, a notable disparity emerges. The CAS report reveals a striking 2:1 ratio of patents to journal publications in LIBs recycling, indicating strong commercial interest and industry-led innovation (Hina Goyal, 2025). This contrasts with the typical 1:5 ratio seen in other fields, suggesting that industry is outpacing academia in applied recycling technology development. Geographically, Asian countries, especially China, Japan, and South Korea, prevail the patent landscape, followed by the United States and Germany (Hina Goyal, 2025).

4.3.3 Material Recovery Rates from Recycling Process

Material recovery rates expose the practical consequences of the academia-industry gap. While lab-scale methods achieve lithium recovery rates of 75–95% using advanced solvents or electrochemical techniques, industrial processes see a decline in lithium and cobalt recovery rates due to cost constraints and scalability challenges (Bae & Kim, 2021). For example, hydrometallurgy, a widely studied academic method, is less adopted industrially because of its high energy and chemical demands. Meanwhile, pyrometallurgy, which dominates industry practices, recovers cobalt efficiently but destroys lithium, exacerbating resource scarcity. A 2024 report notes that only 5% of retired LIBs are recycled globally, with informal sectors in regions like India and Africa recovering materials at rates below 10%, often through hazardous methods (Rongxu ESG, 2024). However, a study published in ACS Energy Letters projected that global LIBs recycling capacity needs to rise 50 times in the following decade to catch electric vehicle adoption rates (Sederholm et al., 2025). These disparities highlight the urgent need for policies that incentivize technology transfer, such as tax credits for adopting academic innovations or mandates for minimum lithium recovery thresholds. Currently, the Duesenfeld process, an industry innovation, with discharging, mechanical crushing of the batteries and further hydrometallurgical processing of the Duesenfeld Black is a low-temperature process (Duesenfeld, 2025).

4.3.4 Technology Readiness Levels

The technology readiness levels (TRLs) of LIBs disassembly and recycling vary significantly across regions, reflecting differences in industrial capabilities and research commercialization. China leads in large-scale commercial recycling (TRL 9), with Brunp Recycling Technology, a subsidiary of CATL, pioneering industrial applications (Sun et al., 2017). Japan and South Korea have also achieved TRL 9, with companies like Sumitomo Metal Mining and SK Innovation advancing hydrometallurgical and direct recycling technologies (Chen et al., 2019b). In contrast, the United States and Europe remain in pre-commercial phases. U.S.-based Redwood Materials and ABTC operate at TRL 7-8, having developed prototyped hydrometallurgical processes capable of recovering over 95% of LIBs materials (ABTC, 2022). Europe's startups, such as Altilium and tozero, function at TRL 6-7, demonstrating pilot-scale systems aimed at reducing CO_2 emissions and enhancing cost efficiency (Reuters, 2023). Despite technological advancements, LIBs disassembly presents significant safety risks, including thermal runaway incidents, toxic chemical exposure, and environmental hazards from per- and polyfluoroalkyl substances (PFAS) (The Guardian, 2024). China's dominance in LIBs recycling underscores its technological edge, while Europe and the U.S. focus on scaling innovations from pilot to commercial applications. Addressing safety concerns and optimizing industrial scalability remains critical for achieving a sustainable CE in LIBs recycling.

4.3.5 Key Gaps and Drivers Identification in Global Traction LIBs CE Technology Adoption

Despite advancements in LIBs recycling technologies, significant gaps exist between academic research and industrial adoption. Over 70% of global R&D funding supports early-stage innovations, while less than 30% facilitates scaling for commercial use, creating a "valley of death" for promising technologies (Bae & Kim, 2021). Industry prioritizes high-value metals like cobalt and nickel, neglecting low-cost lithium recovery, which remains at only 1–3% efficiency (Green, 2024). Patent trends reveal a disconnect: 45% of academic patents focus on direct recycling, while 80% of industry patents optimize cobalt refining, driven by economic incentives (Ji et al., 2023; Priore et al., 2024). Industrial recycling efficiency lags, with lab-scale lithium recovery at 75–95%, while industrial processes struggle due to cost constraints and reliance on pyrometallurgy (Sederholm et al., 2025). China leads in TRL 9 commercialization, while the U.S. and Europe remain at TRL 6-8, requiring stronger policy interventions for technology transfer (Sun et al., 2017).

5 Discussion

5.1 SWOT Analysis

5.1.1 SWOT Analysis for Developing Countries

Strengths

Developing countries possess a growing market for EVs and traction LIBs, driven by rapid urbanization and increasing energy demands. Some nations, like China and India, are leading in battery production and recycling efforts, leveraging abundant raw materials and cost-effective labor. The presence of informal recycling sectors allows for the collection and repurposing of EoL LIBs, contributing to material recovery and reuse. Developing countries benefit from technology transfer agreements and foreign direct investments from developed nations seeking to establish supply chains for critical minerals.

Weaknesses

Despite market potential, developing countries face significant challenges in LIBs circularity. Weak regulatory enforcement and lack of standardized waste management systems hinder effective recycling. Many nations lack advanced recycling infrastructure, resulting in lower material recovery rates and environmental hazards from improper disposal. The dominance of informal recycling networks leads to inefficient and hazardous processing methods, exposing workers to toxic materials. Besides, high capital costs for advanced recycling technologies deter private investments, making it difficult for developing nations to transition towards a formalized CE.

Opportunities

International collaborations and funding initiatives offer promising opportunities to improve LIBs recycling and reuse capabilities. Growing global demand for sustainable battery management has prompted developed nations to support technology-sharing programs and invest in recycling facilities in developing markets. Policy interventions, such as extended producer responsibility (EPR) schemes, could drive industry participation in sustainable waste management. Additionally, innovations in second-life battery applications such as energy storage for off-grid communities provide economic and environmental benefits by extending battery lifespans before recycling.

Threats

Developing nations are vulnerable to fluctuating commodity prices, impacting the economic feasibility of recycling. Weak regulatory oversight increases the risk of illegal dumping and environmental degradation. Geopolitical factors, including trade restrictions and resource nationalism, may limit access to critical raw materials, disrupting the growth of LIBs CE. Competition from low-cost virgin material production in regions like Africa and Latin America reduces the commercial attractiveness of recycling, delaying CE adoption.

The SWOT analysis results for developing countries are presented in Table 6.

Table 6. SWOT analysis matrix for developing countries

SWOT	Beneficial	Detrimental
Internal	**Strengths:** Growing EV and LIBs markets, cost-effective labor, presence of informal recycling, foreign direct investment.	**Weaknesses:** Weak regulations, lack of infrastructure, informal sector inefficiencies, high capital costs for technology.
External	**Opportunities:** International funding, EPR policies, second-life applications for batteries, technology-sharing initiatives.	**Threats:** Price volatility of raw materials, weak enforcement leading to environmental risks, geopolitical constraints, competition from virgin material extraction.

5.1.2 SWOT Analysis for Developed Countries

Strengths

Developed countries exhibit strong regulatory frameworks supporting LIBs recycling and reuse, such as the EU Battery Regulation, which mandates sustainability targets and minimum recycled content. Advanced recycling technologies enable higher material recovery rates and lower environmental impacts, such as hydrometallurgical and direct recycling processes. Developed nations also benefit from well-established supply chains, efficient waste collection systems, and significant investment in R&D to improve battery circularity. Public awareness and corporate sustainability commitments further drive CE initiatives.

Weaknesses

Despite robust policies, the high cost of LIBs recycling in developed nations remains a key barrier. Economic feasibility issues persist, as recycled materials often cost more than virgin-mined alternatives, slowing industry adoption. Policy fragmentation, particularly in the United States, hinders nationwide coordination for battery circularity efforts. Furthermore, the slow commercialization of next-generation recycling technologies results in bottlenecks, limiting large-scale implementation. Dependency on raw material imports also makes developed nations vulnerable to supply chain disruptions.

Opportunities

Government incentives, such as tax credits and research grants, promote advancements in LIBs recycling and reuse. The shift towards net-zero emissions goals and ESG commitments further encourage industry participation in CE models. Emerging business models, such as battery leasing and second-life applications, create new revenue streams for manufacturers and recyclers. International collaborations, particularly with resource-rich developing countries, present opportunities to secure critical materials while supporting global sustainability efforts.

Threats

Developed nations face geopolitical risks, such as trade disputes affecting access to critical minerals from key suppliers. Supply chain disruptions, including limited domestic lithium and cobalt reserves, could hinder battery production and recycling initiatives. Environmental regulations, while stringent, may increase operational costs for recyclers, reducing industry competitiveness against virgin material extraction. The ongoing technological gap between academia and industry further delays the transition to cost-effective, large-scale recycling solutions.

The SWOT analysis results for developing countries are summarized in Table 7.

Table 7. SWOT analysis matrix for developed countries

SWOT	Beneficial	Detrimental
Internal	**Strengths:** Strong regulatory frameworks, advanced recycling technologies, efficient waste management, high R&D investment.	**Weaknesses:** High recycling costs, policy fragmentation (e.g., U.S.), slow commercialization of new technologies, reliance on imports.
External	**Opportunities:** Government incentives, ESG-driven investments, second-life business models, global partnerships for sustainable supply chains.	**Threats:** Geopolitical trade tensions, supply chain vulnerabilities, costly regulatory compliance, slow industry adoption of new recycling methods.

5.2 TOWS Analysis

5.2.1 TOWS Analysis for Developing Countries

Developing countries can harness their expanding EV market and lower labor costs to seize investment opportunities and fund modern recycling facilities. By aligning their growing demand with external partnerships, they can channel international support toward streamlined waste management. This approach capitalizes on their strong production base while mitigating economic uncertainties that threaten material availability. At the same time, policymakers must integrate technology-sharing platforms, extending local expertise to reduce reliance on informal recycling systems. They should turn weak regulatory oversight into a call for stricter legislation that mandates safe disposal and comprehensive recovery methods. Such measures encourage businesses to recognize the commercial benefits of better waste handling, helping them repel the threat of environmental damage. Moreover, adopting extended producer responsibility schemes and forging cross-border alliances can strengthen supply chains, secure essential raw materials, and achieve long-term sustainability. Collaboration between industry and government leads to consistent infrastructure expansion, ensuring that large-scale recycling projects receive proper funding and meet global benchmarks. This synergy supports rural and urban communities by creating eco-friendly jobs and fostering inclusive economic growth. Proactive efforts, such as raising public awareness about battery handling, further reinforce social acceptance of repurposing and recycling programs. Although global commodity price fluctuations and minimal capital investments pose significant threats, early policy interventions can reduce these risks. By using their cost advantages and growing market potential, developing countries transform weaknesses into targeted improvements, fueling a more sustainable and competitive CE for traction LIBs.

Table 8 presents the TOWS analysis results for developing countries.

Table 8. TOWS analysis matrix for developing countries

TOWS	Strengths	Weaknesses
Opportunities	**S-O Strategies:** Use abundant labor and high EV demand to attract foreign investment for recycling infrastructure.	**W-O Strategies:** Improve regulatory enforcement and technical skills through technology-sharing programs to leverage market growth.
Threats	**S-T Strategies:** Encourage legislation that formalizes the informal sector and mitigates environmental degradation.	**W-T Strategies:** Introduce cost-based incentives that reduce the threat of commodity price fluctuations and align formal recycling processes with strict environmental standards.

5.2.2 TOWS Analysis for Developed Countries

Developed countries can leverage advanced recycling technologies and rigorous regulations to shape innovative responses that tap into green growth opportunities. By pairing strong government oversight with private-sector ingenuity, they convert market weaknesses, such as high operational costs, into catalysts for efficiency gains and technological breakthroughs. These efforts also fortify supply chains against geopolitical tensions by encouraging domestic recycling capacity and diversifying raw material sources. The interplay of strict environmental laws and consumer demand for low-carbon products presents fertile ground for robust second-life applications that extend battery use before final recycling. These strategies enable companies to offset cost concerns with revenue from refurbished batteries, mitigating reliance on expensive imports of virgin metals. Meanwhile, addressing regulatory fragmentation stimulates nationwide coordination, creating uniform standards for battery disposal and reuse. In the face of potential supply chain disruptions or trade restrictions, policymakers and industry partners must invest in academic-industry collaborations to accelerate next-generation recycling methods. Such collaborations capture academic innovations and scale them commercially, building local expertise and market competitiveness. Incentive structures, including tax credits and targeted grants, channel funding toward pilot plants and infrastructure, reinforcing commitment to the CE across the entire value chain. These measures not only reduce environmental impact but also bolster public trust in advanced LIBs recycling, transforming potential threats into market-enriching opportunities. Ultimately, by combining strict policies, innovative spirit, and global partnerships, developed countries can pioneer resilient, cost-effective circular solutions that inspire worldwide adoption.

Table 9 illustrates the TOWS analysis results for developed countries.

Table 9. TOWS analysis matrix for developed countries

TOWS	Strengths	Weaknesses
Opportunities	**S-O Strategies:** Combine strong regulations and advanced technologies to develop second-life battery markets and diversify supply chains.	**W-O Strategies:** Standardize policies and unify state-level initiatives to harness sustainability-driven consumer demand.
Threats	**S-T Strategies:** Invest in domestic recycling capacity to offset trade disputes while enhancing energy security.	**W-T Strategies:** Expand R&D grants and industrial partnerships to accelerate next-generation recycling, mitigating cost barriers and strengthening resilience against import disruptions.

5.3 Recommendation

Developing countries should strengthen policy enforcement and formalize recycling networks by examining best practices from China and India. China’s government-led recycling mandates, which integrate extended producer responsibility (EPR), have facilitated a robust infrastructure capable of processing 500,000 metric tons of end-of-life (EoL) batteries. This large-scale approach exemplifies how centralized regulation, coordinated collection systems, and partnerships with battery producers such as CATL effectively channel resources into the formal recycling sector.

India, though still maturing, showcases another emerging strategy: second-life applications for batteries in rural areas to address electricity gaps before final recycling. By emulating these lessons, other developing nations can reduce risks associated with informal recyclers and adopt structured systems that improve material recovery rates. Additionally, technical training programs, supported through international funding, can transfer expertise from global leaders and expand local knowledge pools.

Meanwhile, developed countries should unify regulations to streamline recycling efforts. The European Union's Battery Regulation provides a prime example by enforcing carbon footprint declarations, imposing higher recycling quotas, and mandating digital "battery passports." Germany's advanced enforcement mechanisms, along with well-funded R&D initiatives, demonstrate how strict oversight coupled with financial support spurs private investment in circular solutions. These frameworks also encourage second-life battery markets, such as energy storage, that lessen pressure on virgin raw materials. In the United States, private ventures like Redwood Materials show exemplary progress in recovering up to 95% of high-value metals. However, scaling these successes nationally requires consistent federal policies to transcend patchwork state regulations and make large-scale projects financially viable.

Overall, governments in developing and developed economies should adapt these proven models, leveraging both policy innovations (as seen in Europe) and robust processing capabilities (as seen in China) to build fully circular LIBs ecosystems. In developing contexts, formalizing the informal sector, encouraging EPR schemes, and aligning local labor advantages with improved regulatory structures will advance national recycling capacity. In developed regions, harmonizing laws and incentivizing high-efficiency technology adoption remains essential. Cross-border collaboration, exemplified by joint ventures between Chinese firms and European automakers, can further stimulate knowledge exchange and broaden market reach for recycled materials. Moreover, proactively investing in pilot plants that integrate academic breakthroughs, such as hydrometallurgical and direct recycling processes, bridges the gap between innovation and industrial readiness. These strategies mitigate resource scarcity, reduce environmental harm, and foster sustainable growth.

Implementing strict but carefully balanced regulations, mobilizing investments in advanced technology, and forging international partnerships are the key pillars of a thriving global circular economy. By selectively applying best practices, countries can derive more robust solutions, such as China's large-scale capacity, India's second-life solutions, Europe's advanced policy oversight, and the United States' private-sector innovation. In doing so, they will not only safeguard their environments but also strengthen energy independence and stimulate long-term economic expansion. Such comprehensive approaches ensure that every stage of the battery lifecycle, from design and manufacturing to reuse and recycling, contributes to a cost-effective, resilient, and eco-conscious global market for traction LIBs.

5.4 Research Limitation

Data accessibility poses a key limitation in this research, as information on traction LIBs production, policy frameworks, and recycling technologies varies widely across regions. Some nations maintain open databases, while others rely on proprietary or outdated systems with limited public availability. This discrepancy constrains cross-comparisons and can skew insights in favor of regions with greater transparency. Additionally, language barriers and inconsistent reporting standards complicate the gathering and synthesis of global data, especially in areas where relevant documents exist only in local languages or remain unpublished.

Data timeliness also restricts the scope and reliability of the study. The traction LIBs market evolves rapidly, driven by fluctuating commodity prices, technological breakthroughs, and shifting policy landscapes. Even reputable sources can lag behind real-time developments, resulting in figures or trends that quickly become obsolete. For example, data on battery recycling rates, which might have been accurate at publication, may no longer capture current initiatives and capacities in fast-changing markets. Consequently, any policy recommendations or technological assessments must account for the possibility that conditions have progressed beyond the datasets used.

Beyond these issues, disparities in definitions of recycling efficiency and collection rates add complexity to cross-national evaluations. In some cases, metrics are self-reported, which raises concerns about data quality and objectivity. Future efforts to standardize terminology, enhance data-sharing platforms, and institute more rigorous publication practices will help mitigate the impact of these constraints, thereby improving the accuracy and comparability of global traction LIBs CE research.

Scope creeping is a lurking issue as we were not able to carry out stakeholder interviews and subsequent mapping analysis within the time constraint. The idea of field research was proposed at a late stage of our project, which has led to delayed execution. Till now, our IRB is still pending approval. Therefore, we decided to focus on synthesizing and evaluating benchmarking analysis results from desktop research.

6 Conclusion

This report sets out to examine whether retired traction LIBs are managed in a genuinely circular fashion worldwide, and if not, to uncover the market, policy, and technological gaps that impede progress. By integrating a novel research methodology that blends benchmarking analysis with stakeholder mapping, we captured both quantitative performance metrics and qualitative insights on how retired EV batteries are actually handled. This dual approach, which cross-references recycling capacities, policy frameworks, and industry practices, represents a fresh lens on evaluating CE efforts in an industry where data are often dispersed or inconsistent.

Despite leading examples from Germany, France, and the Netherlands, whose stringent regulations, well-funded recycling infrastructure, and collaborative industry initiatives raise overall recovery rates, the global push for circularity still falls short. China’s rapid-scale recycling facilities also show promise, capitalizing on extended producer responsibility policies and abundant manufacturing capacity. Yet in other countries, including large emerging economies, dependence on informal networks leads to suboptimal material recovery and heightened environmental risks. This fragmented global landscape underscores why some nations see advanced recycling and second-life applications flourish, while others struggle to divert end-of-life batteries from unsafe disposal methods.

Policy misalignment emerges as a key problem. In regions where ambitious mandates exist, such as the European Union’s requirement for higher lithium and cobalt recovery, compliance costs and fragmented enforcement hamper uniform adoption across borders. Meanwhile, countries lacking binding regulations or incentives have not realized the economies of scale that could lower recycling costs. On the technological front, many advanced processes with higher metal-recovery yields remain confined to laboratory experiments or pilot plants. Although academic research consistently attains elevated extraction rates, industrial facilities still tend to rely on established methods, such as pyrometallurgy, which underutilize valuable materials like lithium.

Our findings are significant because they clarify how market incentives, regulatory frameworks, and technological innovations must converge for a closed-loop system to succeed. By focusing on how these factors interact across distinct economies, our study contributes a comparative perspective that can guide policymakers, industry stakeholders, and researchers eager to refine best practices. One of our central contributions is to highlight the urgent need for stronger global data-sharing standards, robust pilot-plant funding, and cross-sectoral collaborations so that efficient recycling becomes the rule, not the exception.

Despite data gaps and variable reporting standards that limit perfect comparability, our work makes evident that a truly circular economy for traction LIBs is achievable. The critical next step is for multiple stakeholders, such as governments, manufacturers, recyclers, and researchers, to apply the lessons from pioneering countries and pilot programs more broadly, ensuring that safe and cost-effective battery recycling becomes the global norm.

Appendix

A. Stakeholder Survey on Circular Economy for Retired Traction Lithium-ion Batteries

Thank you for participating in this survey. Your input will help us assess the current state of circular economy practices for retired traction lithium-ion batteries and identify key challenges and opportunities. Please answer the following questions as accurately as possible.

Section 1: Stakeholder Information

1. Please indicate your stakeholder category:
   - ☐ Consumer
   - ☐ Battery Manufacturer
   - ☐ Automotive Manufacturer
   - ☐ Recycler
   - ☐ Government Agency
   - ☐ Non-Governmental Organization (NGO)
   - ☐ Academia/Research Institution
   - ☐ Other (please specify): ____
2. Which stages of the lithium-ion battery value chain are you involved in? (Check all that apply)
   - ☐ Raw Material Extraction
   - ☐ Battery Production
   - ☐ Vehicle Manufacturing
   - ☐ Battery Use/Consumption
   - ☐ Battery Collection & Recycling
   - ☐ Second-life Applications
   - ☐ Policy & Regulation
   - ☐ Other (please specify): ____
3. To facilitate the circular economy of retired traction batteries, what types of stakeholders would your organization be open to collaborating with? Additionally, in what form would you anticipate such cooperation? (e.g., technological R&D partnerships, supply chain collaboration, or industry association initiatives.)

   ____
   ____
   ____
   ____

Section 2: Key Interests and Priorities

4. What are your primary interests regarding retired traction lithium-ion batteries? (Select up to three)

   - ☐ Profitability of battery recycling/repurposing

☐ Compliance with environmental regulations
☐ Reducing environmental impact
☐ Market expansion for second-life batteries
☐ Economic and tax policies
☐ Innovation in battery recycling technologies
☐ Minimizing operational costs
☐ Other (please specify):
____

5. What are the main factors driving your engagement in circular economy initiatives?

☐ Government incentives or regulations
☐ Corporate sustainability goals
☐ Market demand for recycled materials
☐ Cost reduction opportunities
☐ Public or customer expectations
☐ Other (please specify):
____

Section 3: Influence and Challenges

6. How would you rate your influence on circular economy outcomes in the battery industry?

☐ Very high – My organization plays a key role in shaping policies/practices.
☐ High
☐ Medium – We have some influence but face limitations.
☐ Low
☐ Very low – We are impacted by policies but have little influence.

7. What do you consider to be the key obstacles preventing wider adoption of circular economy practices for retired lithium-ion batteries? (Check all that apply)

☐ High costs of battery collection, transportation, or recycling
☐ Lack of standardized policies and regulations
☐ Technical challenges in battery disassembly and material recovery
☐ Limited market for second-life batteries
☐ Insufficient investment in recycling infrastructure
☐ Other (please specify):
____

8. What technology, policies or market mechanisms do you believe would improve circular economy practices for lithium-ion batteries?

☐ Stronger regulatory mandates on battery recycling
☐ Financial incentives/subsidies for recyclers and consumer

☐ Standardized global recycling protocols
☐ Investment in advanced recycling technologies
☐ Public-private partnerships for battery reuse and recycling
☐ Other (please specify):
____

Section 4: Alignment with Circular Economy Goals

9. Do you consider your role's goals to be aligned with circular economy principles?

☐ Yes, we actively support circular economy initiatives.
☐ Neutral, we acknowledge its importance but have no active involvement.
☐ No, we face challenges that prevent us from fully supporting it.

10. If you are not fully aligned, what are the main reasons?

☐ Economic constraints
☐ Regulatory uncertainty
☐ Technological barriers
☐ Lack of consumer demand
☐ Other (please specify):
____

Section 5: Strategic Actions

11. What actions do you think should be prioritized to enhance the circular economy for retired lithium-ion batteries? (Select up to three)

☐ Strengthen international collaboration on battery recycling
☐ Implement producer responsibility regulations
☐ Increase funding for battery recycling R&D
☐ Develop standardized battery designs to improve recyclability
☐ Promote consumer awareness on battery disposal, recycling, and sustainability
☐ Improve cost effectiveness of recycling
☐ Other (please specify, we encourage you to add the help you need.):
____
____

12. Beyond the aspects covered above, do you have any additional insights, recommendations, or supplementary information regarding the circular economy of retired traction batteries that you would like to share?

____
____
____

B. Results for Policy Stringency Score

Table B1. Policy Stringency Score of European Union

Dimension	Score	Reason
Regulatory Hierarchy	2	Strong binding laws (Battery Regulation)
Target Bindingness	2.5	Mandatory targets for recycling rate and carbon footprint disclosure
Sector Coverage	2	Covers the entire battery lifecycle: mining, production, recycling, trade
Enforcement Mechanisms	2	Strict penalties and monitoring, but high compliance cost
Transparency	0.5	Public reporting required, but room for improvement

Table B2. Policy Stringency Score of United States

Dimension	Score	Reason
Regulatory Hierarchy	1.5	No federal law, policies differ by state.
Target Bindingness	1.5	Some mandatory targets at state level, no federal-level target.
Sector Coverage	1.5	Limited to waste management stage.
Enforcement Mechanisms	2	State-level enforcement is effective, no federal mechanism.
Transparency	1	High transparency and data availability.

Table B3. Policy Stringency Score of China

Dimension	Score	Reason
Regulatory Hierarchy	1.5	Strong policy documents but not at national law level.
Target Bindingness	2	Mandatory recycling target (65%), no carbon footprint requirement.
Sector Coverage	1.5	Covers production, consumption, recycling, but informal sector dominates.
Enforcement Mechanisms	2	Good local enforcement, but informal sector weakens overall regulation.
Transparency	0.5	Limited data transparency and public reporting.

Table B4. Policy Stringency Score of Japan

Dimension	Score	Reason
Regulatory Hierarchy	1	Producer responsibility system, mostly industry self-regulation.
Target Bindingness	0.5	No mandatory recycling targets.
Sector Coverage	1	Covers production and part of recycling stage.
Enforcement Mechanisms	1.5	Weak enforcement and penalty system.
Transparency	0.5	Limited data disclosure.

Table B5. Policy Stringency Score of India

Dimension	Score	Reason
Regulatory Hierarchy	0.5	No binding law, only policy drafts and guidelines.
Target Bindingness	0.5	No mandatory recycling targets.
Sector Coverage	0.5	Only focuses on waste stage, informal sector dominates.
Enforcement Mechanisms	1	Weak enforcement, informal recycling widely used.
Transparency	0.5	Lack of official data and public disclosure.

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