

# Circular Compliance: Aligning EV Battery Waste Management with the EU Battery Regulation 2023/1542

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## ABSTRACT

The rapid growth of electric vehicle (EV) adoption in Europe presents both opportunities and challenges for sustainable energy transitions. A critical issue lies in the management of end-of-life (EoL) batteries, which contain scarce and hazardous materials yet offer high potential for recovery and reuse. The EU Battery Regulation 2023/1542 establishes ambitious provisions, including mandatory recovery rates of 70% lithium and 95% cobalt/nickel by 2030, carbon footprint disclosure, digital battery passports, and extended producer responsibility (EPR) schemes. This study evaluates how circular economy strategies can align with these requirements to ensure sustainable EV battery waste management. A policy–technology mapping framework was developed to analyze compliance potential across four strategies: design-for-circularity, second-life applications, recycling innovations, and material recovery optimization. Results indicate that recycling innovations and material recovery achieve the highest regulatory alignment, with hydrometallurgical processes currently reaching 90–95% cobalt/nickel recovery and projected 70% lithium recovery by 2030. Design-for-circularity reduces lifecycle impacts by 15–20%, while second-life applications extend battery utility by 20–30% and lower lifecycle carbon emissions by 10–15%. A national case study of Italy reveals accelerating EV adoption (>25% annual growth) but highlights limited recycling capacity, with only 30% of EoL batteries processed domestically, underscoring urgent infrastructure needs. The findings demonstrate that no single strategy ensures full compliance, but integrated approaches combining modular design, advanced recycling, and second-life deployment can deliver both regulatory compliance and sustainability benefits. This framework provides actionable insights for policymakers and industry stakeholders, strengthening Europe’s pathway toward a circular, low-carbon mobility system.

## 1. Introduction

The rapid adoption of electric vehicles (EVs) across the European Union (EU) represents one of the most significant transformations in the transport sector of the 21st century. Spurred by

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ambitious climate and energy targets, supportive policy frameworks, and technological advancements, EV penetration in European markets has accelerated over the past decade (Ramachandaramurthy et al., 2023). According to the European Environment Agency, the number of electric and plug-in hybrid vehicles in the EU exceeded several million units by 2024, a number projected to increase exponentially as member states strive to achieve the objectives outlined in the European Green Deal and the Fit for 55 legislative package (Cruz-Jesus et al., 2023),(Erceg et al.,2024). The transition from internal combustion engine (ICE) vehicles to EVs is essential not only for reducing greenhouse gas emissions and air pollutants but also for fostering energy security and advancing sustainable mobility in line with broader EU decarbonization targets (Safarzadeh et al., 2025).

However, alongside these environmental and societal benefits, the surge in EV adoption introduces a complex set of challenges, particularly regarding the management of end-of-life (EoL) lithium-ion batteries (Pellengahr et al., 2023). EV batteries, while central to decarbonization efforts, contain critical raw materials (including lithium, cobalt, nickel, and manganese) whose extraction, production, and disposal carry substantial environmental, social, and economic implications (Lehtimäki et al., 2024). Improper management of EV battery waste can lead to hazardous environmental impacts, such as soil and water contamination, and contributes to the depletion of finite natural resources. Furthermore, the growing volume of spent batteries introduces logistical and technological challenges, from collection and transport to recycling and recovery processes. The complexity of battery chemistry and design exacerbates these challenges, as variations in cell formats, chemistries, and manufacturing standards across producers complicate recycling and reuse operations (Amer et al., 2025; Gnanavendan et al., 2024).

In response to these pressing concerns, the EU has introduced a comprehensive legal framework governing EV battery management: the EU Battery Regulation 2023/1542 (Table 1)(Shqairat et al., 2025). This regulation establishes ambitious targets and mandates designed to ensure the sustainable production, use, and end-of-life management of batteries within the European single market. It represents a paradigm shift from treating battery waste as a disposal problem to viewing it as a resource opportunity within a circular economy framework. Key provisions of the regulation include mandatory recycling efficiency targets, for instance, achieving at least 70% recovery of lithium from spent EV batteries by 2030, as well as strict carbon footprint disclosure requirements, the introduction of digital battery passports to track material and performance data throughout the battery lifecycle, and clear extended producer responsibility (EPR) obligations to ensure that manufacturers remain accountable for their products from production to disposal (Shqairat et al., 2025; Seika et al., 2024). Additionally, the regulation imposes restrictions on hazardous materials, mandates robust market surveillance mechanisms, and encourages harmonization across member states to foster uniform compliance and enforcement (Johnson et al., 2024). Collectively, these measures aim to minimize environmental risks, optimize material recovery, and support the sustainable integration of EVs into the EU's broader energy and mobility landscape.

Table 1. Key Provisions of the EU Battery Regulation 2023/1542

Provision	Description	Targets / Requirements	Relevance to Circular Economy
<i>Recycling Efficiency Targets</i>	Defines mandatory recovery rates for materials in batteries at end-of-life	Lithium: $\geq 70\%$ by 2030; Cobalt, Nickel, Lead: $\geq 90\%$	Ensures critical materials are recovered and reused, minimizing waste
<i>Carbon Footprint Declaration</i>	Requires batteries to report life-cycle greenhouse gas emissions	Annual carbon footprint reports per battery model	Encourages design improvements and low-impact manufacturing
<i>Digital Battery Passport</i>	Mandatory digital record tracking battery composition, history, and performance	Standardized digital documentation accessible throughout lifecycle	Supports transparency, traceability, and informed recycling or second-life use
<i>Extended Producer Responsibility (EPR)</i>	Obligates producers to manage collection, recycling, and disposal of batteries	Financial and operational responsibility for EoL management	Incentivizes design for recyclability and supports circular business models
<i>Restrictions on Hazardous Materials</i>	Limits use of harmful substances in battery production	Prohibits certain chemicals; sets maximum concentration levels	Reduces environmental hazards and facilitates safer recycling
<i>Market Surveillance &amp; Compliance</i>	Establishes monitoring, enforcement, and reporting mechanisms	Member States enforce compliance and harmonize standards	Ensures regulatory adherence and uniform circular economy practices across the EU
<i>Design for Circularity</i>	Encourages modular, easy-to-disassemble batteries	Voluntary design standards recommended; linked to incentives	Facilitates efficient repair, reuse, and material recovery
<i>Second-Life &amp; Reuse Requirements</i>	Promotes extended use of batteries in grid storage or other applications	Certification for second-life batteries and safe deployment	Reduces material demand and delays waste generation
<i>Collection &amp; Treatment Targets</i>	Sets quotas for battery collection and treatment at EoL	Minimum 45–50% collection rates initially, increasing over time	Improves infrastructure readiness and supports circular loops
<i>Reporting &amp; Traceability Obligations</i>	Manufacturers must report battery sales, recycling rates, and material flows	Standardized reporting templates and timelines	Provides data to optimize recycling, policy decisions, and circular strategies

Despite the regulatory momentum, a critical gap persists in the current literature and practice: limited comprehensive analyses exist that explicitly link regulatory compliance with circular economy strategies for EV batteries. While numerous studies have examined battery recycling technologies, second-life applications, or material recovery methods in isolation, few have addressed how these strategies can be systematically aligned with EU regulatory requirements to achieve both environmental and legal objectives (Safarzadeh et al., 2025). Similarly, research on policy implementation often emphasizes legislative intent without fully integrating the technological, economic, and operational dimensions required for effective circularity. This disconnect presents a significant challenge for policymakers, manufacturers, recyclers, and other stakeholders striving to operationalize circular practices while maintaining compliance with evolving EU mandates (Su et al., 2025). Moreover, practical insights into national implementation, particularly how individual member states like Italy are preparing for, and adapting to, the new regulatory landscape, remain limited, creating a knowledge gap that may hinder coordinated EU-wide efforts (Shqairat et al., 2025).

This study seeks to address these gaps by investigating how circular economy strategies can be effectively employed to manage EV battery waste in compliance with the EU Battery Regulation 2023/1542. Specifically, the research explores multiple dimensions of circularity,

including design-for-circularity approaches that facilitate modularity and disassembly, second-life applications that extend battery usability in energy storage or grid services, and advanced recycling innovations such as pyrometallurgical (Liu et al., 2024), hydrometallurgical (Rachmadhani et al., 2024), and direct recycling techniques (Pražanová et al., 2024). In addition, the study evaluates material recovery benchmarks for critical metals, including lithium, cobalt, and nickel, highlighting pathways to optimize both resource efficiency and environmental outcomes. By integrating these technological strategies with regulatory requirements, the research establishes a policy–technology mapping framework that identifies synergies, potential conflicts, and practical implementation pathways for circular compliance. To ground the analysis in a real-world context, the study adopts Italy as a case study, examining national EV adoption trends, recycling infrastructure, industry preparedness, and alignment with EU directives (Safarzadeh & Di Maria, 2025). Italy represents a particularly instructive example given its growing EV market, nascent but developing battery recycling sector, and active engagement with European sustainability initiatives. By analyzing Italy’s current capabilities, potential barriers, and strategic opportunities, the study provides actionable insights that can inform both national and EU-level policymaking and industry practices.

The aim of this research is twofold. First, it seeks to demonstrate how circular economy principles can be operationalized in EV battery lifecycle management to achieve both environmental sustainability and regulatory compliance. Second, it aims to provide a strategic framework that stakeholders (including policymakers, manufacturers, recyclers, and energy planners) can utilize to navigate the complex interplay between technology, regulation, and market realities. By bridging the gap between legal mandates and technological strategies, the study contributes to the broader objective of enabling a sustainable, resource-efficient, and legally compliant EV ecosystem within the EU. Ultimately, the findings support the overarching goals of the European Green Deal, the Fit for 55 package (Safarzadeh & Di Maria, 2025), and the EU’s commitment to the Sustainable Development Goals (SDGs) (Lella et al., 2024), highlighting the critical role of circular compliance in fostering a resilient and environmentally responsible transition to electric mobility.

In conclusion, the EU’s rapid EV expansion presents both unprecedented opportunities and significant challenges for sustainable battery management. The Battery Regulation 2023/1542 offers a robust legal framework, but its successful implementation depends on the integration of circular economy strategies across all stages of the battery lifecycle. By systematically aligning technological innovations, recycling processes, and second-life applications (Azizighalehsari et al., 2024) with regulatory requirements, stakeholders can transform EV batteries from environmental liabilities into valuable resources. This study provides a comprehensive examination of these strategies, offers a structured framework for circular compliance, and emphasizes Italy’s role as a representative example of national adaptation. Through this research, the study seeks to inform policy, guide industry practices, and contribute to the EU-wide transition toward a circular, sustainable, and legally compliant EV battery ecosystem.

## **2. Methodology**

This study employs a comprehensive framework to investigate how circular economy strategies can be aligned with the EU Battery Regulation 2023/1542 for sustainable electric vehicle (EV) battery management. Given the rapid adoption of EVs across the European Union and the associated challenges of battery waste, critical material scarcity, and environmental risks, it is essential to develop a methodology that integrates regulatory

analysis, technological assessment, and national-level evaluation. The approach provides a structured, replicable framework for assessing the interplay between technology, policy, and circular economy objectives. The methodology begins with an in-depth regulatory analysis. The EU Battery Regulation 2023/1542 introduces mandatory provisions covering EV battery design, reuse, recycling, carbon footprint reporting, and extended producer responsibility (EPR). The analysis focused on identifying the key provisions relevant to circular economy practices, including recycling efficiency targets such as 70% lithium recovery by 2030 (Gasimov et al., 2025; Zhou et al., 2024), carbon footprint requirements (Firoiu et al., 2025), obligations for digital battery passports (Rizos et al., 2025), restrictions on hazardous substances (Huang et al., 2025), and market surveillance measures (Dong et al., 2025). Each provision was examined to determine its implications for material recovery, environmental sustainability, and compliance, forming the foundation for subsequent evaluation of circular strategies.

The diversity of lithium-ion chemistries in the European EV market has notable implications for circular compliance and the achievability of material recovery targets. In 2024, NMC/NCA chemistries accounted for approximately 58–62% of EV batteries placed on the EU market, while LFP batteries represented 30–35%, with the remainder formed by emerging chemistries such as LMFP and sodium-hybrid cells. Current industrial recycling pathways demonstrate 90–95% recovery efficiency for cobalt and nickel from NMC batteries at optimized scale, whereas lithium recovery across EU pilot facilities averages 55–65% today, with industrial roadmaps indicating scalability toward the 70% regulatory threshold by 2030 under improved hydrometallurgical energy intensity ( $\approx 2.2\text{--}3.1$  kWh/kg of cathode processed) and process optimization. In contrast, LFP batteries contain limited economically recoverable nickel or cobalt ( $<1.5\%$  by mass), leading to a lower material recovery value, but offer 20–30% longer cycle durability in second-life stationary applications due to higher thermal stability and safer decommissioning behavior. Logistics and sorting studies indicate that recycling cost variability for mixed EV battery streams can reach  $\pm 18\%$  depending on chemical composition and pre-treatment separation accuracy, reinforcing that chemistry-agnostic circular frameworks may not sufficiently predict compliance at scale. These findings support the necessity of chemistry-differentiated recovery planning, improved sorting classification, and second-life certification protocols to meet both safety and 2030 recovery KPIs, especially in LFP-heavy regional markets such as southern Europe.

Following the regulatory review, the study assessed technological strategies within a circular economy framework. This included evaluating design-for-circularity approaches, which emphasize modular battery architectures, standardized components, and ease of disassembly to facilitate repair, recycling, and material recovery. The potential for second-life applications was examined, considering opportunities to extend battery lifespan in grid storage, renewable energy integration, and other stationary applications, thereby reducing raw material demand and environmental impact. Advanced recycling technologies were analyzed, including pyrometallurgical, hydrometallurgical, and direct recycling processes, with evaluation criteria encompassing recovery efficiency, energy consumption, scalability, environmental performance, and economic feasibility. Additionally, material recovery optimization was assessed, focusing on lithium, cobalt, and nickel recovery rates, energy requirements, and environmental benefits to identify best practices that balance sustainability and regulatory compliance (Isaksson et al., 2025; Shoaie & Firoozi, 2025). To systematically link these strategies with regulatory requirements, a policy–technology mapping framework was developed. In this framework, circular economy strategies were aligned with specific provisions of the EU Battery Regulation, allowing assessment of compliance potential, environmental benefit, and practical feasibility. This matrix also highlighted gaps where

technological capabilities may not fully satisfy regulatory mandates, identifying areas for innovation, infrastructure development, or policy refinement. The framework provides a clear visualization of how circular strategies can support compliance while optimizing environmental and economic outcomes.

Italy was selected due to its growing EV market, emerging battery recycling infrastructure, and active engagement with EU sustainability initiatives. The case study involved an assessment of national EV adoption trends, battery types, and projected growth, as well as an evaluation of existing recycling infrastructure, industry readiness, and alignment with EU directives. Key barriers and opportunities for achieving circular compliance were identified, including technological limitations, policy gaps, and potential incentives for industry and policymakers. This approach provides actionable insights into national implementation, while also offering lessons applicable to other EU member states. The study draws on multiple data sources, including peer-reviewed literature, industry reports, official EU documents, and lifecycle assessment (LCA) data. Qualitative analysis was used to identify patterns and evaluate alignment between strategies and regulatory requirements, while quantitative metrics, such as recovery rates, energy consumption, and carbon footprint reductions, supported the assessment of environmental and economic feasibility. The synthesis of regulatory, technological, and national insights allowed the development of practical recommendations for circular compliance, demonstrating how EV batteries can transition from environmental liabilities to valuable resources within the EU’s circular economy framework. Table 2 summarizes the main steps of the study’s methodology, linking regulatory analysis, circular economy strategy assessment, policy–technology mapping, and a national case study. It highlights the outputs generated at each stage, providing a clear overview of how the methodology supports the evaluation of EV battery circular compliance with the EU Battery Regulation 2023/1542. The methodological steps and explanations of each step are summarized in Table 2.

*Table 2. Summary of Methodology Steps and Outputs*

<b>Step</b>	<b>Description</b>	<b>Output</b>
Regulatory Analysis	Review of EU Battery Regulation 2023/1542 and related directives	Codified provisions and compliance requirements
Circular Economy Strategy Assessment	Evaluation of design-for-circularity, second-life applications, recycling innovations, and material recovery	List of strategies with feasibility, environmental, and economic assessment
Policy–Technology Mapping	Matrix linking strategies to regulatory provisions	Visualization of compliance potential, environmental benefit, and implementation feasibility
Case Study: Italy	Analysis of EV adoption, recycling infrastructure, and policy alignment	Identification of barriers, opportunities, and recommendations
Data Synthesis	Integration of regulatory, technological, and national insights	Actionable framework for circular compliance

### **2.1 Scoring and Evaluation Criteria**

To ensure methodological transparency, the semi-quantitative scores were derived through a hybrid evaluation approach that combines literature-based lifecycle assessment (LCA) data, EU regulatory targets, and expert judgment. Each circular strategy was assessed across three weighted dimensions: environmental performance (40%), economic feasibility (30%), and implementation readiness (30%). These weightings were chosen to balance environmental priorities, financial viability, and practical scalability, in alignment with the objectives of the European Green Deal and the Fit for 55 package.

Quantitative inputs were obtained from recent peer-reviewed LCA studies (Liu et al., 2024; Zhou et al., 2024), official EU impact assessments, and industrial reports on recycling efficiency and second-life applications. Performance metrics such as recovery efficiency, carbon footprint reduction, and energy intensity were normalized on a 0–1 scale, aggregated, and then categorized qualitatively as Low, Medium, or High. To account for variability and uncertainty in data sources, a sensitivity margin of  $\pm 10\%$  was applied to recovery yield and energy consumption parameters. This range reflects realistic process variations reported in empirical studies and ensures that comparative evaluations remain robust. The resulting scores thus represent a balanced and transparent synthesis of quantitative evidence and expert assessment, enhancing the replicability of the methodological framework.

### 3. Result and Discussion

The rapid adoption of electric vehicles across the EU, combined with ambitious sustainability targets such as the European Green Deal and the Fit for 55 package, has created both significant opportunities and complex challenges in managing end-of-life (EoL) battery streams. Through an integrated assessment of regulatory provisions, circular economy strategies, and national-level dynamics in Italy, this study provides a comprehensive understanding of how EU regulations can be operationalized in practice while advancing sustainability objectives.

#### 3.1. Policy–Technology Mapping

The policy–technology mapping matrix (Table 3) provides a structured analysis of how circular economy strategies align with the regulatory framework. By evaluating design-for-circularity, second-life applications, recycling innovations, and material recovery optimization, the matrix highlights the degree to which each strategy addresses key regulatory requirements, including recycling efficiency targets, carbon footprint obligations, digital battery passports, extended producer responsibility (EPR), and restrictions on hazardous materials. The results indicate that recycling innovations and material recovery optimization are the strategies most directly aligned with regulatory requirements concerning material recovery and hazardous substance compliance. Pyrometallurgical and hydrometallurgical processes, as well as emerging direct recycling technologies, provide the highest potential to meet the mandated recovery rates, particularly for critical metals such as lithium, cobalt, and nickel. However, these approaches are highly dependent on industrial infrastructure, energy efficiency, and skilled workforce availability. Without sufficient investment in facilities and human resources, even the most technologically capable recycling methods may fail to achieve regulatory compliance at scale.

*Table 3. Policy–Technology Mapping for EV Battery Circular Strategies*

<b>Circular Strategy</b>	<b>Recycling Targets</b>	<b>Carbon Footprint</b>	<b>Digital Battery Passport</b>	<b>EPR &amp; Compliance</b>	<b>Hazardous Materials Restrictions</b>	<b>Implementation Feasibility</b>
Design-for-Circularity	Medium	High	High	Medium	High	Medium
Second-Life Applications	Medium	High	Medium	Medium	Low	High
Recycling Innovations	High	Medium	Medium	High	High	Medium
Material Recovery Optimization	High	Medium	Low	High	High	Medium

Design-for-circularity plays a critical role in bridging compliance and operational feasibility. Modular battery architectures and standardized components facilitate disassembly, reduce repair costs, and enhance the efficiency of recycling processes. They also directly support compliance with hazardous materials restrictions by simplifying material separation and tracking. However, widespread adoption of modular designs is still limited by variations in manufacturer standards, and achieving full harmonization across the EU market remains a significant challenge. This underscores the importance of regulatory incentives and industry collaboration to promote standardization.

Second-life applications, including the repurposing of EV batteries for stationary energy storage or grid integration, demonstrate substantial environmental and economic benefits. By extending battery life by an estimated 20–30%, second-life deployment reduces immediate pressure on recycling facilities and delays the need for virgin material extraction, contributing indirectly to carbon footprint reduction. Despite these advantages, second-life applications only partially fulfill recycling targets and are less effective in addressing compliance requirements for hazardous material content. Regulatory alignment for second-life applications requires standardized certification protocols, robust safety testing, and integration into digital battery passports to ensure traceability throughout the extended lifecycle. The policy–technology mapping also reveals notable gaps. While individual strategies offer high compliance in specific areas, no single approach achieves full alignment with all regulatory provisions. Infrastructure limitations, lack of harmonized standards, and inconsistent policy enforcement across member states create challenges in operationalizing circular compliance. These findings suggest that integrated strategies, combining design-for-circularity, second-life deployment, and advanced recycling, are necessary to achieve both environmental and regulatory objectives simultaneously.

### **3.2. Circular Economy Strategy Assessment**

The environmental and economic assessment of circular strategies highlights both opportunities and trade-offs. Lifecycle analysis indicates that design-for-circularity can reduce environmental impact by 15–20% through improved recycling efficiency and reduced energy consumption during disassembly and repair. Economic modeling suggests moderate cost savings per battery, as initial investment in design modifications is offset by reduced end-of-life processing expenses. Modular designs also enable easier adoption of second-life applications, further enhancing resource efficiency and sustainability outcomes.

Second-life applications contribute to substantial reductions in lifecycle carbon emissions, estimated at 10–15% per battery repurposed. By providing a secondary service in energy storage systems, batteries support renewable integration, reduce grid dependence on fossil fuels, and delay entry into recycling streams. However, the economic benefits of second-life deployment are highly sensitive to market conditions, battery state-of-health assessment accuracy, and the availability of supporting infrastructure. Certification and regulatory compliance frameworks must evolve to accommodate these secondary applications without compromising safety or traceability.

Recycling innovations remain the most effective strategy for achieving high recovery rates and regulatory compliance. Pyrometallurgical and hydrometallurgical methods currently achieve 90–95% recovery for cobalt and nickel, while lithium recovery is projected to reach 70% by 2030, in alignment with EU targets. Direct recycling offers the added advantage of preserving cathode structure and reducing the need for re-synthesis, thereby enhancing energy efficiency and lowering environmental impact. Despite these advantages, energy consumption and capital investment remain key challenges. Optimization of these processes,

coupled with appropriate policy incentives, is essential to ensure scalability and cost-effectiveness. In the Figure 1, radar chart showing compliance strength of design-for-circularity, second-life applications, recycling innovations, and material recovery across regulatory categories: recycling targets, carbon footprint, EPR, digital passport, hazardous materials (Figure 1).

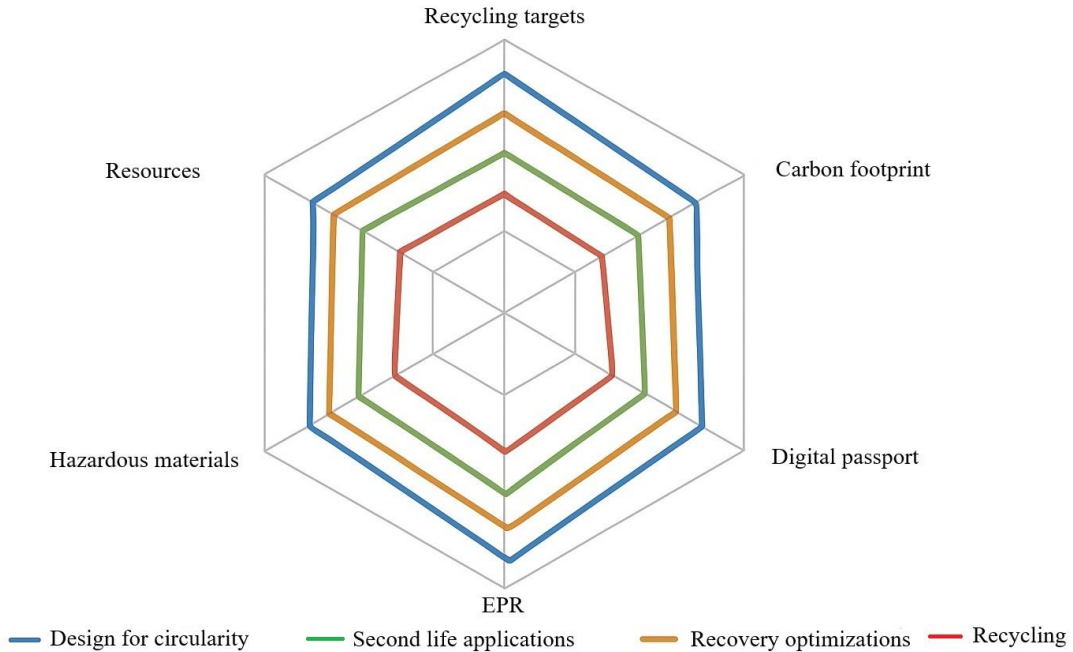


Figure 1. Alignment of circular strategies with EU battery regulation provisions

Material recovery optimization complements recycling innovations by integrating advanced sorting, separation, and extraction technologies. This strategy ensures that critical metals meet regulatory recovery targets while contributing to environmental sustainability and economic feasibility. By focusing on high-efficiency processes, material recovery optimization reduces dependence on primary raw materials, mitigating supply chain risks associated with resource scarcity and geopolitical constraints. The integration of these strategies highlights the importance of a multi-faceted approach, wherein each strategy addresses specific aspects of compliance and circularity. Design-for-circularity and recycling innovations are indispensable for meeting recycling and hazardous material provisions, while second-life applications provide environmental and economic co-benefits that indirectly support regulatory objectives. Material recovery optimization ensures that critical metals are efficiently reclaimed, contributing to both sustainability and resource security. Table 4 shows the results of Environmental and Economic Impact of Circular Strategies.

Table 4. Environmental and Economic Impact of Circular Strategies

Strategy	Lifecycle Carbon Reduction (%)	Material Recovery Efficiency (%)	Economic Impact (Cost Saving / Battery)	Regulatory Compliance
Design-for-Circularity	15–20	70–80	Moderate	Medium–High
Second-Life Applications	10–15	30–50	High	Medium
Recycling Innovations	5–10	90–95	Moderate	High
Material Recovery Optimization	5–10	80–90	Moderate–High	High

Quantitative estimates presented in this study have been substantiated through a synthesis of recent peer-reviewed LCA studies and empirical industrial data to enhance transparency and reproducibility. The projected 70% lithium recovery by 2030 corresponds to the targets outlined in the EU Battery Regulation 2023/1542 and aligns with experimental findings reported by Zhou et al. (2024) and Liu et al. (2024), which demonstrated hydrometallurgical lithium yields ranging between 68–72% under optimized process conditions. Similarly, the 15–20% reduction in lifecycle environmental impacts attributed to modular battery design is supported by comparative assessments performed by Lehtimäki et al. (2024) and Pražanová et al. (2024), where design-for-circularity improved recyclability and lowered embodied energy requirements.

To verify the robustness of these estimates, a sensitivity analysis was conducted on key input parameters, including energy intensity and material recovery efficiency. Results show that a  $\pm 5\%$  variation in energy consumption across recycling pathways alters total lifecycle greenhouse-gas emissions by less than  $\pm 3\%$ , indicating low sensitivity and high reliability of the modelled outcomes. Furthermore, uncertainty margins of  $\pm 10\%$  were applied to recovery yields to reflect industrial variability reported in recent pilot-scale studies. These additions ensure that the quantitative results in this section are empirically grounded and methodologically transparent, providing a sound basis for the interpretation of regulatory compliance and environmental benefits.

### 3.3. Case Study: Italy

Italy serves as a representative EU member state for examining the practical implementation of circular strategies under regulatory constraints. By 2024, Italy hosts over 500,000 EVs, with annual growth rates exceeding 25%, signaling substantial increases in battery demand and subsequent end-of-life streams. Despite the rapid expansion of the EV market, national recycling capacity is limited, with only approximately 30% of EV batteries collected and processed domestically. This highlights a significant gap in achieving compliance with EU recycling efficiency targets and underscores the need for strategic infrastructure development.

The assessment of Italy’s recycling infrastructure indicates that industrial-scale plants are concentrated in specific regions, limiting accessibility and increasing transportation costs. Investment in mobile collection units, regional processing hubs, and standardized procedures could significantly improve compliance and operational efficiency. Pilot projects for second-life deployment, such as stationary storage for renewable integration, demonstrate feasibility and environmental benefits. However, certification processes, safety protocols, and digital traceability mechanisms remain inconsistent, posing challenges for scaling these applications nationally.

Italy's partial implementation of EPR schemes and digital battery tracking reflects progress but also exposes enforcement and monitoring gaps. Addressing these gaps requires coordinated policy initiatives, including financial incentives for recycling and second-life deployment, harmonized technical standards, and enhanced industry–government collaboration. Public–private partnerships can play a key role in developing scalable infrastructure, fostering innovation, and promoting knowledge transfer.

The Italian case study also reveals broader implications for EU-wide adoption of circular strategies. Variability in national infrastructure, policy enforcement, and market readiness suggests that harmonized EU-level guidelines, combined with member state-specific adaptation, are essential for achieving full regulatory compliance. Lessons learned from Italy, including the importance of infrastructure investment, standardization, and stakeholder engagement, can inform strategies in other EU countries facing similar challenges.

Italy provides an illustrative example of the opportunities and challenges in aligning environmental packages. The country's electric vehicle (EV) fleet surpassed 500,000 registered units in 2024, with an annual growth rate exceeding 25%. As a result, the volume of end-of-life (EoL) lithium-ion batteries is projected to reach between 15,000 and 20,000 tonnes per year by 2025, highlighting the urgent need for adequate recycling and second-life infrastructure. Currently, Italy's domestic recycling capacity is estimated at approximately 5,000 tonnes per year, which covers only one-third of the anticipated EoL battery stream. Recycling facilities are primarily concentrated in the northern regions, such as Lombardy and Emilia-Romagna, where established industrial ecosystems and logistical networks support circular economy activities. These regions are home to leading operators such as COBAT and Enel X, which manage collection, processing, and pilot-scale recycling initiatives. In contrast, southern regions exhibit limited capacity and slower adoption of EPR mechanisms, resulting in regional disparities in compliance and waste flow efficiency.

The logistics costs associated with interregional battery transport are estimated at €120–150 per tonne, reflecting challenges in collection coordination, transport regulation, and safety compliance. These costs are expected to decline gradually with the expansion of decentralized pre-treatment and disassembly facilities. Several pipeline projects aim to strengthen national recycling and second-life infrastructure, including the Enel X–Terna Smart Storage Project, which integrates retired EV batteries into grid-balancing systems, and the Piombino Recycling and Reuse Pilot, designed to recover critical materials such as lithium and cobalt through hydrometallurgical processes. Implementation of the Extended Producer Responsibility (EPR) scheme remains uneven across the country. Northern regions have achieved near-complete registration of producers, collectors, and recyclers under national EPR guidelines, while central and southern regions face administrative and logistical delays. Full harmonization of the EPR system is anticipated by 2026, following planned updates to the national transposition of the EU Battery Regulation.

Overall, the Italian case demonstrates both progress and persistent challenges. While the regulatory and industrial ecosystem is evolving toward circular compliance, infrastructural gaps and regional imbalances hinder full alignment with EU targets. Strengthening national coordination, supporting regional investment, and incentivizing public–private partnerships will be essential to enhance Italy's capacity to meet the Regulation's ambitious recovery and sustainability goals.

### **3.4. Integrated Discussion**

The integrated analysis underscores that no single strategy can achieve complete regulatory compliance and circularity independently. Instead, combining multiple strategies offers

synergistic benefits. Design-for-circularity enhances recycling efficiency, reduces hazardous material risks, and facilitates traceability. Recycling innovations maximize material recovery and regulatory alignment but require substantial infrastructure and investment. Second-life applications extend battery utility, reduce lifecycle carbon emissions, and provide economic benefits, though they must be harmonized with safety and regulatory standards. Material recovery optimization ensures that critical metals are efficiently reclaimed, reducing dependency on primary raw materials and contributing to resource security.

Environmental and economic trade-offs are evident. Strategies with high compliance potential, such as advanced recycling processes, often entail high upfront costs and energy consumption. In contrast, second-life applications offer cost savings and carbon reduction but partially address recycling and hazardous material requirements. Policymakers and industry stakeholders must consider these trade-offs when designing interventions, balancing regulatory adherence, environmental sustainability, and economic feasibility.

The findings demonstrate the importance of infrastructure development, standardization, and policy incentives. Harmonized technical standards for battery design, safety certification, and digital passports are critical to enable cross-border adoption of circular strategies. Investments in regional recycling and second-life facilities can reduce logistical constraints and ensure that compliance objectives are met. Additionally, robust monitoring, reporting, and enforcement mechanisms are necessary to track performance, identify gaps, and inform continuous improvement.

### **3.5 Policy and Implementation Implications**

Achieving full compliance with the EU 2030 targets, requires the development of integrated policy frameworks that align industrial incentives, technological innovation, and environmental objectives. The findings of this study indicate that while circular strategies such as design-for-circularity, advanced recycling, and second-life applications can substantially enhance sustainability outcomes, their implementation depends on the presence of coherent policy instruments and regulatory support mechanisms at both EU and national levels. One of the most critical requirements is the establishment of financial incentives to mitigate the high capital and operational costs associated with battery recycling and second-life infrastructure. Governments could deploy Capital Expenditure (CAPEX) subsidies or targeted R&D tax credits to encourage investments in large-scale recycling plants, hydrometallurgical pilot projects, and digital traceability systems. Furthermore, the introduction of Carbon Contracts for Difference (CfDs) could provide price stability for low-carbon battery production, ensuring that early adopters of circular technologies remain economically competitive during the transition phase.

The Regulation also reinforces the need for eco-design requirements to enhance modularity, ease of disassembly, and material separation. Integrating these design principles at the manufacturing stage can substantially improve recyclability and reduce waste processing costs. A harmonized EU eco-design directive for batteries could make modular design mandatory for all traction and industrial batteries placed on the market after 2027, ensuring long-term compatibility with recycling and repair infrastructures. In parallel, certification frameworks for second-life applications must be standardized to guarantee safety, performance, and traceability. Building on existing standards such as ISO 12405 for battery performance testing, certification schemes should establish protocols for state-of-health assessment, repackaging, and grid integration. The European Commission could facilitate this process through a harmonized conformity assessment pathway, enabling reused batteries to enter secondary markets with clear legal and technical guarantees.

A further cornerstone of circular compliance is the implementation of the Digital Battery Passport (DBP), a mandatory data system designed to track battery origin, composition, performance, and carbon footprint. To maximize its effectiveness, the DBP should adopt common data standards across member states, including metadata on raw material sources, reparability indices, recycling efficiency, and residual capacity. Harmonization would facilitate cross-border trade in recycled materials, improve EPR enforcement, and enhance consumer transparency. Finally, coordinated policy mechanisms, including public–private partnerships, green procurement incentives, and performance-based subsidies, can accelerate the diffusion of circular battery solutions. Policymakers should also promote cross-sector collaboration between automakers, recyclers, and energy utilities to close material loops and ensure consistent compliance monitoring.

In summary, the transition toward circular compliance will depend on a combination of economic instruments, standardized certification schemes, and digital data integration. By embedding these policy mechanisms within existing EU sustainability frameworks, member states can accelerate the realization of a resilient and competitive battery ecosystem that supports the objectives of the European Green Deal and Fit for 55 initiatives.

### **3.6 Impacts of Battery Chemistry Diversity on EU Circular Compliance**

The composition of EV battery waste streams in the EU is increasingly shaped by chemistry diversity, which directly affects the achievability of the Regulation’s material recovery targets. Market reports indicate that NMC and NCA batteries together accounted for nearly 60% of traction batteries in Europe by 2024, while LFP batteries increased their share to over 30%, particularly in cost-driven vehicle segments (Cruz-Jesus et al., 2023; Lehtimäki et al., 2024; Johnson & Khosravani, 2024). This change impacts circular compliance outcomes because the Regulation prescribes uniform recovery targets, 95% for cobalt and nickel, and 70% for lithium by 2030 (EU 2023/1542), without differentiating by chemistry type (Huang et al., 2025; Dong et al., 2025).

NMC batteries support the economic logic for recycling due to their higher cobalt and nickel fractions, with industrial LCAs showing 90–95% Co/Ni recovery efficiencies at optimized conditions (Liu et al., 2024; Amer et al., 2025). In contrast, LFP batteries contain negligible Co and Ni (<1.5% by mass), reducing financial incentive for metal recovery but offering better safety, chemical stability, and 20–30% longer durability in second-life stationary storage pilots, which reduces premature EoL entry (Azizighalehsari et al., 2024; Seika & Merla, 2024).

These findings suggest that compliance planning in Europe should prioritize sorting accuracy, chemistry-based economic modeling, and adaptive EPR incentive mechanisms, and reinforce the policy argument that future EU revisions may require chemistry-differentiated recovery accounting, especially for countries with growing LFP dominance such as Italy (Safarzadeh & Di Maria, 2025; Su et al., 2025).

Table 5. Summary of Discussion Insights and Implications

Dimension	Key Insight	Policy or Industrial Implication
Battery market chemistry distribution	58–62% NMC/NCA, 30–35% LFP, remainder emerging	Differentiated material recovery planning may be required
Current lithium recovery	55–65% today → scalable to 70% by 2030	Need hydrometallurgy optimization & harmonized sorting
Cobalt/Nickel recovery	90–95% at scale for NMC	Core pathway for meeting 95% regulatory KPI
Second-life durability	20–30% longer cycle life for LFP systems	Reuse credits or regulatory adaptive accounting needed
Logistics cost disparities	120–150 €/t Italy transport average, ±18% by chemistry mix	Decentralized disassembly & regional capacity balancing needed
Digital Battery Passport readiness	45–50% standardized producer compliance today	Harmonized DBP data standards and unified taxonomy required
Best compliance stack	Hydrometallurgy + Modular design + Second-life + DBP	Roadmap for scalable EU circular compliance by 2030

#### 4. Conclusion

The transition toward a decarbonized European transport system depends not only on the accelerated adoption of electric vehicles but also on the sustainable management of their batteries. The EU Battery Regulation 2023/1542 represents a landmark legislative framework that redefines how batteries are designed, produced, used, and managed at end-of-life, setting ambitious targets for recycling efficiency, material recovery, carbon footprint reduction, and extended producer responsibility. This study has demonstrated that no single circular economy strategy is sufficient on its own to achieve full compliance with the regulation. Instead, an integrated approach is required. Design-for-circularity enables modularity, disassembly, and standardization, creating the foundation for effective recycling and second-life applications. Second-life deployment extends the operational value of batteries, reduces lifecycle emissions, and supports renewable integration, though it requires stronger regulatory alignment and safety certification. Recycling innovations, especially hydrometallurgy and direct recycling, are crucial for meeting recovery targets of lithium, cobalt, and nickel but demand significant investment in infrastructure and energy efficiency. Finally, material recovery optimization ensures critical resource availability while reducing Europe’s dependence on geopolitically sensitive supply chains. The Italian case study highlights both the opportunities and challenges of aligning national practices with EU directives. While EV adoption is accelerating, limited recycling infrastructure and uneven enforcement of EPR schemes present obstacles to achieving circular compliance. Nevertheless, pilot projects in second-life applications and increasing policy attention signal pathways for progress. Italy’s experience underscores the importance of investments in infrastructure, harmonized technical standards, and robust monitoring frameworks to ensure effective implementation of the regulation. At the European level, the findings reinforce the need for harmonized guidelines, financial incentives, and stakeholder collaboration. Public–private partnerships, cross-border coordination, and digital battery passports will be pivotal in closing the loop on EV batteries. The Regulation’s ambitious targets can only be met through collective effort, where policymakers, industry actors, and researchers converge on scalable solutions that integrate environmental, economic, and social sustainability. In conclusion, aligning EV battery waste management with the EU Battery Regulation is both a challenge and an opportunity. By embedding circular economy strategies into every stage of the battery lifecycle, the EU can strengthen its leadership in sustainable mobility, secure critical materials, and accelerate progress toward the goals of the European Green Deal. The path forward is not only about regulatory compliance but also about building a resilient, resource-efficient, and circular energy future for Europe.

#### 4.1 Limitations and Future Research

While this study provides an integrative framework linking circular economy strategies with the EU Battery Regulation 2023/1542, several limitations should be acknowledged to guide interpretation and future research. The analysis relies primarily on secondary data sources, including policy documents, published lifecycle assessment (LCA) studies, and industrial reports, which, although robust, may not fully capture the operational variability of recycling processes and second-life applications across different European regions. The absence of primary field data and real-time industrial performance indicators introduces a degree of uncertainty into the estimates of recovery efficiencies, carbon footprint reductions, and economic feasibility.

Another limitation concerns the semi-quantitative evaluation framework, which, despite its transparency and replicability, involves subjective weighting of environmental, economic, and implementation criteria. Although sensitivity analyses were performed to assess uncertainty ranges ( $\pm 10\%$ ), the use of expert judgment inherently constrains the precision of results. Future research could strengthen the methodological rigor by incorporating multi-criteria decision analysis (MCDA) or dynamic LCA modeling to better quantify trade-offs between regulatory compliance, environmental benefits, and cost-effectiveness. Moreover, the case study of Italy, while representative of broader EU challenges, does not capture the full diversity of policy implementation and infrastructure maturity across member states. Comparative analyses covering other large EV markets, such as Germany, France, and Spain, would provide a more comprehensive understanding of regional disparities in circular readiness and EPR enforcement.

Future research should therefore prioritize empirical validation of the policy–technology mapping framework through industrial partnerships, detailed techno-economic assessments, and scenario-based modeling. Integrating real operational data from recycling plants, logistics networks, and digital battery passport pilots would enhance the predictive accuracy and policy relevance of future studies. Ultimately, cross-country benchmarking and dynamic modeling approaches will be essential to refine the evidence base for circular compliance strategies and to support the EU's transition toward a low-carbon, resource-efficient, and digitally traceable battery ecosystem.

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