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Understanding Lithium-ion Battery Recycling

A Document Analysis of EU Battery Recycling Strategy

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Abstract

As lithium-ion batteries become central to the European Union's (EU) clean energy transition, particularly in electric vehicles and energy storage systems, concerns have grown regarding the sustainability of their full lifecycle. Recycling is increasingly recognized as a key strategy to mitigate environmental impacts, reduce reliance on primary raw materials, and support the EU's circular economy and climate neutrality goals. However, existing research on lithium-ion battery recycling is fragmented, differing significantly in focus, methodology, and target audience, which may hinder coherent policy development and the achievement of environmental objectives.

This thesis examines the current state, underlying rationales and concerns, as well as key challenges and opportunities associated with lithium-ion battery recycling in the EU. A qualitative research approach was employed, involving comprehensive document analysis of 93 primary and 198 secondary sources, including EU policy documents, industry reports, academic literature, and stakeholder statements. Thematic analysis was guided by a conceptual framework that considers battery collection, material recovery, and secondary material markets, explored through political, economic, social, and technical (PEST) dimensions.

Findings show that the EU's battery recycling landscape is in a nascent but promising stage, with progress driven by policy support, economic incentives, technological innovation, and public awareness. Nonetheless, persistent challenges remain, such as high recycling costs, inconsistent collection practices, technical barriers in recovery, and immature markets for recycled materials. The development of battery recycling is underpinned by a broad consensus that it forms a cornerstone of a sustainable and resilient battery value chain. Opportunities and challenges are distributed along all stages of the recycling process; however, the opportunities currently outweigh the barriers. Yet, if unresolved, these barriers could impede further progress. This study contributes to the growing body of knowledge by offering a system-wide perspective on recycling dynamics to support circular economy objectives in the EU battery sector.

Keywords: Lithium-ion Battery Recycling, Circular economy, End-of-life Management, PEST Analysis, European Union.

Executive Summary

Problem Definition

Lithium-ion batteries have become a vital component of the global battery market, driven largely by the rapid expansion of electric vehicles and their integration into energy storage systems. They are widely regarded as a key enabler of the transition toward decarbonized transportation and energy sectors. However, despite their potential to support sustainable development, the lithium-ion battery industry faces substantial sustainability challenges. These concerns not only raise questions about the long-term viability of the sector but also cast doubt on the extent to which batteries can serve as a truly sustainable foundation for a low-carbon economy.

Achieving sustainability requires more than deploying low-carbon technologies, it also demands ensuring that these technologies do not contribute to environmental degradation. In this context, circular economy strategies have gained increasing attention as pathways to address the environmental and resource-related challenges of battery production and disposal. Among these strategies, the end-of-life phase is particularly critical, as it plays a central role in closing the product lifecycle loop and enabling circularity. Approaches such as remanufacturing, repurposing, and recycling have been explored, with recycling emerging as the most widely discussed and implemented option.

Despite growing momentum, research on lithium-ion battery recycling remains fragmented. Studies vary considerably in their focus, methodology, and target audience, leading to disjointed insights and inconsistencies in identifying key challenges and opportunities. This fragmentation hampers effective decision-making and policy development. From an environmental management perspective, a more integrated, multidisciplinary approach is essential to develop a holistic understanding of the system dynamics and to better align environmental objectives with industrial development goals.

Aim and Research Questions

This thesis aims to provide a comprehensive overview of the adoption of lithium-ion battery recycling strategies, with a particular focus on the European Union (EU). It explores the current state of recycling practices, examines the key rationales and concerns that drive their implementation, and critically assesses the associated challenges and opportunities. The EU serves as an insightful case study due to its ambitious environmental objectives and strong industrial policy framework supporting circular economy transitions.

To fulfil this aim, the research is guided by the following questions:

RQ 1: How does the state-of-the-art of lithium-ion battery recycling within the European Union look like?

RQ 2: What are the perceived rationales and concerns for lithium-ion battery recycling?

RQ 3: What are stated opportunities and challenges of lithium-ion battery recycling?

Methodology

This study adopts a qualitative research design to develop an in-depth understanding of lithium-ion battery recycling within the European Union (EU). Document analysis was selected as the primary method, as the sector is still emerging and many initiatives remain at the planning or early implementation stage. This approach allows for the examination of evolving programs and multi-stakeholder activities over time, offering valuable longitudinal insights (Bowen, 2009).

Data were collected from both primary and secondary documentary sources. Primary sources included original policy documents, legislative drafts, and industry reports addressing lithium-ion battery recycling in the EU. Secondary sources comprised peer-reviewed journal articles, grey literature, and media coverage that encompassed broader perspectives on battery recycling systems, including global practices beyond the EU context. In total, 93 primary documents and 198 secondary documents were analysed. Information was extracted by examining legal texts, policy content, corporate disclosuins, academic analyses, and stakeholder statements found in articles and online sources.

The collected materials were analysed through a multi-step, iterative process involving skimming, detailed reading, and interpretation. Only content directly relevant to the research questions was retained, while less pertinent material was excluded. The conceptual framework introduced in Subsection 2.2, focusing on battery collection, material recovery, recycled material markets, and the political, economic, social, and technical (PEST) dimensions, served as the basis for data categorization and thematic analysis. The interpretation of emerging themes was guided by this framework, along with the researcher's analytical stance, scholarly commitments, and contextual understanding.

Main Findings

This study set out to answer three research questions aimed at exploring the current state of lithium-ion battery recycling practices in the European Union (EU), examining the key rationales and concerns driving their adoption, and critically assessing the associated challenges and opportunities.

(RQ1) State of the Art of Lithium-Ion Battery Recycling in the European Union

Lithium-ion batteries are considered a strategic priority within the EU, playing a crucial role in the decarbonisation of transport and energy systems, particularly through their use in electric vehicles, grid storage, and portable electronics. In alignment with its goal to achieve climate neutrality by 2050, the EU has identified lithium-ion battery recycling as a key strategy to promote sustainability, resource efficiency, and circularity within its battery value chain.

The EU provides a highly supportive political environment for advancing lithium-ion battery recycling, underpinned by policies such as the EU Battery Regulation (2023/1542), the Circular Economy Action Plan (2020), and the Critical Raw Materials Act (EU Regulation 2024/1252). These frameworks aim to ensure sustainability, material security, and climate neutrality, and are reinforced by mechanisms such as Extended Producer Responsibility (EPR) schemes. However, political challenges persist. Differences in regulatory transposition, institutional capacity, enforcement mechanisms, and stakeholder engagement across member states result in uneven implementation, limiting the coherence and effectiveness of the EU's overall recycling strategy.

Economically, the sector is supported by growing battery demand driven by climate targets, increased investment in recycling technologies, and expanding infrastructure. Additionally, the rising volume of end-of-life batteries presents valuable input streams, and economic benefits can be derived from EPR schemes and the resale of recovered critical metals. Nevertheless, several economic challenges remain. High recycling costs, shifting battery chemistries, constrained input volumes, and the underdevelopment of markets for secondary materials like lithium, cobalt, and nickel pose risks to the sector's economic viability and operational stability.

From a social perspective, the development of lithium-ion battery recycling is increasingly supported by rising public awareness around ethical and environmentally responsible sourcing. However, behavioral barriers, such as improper disposal, battery hoarding, and public concerns over potential environmental and health risks associated with recycling facilities, continue to hinder progress.

Technologically, the EU has made notable advancements in developing innovative recycling technologies and infrastructure. Still, the sector faces several limitations, including gaps in reliable and harmonized data, insufficient and unevenly distributed collection systems, and variability in the recovery capabilities of current technologies. The absence of design-for-recycling in battery manufacturing further complicates efficient material recovery processes.

In summary, the EU's lithium-ion battery recycling landscape reflects a strategically coordinated effort driven by ambitious climate policies, economic incentives, growing societal demand, and technological innovation. However, to realize a fully circular and resilient battery value chain, continued efforts are required to address persistent challenges related to infrastructure, public participation, and technical integration.

(RQ2) Perceived Rationales and Concerns for Lithium-Ion Battery Recycling

Stakeholder perspectives on lithium-ion battery recycling in the EU are broadly divided into two main camps: those emphasizing its strategic importance and those expressing caution regarding its practical implementation. Proponents highlight the environmental, economic, and social benefits of establishing a robust recycling system. For instance, stakeholders in battery manufacturing argue that integrating recycling into production processes can reduce dependence on primary raw material extraction, thereby lessening associated environmental impacts. Beyond industrial motivations, policymakers increasingly view lithium-ion battery recycling as a strategic priority to enhance resource security, mitigate geopolitical risks, and strengthen the EU's autonomy in critical raw materials.

Conversely, some stakeholders' express skepticism about the current feasibility and effectiveness of recycling efforts. Their concerns focus on structural and systemic limitations, including the economic viability of recycling operations, technical barriers to the efficient recovery of specific materials, and uncertainty surrounding the development of secondary raw material markets.

Despite these differing perspectives, there is broad consensus that lithium-ion battery recycling is essential to the development of a sustainable and resilient battery industry in the EU. This shared understanding underscores the importance of continued investment, policy support, and stakeholder collaboration to overcome existing challenges and unlock the full potential of battery recycling.

(RQ3) Stated Opportunities and Challenges of Lithium-Ion Battery Recycling

The European Union faces a mix of challenges and opportunities across the three main stages of the lithium-ion battery recycling process: collection, material recovery, and the recycled materials market.

At the collection stage, the EU benefits from strong political support, economic investment, and advancing technical capabilities. However, social factors present persistent barriers, particularly low consumer awareness and inconsistent disposal behavior, which hinder the effectiveness of collection systems. Improving public education and engagement is therefore essential to increasing battery return rates and supporting the broader success of recycling initiatives.

In the material recovery stage, progress is supported by favorable policy frameworks, growing societal endorsement, and technological advancements. Nonetheless, economic challenges remain a key obstacle. The cost of recovering certain materials often exceeds their market value, particularly given the increasing complexity and diversity of battery chemistries. This technical variability demands flexible and adaptive technologies, which are not yet widely available or economically viable. Recyclers are also under pressure to keep pace with evolving regulations while investing in technological upgrades, both of which require substantial financial and operational resources.

The recycled materials market in the EU is still in an emerging phase. Although it benefits from growing political and social support, it is constrained by structural limitations and early-stage market development. Despite these hurdles, long-term prospects remain positive. With continued investment and policy alignment, the EU is expected to develop a mature and resilient market for secondary battery materials in the years to come.

Conclusions

Lithium-ion battery recycling in the EU is in a nascent yet promising stage of development. Although still in its early phases, the sector demonstrates steady progress across political, economic, social, and technical dimensions, indicating strong potential for further advancement and long-term impact. The EU's approach reflects a strategically coordinated effort, underpinned by ambitious climate targets, economic incentives, increasing public awareness, and ongoing technological innovation.

Stakeholders broadly recognize lithium-ion battery recycling as a crucial strategy for advancing circular economy principles, mitigating environmental harm, enhancing resource security, and reinforcing the competitiveness of the EU battery industry. While some stakeholders' express concerns about current technical and economic limitations, there is general consensus that recycling forms a cornerstone of a sustainable and resilient battery value chain.

The analysis of opportunities and challenges across the three main stages of the recycling process, collection, material recovery, and the recycled materials market, reveals that opportunities generally outweigh the challenges. However, these challenges remain significant. If left unaddressed, they could slow progress and hinder the EU's ability to meet its recycling targets and broader circular economy objectives.

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Abbreviations

CE : Circular Economy

EOL : End-of-life

EPR : Extended Producer Responsibility

ESS : Energy Storage System

EU : European Union

EVs : Electric Vehicles

GHG : Greenhouse Gas

LCO : Lithium Cobalt Oxide

LFP : Lithium Iron Phosphate

LMO : Lithium Manganese Oxide

NCA : Lithium Nickel Cobalt Aluminium oxide

NMC : Nickel Manganese Cobalt oxide

PEST : Political, Economic, Social, and Technical

1 Introduction

Since it becomes commercially available in 1991, lithium-ion batteries have become a key player in the global battery market. The global demand for lithium-ion batteries is projected to rise from 700 gigawatt-hours (GWh) in 2022 to over 4,700 GWh by 2030 (McKinsey & Company, 2023b). Consequently, the market for these batteries has been expanding rapidly, and it is projected to reach nearly USD 80 billion by 2025 (Statista, 2021). The appeal of lithium-ion batteries lies in their distinct advantages, including cost-efficiency, space saving installation, and low self-discharge rates, making them more attractive than older technologies like lead-acid and nickel-cadmium batteries in promoting a low-carbon economy as discussed further in Section 2.1.1.

Widely utilized in a range of electronic devices such as cell phones, laptops, digital cameras, and power tools, the significance of lithium-ion batteries has escalated, particularly with the rapid rise in electric vehicle sales and their integration into energy storage system. According to a report by Jakob Fleischmann (2023), electric vehicles (EVs) have the highest share as the user of lithium-ion batteries, followed by stationary storage and consumer electronics. A report by McKinsey & Company (2023a) estimated that the demand for EVs batteries will increase up to 4,300 gigawatt-hours (GWh) by 2030. Another study by McKinsey & Company (2019) predicts that the global demand for energy storage will rise from 7 GWh in 2020 to exceed 180 GWh in 2030, and International Energy Agency (2022) predicted that this number will continue to rise up to 420 GWh by 2040. Lead-acid batteries were initially used in energy storage, however lithium-ion batteries have emerged as a more viable alternative and currently occupy over 90% of the global grid battery storage market (Zablocki, 2019).

The increasing demand for lithium-ion batteries is closely related to decarbonization agenda in transportation and energy sectors. The energy sectors are responsible for 73.2% of global greenhouse gas emissions, with transportation alone contributing to 16.2% (Ritchie, 2020). This agenda is massively carried out in various regions and countries, such as the European Union (EU), the United States (US), Canada and China as part of their commitment to reduce their carbon emissions. The EU, for example, has ambition to reach net-zero emissions by 2050 (European Commission: Directorate-General for Climate, 2019). Some of its member states have even more ambitious goal and plan to reach the goal earlier. For example, Sweden plans to achieve its carbon neutrality by 2045 (Sweden Ministry of Environment, 2019).

Lithium-ion batteries serve as one of the important technologies to support the agenda by enabling electrification. In the transportation sector, many believe one way to help reaching the goal is to replace internal combustion engine vehicles with electric vehicles (EVs). According to International Energy Agency (2021), the sales of EVs is expected to increase from 30 million units in 2022 to over 200 million units by 2030. The automotive industry has started to shift their focus by producing more electric vehicles (Riley, n.d.). Additionally, the increasing adoption and awareness of consumers, as well as government supports has been driving the growth of EVs (Jakob Fleischmann, 2023). The EU through their Regulation 2023/851 about carbon-dioxide ($CO_{2)}$ emission standards for new cars and vans regulated that new cars and vans registered in Europe will be zero-emission by 2035.

In the energy sector, batteries have long served as a foundational technology in stationary energy storage systems. However, the massive expansion of renewable energy sources is seen as the main driver of the additional growing demand of stationary battery storage systems. The idea is that batteries are used to store electricity that has been produced, and that electricity can be deployed when needed. It help mitigating the intermittency issues associated with renewable sources like solar and wind and also allows for a rapid response to fluctuations in demand, especially during peak periods (Zablocki, 2019). The increased adoption of lithium-ion batteries in renewable energy storage systems mainly due to their advantageous attributes have been mentioned earlier, including lower cost, reduce space required for installation and low self-discharge rates (Sanderson, 2024; Zablocki, 2019).

While lithium-ion batteries are widely regarded as indispensable for advancing sustainable development, the industry is confronted with considerable sustainability challenges. Issues related to material extraction and the end-of-life stage, for example, have emerged as critical concerns within the battery sector. Many argue that these challenges bring a complex array of economic, environmental, and social implications (Institute for Energy Research, 2023; Katwala, 2018). These topics have become central to discussions in research on lithium-ion batteries and their sustainability, as well as in environmental and battery-focused forums. Such challenges have not only raised questions about the long-term sustainability of the battery industry but have also fuelled doubts about the role of batteries as a pivotal technology for achieving a low-carbon economy.

1.1 Problem Definition

Achieving sustainability requires more than just adopting new technologies that facilitates shift to low-carbon or carbon-neutral economy. It is crucial to ensure that the technology itself does not harm the environment. In light of the growing concerns over their environmental impact, a growing body of research has highlighted the potential problems associated with the rising use of lithium-ion batteries. These issues are particularly pronounced in relation to the negative impacts of material extraction activities and the challenges of end-of-life management (see Section 2.1.3). Ideally, batteries should not pose any harm to people or the environment, even after they have reached the end of their useful life.

According to Worrell and Reuter (2014a), the sustainability challenge lies in how we manage materials through their entire lifecycle, from production to disposal. Therefore, a number of solutions have been also proposed to overcome these sustainability challenges of the batteries, ranging from implementing sustainable mining, due diligence, or adopting circular economy (Amnesty International, 2019; Baldassarre, 2025; Bolton, 2021; Church & Wuennenberg, 2019; Nogrady, 2020; Rezaei et al., 2025). In this context, circular economy strategies have been discussed as a prominent approach for tackling sustainability issues associated with lithium-ion batteries.

The shift in our economic system from a linear to a circular economy can change the way products are handled when they reach the end-of-life (Ellen Macarthur Foundation, 2024). Key principles of the circular economy is to eliminate waste and pollution, circulate products and material, as well as regenerate nature by establishing a closed-loop system that incorporates practices such as reuse, remanufacturing, repurposing, and recycling (Ellen Macarthur Foundation, 2024; Vanson et al., 2022). By adhering to these principles, it is possible to restore or retain the remaining value of a product even after the product has fulfilled its intended purpose. From this point of view, the end-of-life (EOL) phase is strategically crucial in implementing a circular economy as it serves as the pivotal link in closing the product lifecycle loop, creating circularity (Marconi & Germani, 2017).

The concept of a circular economy can be applied for how batteries should be handled at the end of their life where various end-of-life (EOL) practices can be pursued after spent batteries are collected from disposal sites. In the context of lithium-ion batteries, several studies showed that it is possible to remanufacture (Graner et al., 2023; Kampker et al., 2021; Schimanek et al., 2023; Xiong et al., 2020), repurpose (Akram & Abdul-Kader, 2024; Neigum & Wang, 2024; Quinteros-Condoretty et al., 2025; Spindlegger et al., 2025), and recycle (Costa et al., 2021;

Gaines, 2014; Sloop et al., 2020) spent lithium-ion batteries. Theoretically, implementing all end-of-life strategies are crucial, particularly given their role for managing the end-of-life of lithium-ion batteries. In this context, adopting all available strategies can also enhance the overall sustainability of batteries, at which remanufacturing should be prioritized as the first option, followed by repurposing and, finally, recycling.

Remanufacturing is a strategy aimed at extending the lifespan of lithium-ion batteries by replacing cells that no longer hold sufficient charge to meet usage standards (Charles, 2014). It entails partially disassembling the battery, removing substandard cells, replacing them, and then reassembling the battery (Foster et al., 2014). This strategy is primarily focused on reusing the battery in its original application.

Repurposing involves reengineering batteries for alternative purposes, often by reconfiguring the cells within the battery, developing a different control system, and addressing any damage, similar to remanufacturing (Foster et al., 2014). Batteries that undergo this system will mainly be used for applications that do not require the same level of performance as their initial purpose. In the case of lithium-ion batteries, repurposing primarily focuses on exploring the potential of using electric vehicle (EV) batteries for "second life" applications in stationary storage applications (Akram & Abdul-Kader, 2024; Engel et al., 2019). This idea is mainly based on the consideration that after reaching their calendar life or maximum cycle charges, EV batteries can still retain 70% to 80% of their capacity, therefore deploying them for energy storage system (ESS), is considered feasible (Engel et al., 2019).

Recycling spent lithium-ion batteries entails disassembling cells and safely extracting precious metals, chemicals, and other materials for proper disposal or potential resale on the commodities market (Costa et al., 2021). Although increased efforts are being made to assess the feasibility of remanufacturing and repurposing, which is necessary to ensure the longevity of batteries, as well as to maximize their value, there are some circumstances that make the batteries lose their embedded value. Hence, the batteries should enter the recycling stage. This strategy has become the most widely adopted option for managing batteries that have reached the end of their usable life and cannot be remanufactured or repurposed, necessitating disposal. Recycling is vitally important as the final step that allows materials to stay in the economy and not end up as waste (Ellen Macarthur Foundation, 2022).

Among the various strategies within the circular economy, recycling remains the primary focus of discussions surrounding the end-of-life management of lithium-ion batteries, with numerous investigations exploring its role in advancing battery sustainability. For instance, a Scopus search of article titles, abstracts, and keywords reveals approximately 4,566 documents related to "lithium-ion", "battery", and "recycling", compared to just 159 focused on repurposing and 106 on remanufacturing. This trend highlights a global commitment to sustainability as it reflects the significant attention and resources being directed by academia, policymakers and industries to developing recycling systems as a key aspect of battery lifecycle management. However, existing research often varies significantly in focus, methodology, and target audience. The diversity has resulted in fragmented insights, which can lead to inconsistent identification of challenges and opportunities and complete decision-making processes.

From an environmental management perspective, a multidisciplinary approach is essential to achieve a comprehensive understanding of system dynamics and to reconcile environmental protection with development objectives. Accordingly, this thesis offers a holistic examination of lithium-ion battery recycling strategies. It examines the current state of recycling practices, investigates the underlying rationales and concerns driving their implementation, and critically assesses the associated challenges and opportunities. By presenting an integrative perspective, this work seeks to equip policymakers and industry practitioners with the insights necessary to make informed decisions that advance the sustainable deployment and recycling of lithium-ion batteries.

For the purpose of this research, the European Union (EU) is chosen as a compelling case for examining lithium-ion battery recycling, given its ambitious environmental and industrial goals. Under the framework of the European Green Deal, the EU has pledged to achieve carbon neutrality by 2050 (European Commission, n.d.-a). Reaching this target necessitates substantial progress in reducing carbon emissions, particularly within the transportation and energy sectors, where lithium-ion batteries are expected to play a pivotal role as a key technology. The EU provides a valuable case study for balancing ambitious environmental goals with resource constraints and the challenges of developing recycling infrastructure (European Commission: Directorate-General for Climate, 2019). As the EU lacks domestic sources of key raw materials like lithium, cobalt, and nickel, this research highlights the region's efforts to establish a circular economy for lithium-ion batteries.

1.2 Research Questions and Objectives

Building on the problem definition outlined above and in line with the objective of developing a comprehensive understanding of lithium-ion battery recycling, this study aims to present a holistic overview of the adoption of recycling strategies. To achieve this, the research will address the following questions:

RQ 1: How does the state-of-the-art of lithium-ion battery recycling within the European Union look like?

RQ 2: What are the perceived rationales and concerns for lithium-ion battery recycling?

RQ 3: What are stated opportunities and challenges of lithium-ion battery recycling?

The first research question aims to investigate the current landscape of lithium-ion battery recycling in the European Union by examining how the system presently operates or is intended to function. The second question seeks to explore the prevailing discourses and stakeholder perspectives surrounding lithium-ion battery recycling to uncover assumptions underlying the broader sustainability narrative and reveals the complexity and contested nature of lithium-ion battery recycling. The third question facilitates a critical assessment of the enabling factors and barriers influencing the effectiveness of recycling systems to get a better understanding of where strategic actions, policy interventions, or collaborative efforts are most needed to support a sustainable and circular battery value chain in the EU.

1.3 Scope and Limitations

This research takes lithium-ion battery recycling as its focus, and no other end-of-life (EOL) strategies, such remanufacturing and repurposing due to two main reasons. *First,* lithium-ion battery recycling is the main focus of this research. In this research, the author will cover all essential stages within the battery recycling, including spent battery collection, material recovery process, as well as recycled material markets. *Second*, the abundance of research on recycling provides a more extensive knowledge base, which is particularly valuable as this study relies on document analysis as its primary data source, as further discussed in Chapter 3.

Additionally, the author has selected the European Union (EU) as the primary geographical scope of this research, influenced by the author's location during the research period and the accessibility to relevant information. The EU was also chosen because of its strong environmental goals and ambitions, as reflected in their initiatives like the net-zero agenda and the new battery regulation (European Commission, n.d.-a; European Commission: Directorate-General for Climate, 2019). Moreover, the EU is projected to become a major hub for battery manufacturers and electric vehicle (EV) producers and represents one of the largest EV consumer markets, which drives the expansion of the lithium-ion battery industry (IEA, 2024a). References from other regions, such as the United States of America (USA), China, and Canada, will also be considered to enhance or support the core data.

Following the research design and methodology, this research will encounter several limitations. *First,* the study will focus exclusively on the lithium-ion battery recycling system, so given the specific characteristics of lithium-ion batteries, the data and findings might not be directly applicable to the recycling of other battery types. *Second,* due to the geographic scope, the findings may not fully represent conditions in other regions, and additional research would be necessary for other specific locations. *Third,* given the fact that, compared to predicted future amount, most lithium-ion batteries have not reached the end of their lives, battery recycling activities are currently not massively carried out. Consequently, it is possible that the data collected may largely reflect assumptions or plans by stakeholders rather than accurately representing the present situation.

1.4 Ethical Considerations

This research was conducted in accordance with established ethical standards to ensure integrity, credibility, and transparency throughout the study. The researcher critically reflected on potential influences, including personal affiliations, funding sources, or benefits, that might inadvertently affect the interpretation of the data. The thesis was independently conceived and executed, without external funding or institutional ties to the organizations or data sources examined. This independence strengthened the objectivity of the research process and outcomes (Creswell & Creswell, 2018).

All sources used in this study were drawn from publicly available and credible publications, including peer-reviewed academic articles, official reports, verified datasets, videos, books, and online materials published by reputable organizations. These sources are typically subject to rigorous quality control, enhancing the reliability of the information. Copyright and intellectual property rights were strictly observed, with all materials properly cited in accordance with academic standards.

A balanced representation of perspectives was a central priority in this research. Documents presenting both supportive and critical views of the central arguments were incorporated to reduce bias and provide a comprehensive analysis. All data were contextualized accurately to prevent misrepresentation, particularly in cases involving culturally or socially sensitive material.

1.5 Audience

The author hopes that the findings of this research will serve as a valuable resource for stakeholders, including policymakers, industry leaders, and researchers. Policymakers can use the insights to develop informed regulations and incentives that promote sustainable recycling practices. Industry leaders will gain guidance on optimizing recycling processes and adopting innovative technologies to improve sustainability outcomes. Researchers will benefit from a comprehensive overview to advance the field further. Overall, this study seeks to contribute to the effective design and implementation of recycling systems that align with broader sustainability objectives and thus can contribute to the broader field of research focused on battery end-of-life management and policy.

1.6 Disposition

The paper is organized as follows:

Chapter 1 presents the introduction of the paper discussing the background of the study delineating the focus of this research.

Chapter 2 summarizes characteristics of lithium-ion batteries that are relevant to this thesis. It also introduces relevant concepts that have been developed and are used as an analytical framework in this research.

Chapter 3 presents the research design and methods to collect and analyse the data.

Chapter 4 presents the key findings and analysis of the study, focusing on the current state of lithium-ion battery recycling, the debates between rationales and concerns, as well as the identification of the challenges and opportunities associated with recycling these batteries.

Chapter 5 provides a discussion of the findings outlined in Chapter 4 and also addresses the limitations of the study.

Chapter 6 provides the main conclusions of the analysis and outlines areas of future research.

2 Laying the Foundation: Lithium-ion Batteries and their Recycling System

This chapter aims to establish the research context and present a conceptual framework for the study, providing essential guide for the subsequent findings and analysis. The section is intended to provide essential information regarding lithium-ion batteries that are crucial to this research, ranging from its characteristics, lifecycle, the environmental issues, as well as the concept of battery recycling system as battery's end-of-life strategy to enhance its sustainability. The information will then become a foundation for an analytical framework of this study. Given the focus on foundational concepts and the variety of battery types, the discussion will centre on rechargeable batteries, which includes lead-acid, nickel-cadmium, and lithium-ion batteries.

2.1 Lithium-ion Batteries: Key Factors

This section aims to clarify essential aspects of lithium-ion batteries and associated factors that are relevant for its circularity and especially recycling, including the battery lifecycle and environmental concerns.

2.1.1 Lithium-ion Batteries and their Characteristics

Lithium-ion battery is a type of rechargeable battery where the electrical energy is produced by the movement of electrons from the anode to the cathode during discharge and inverse when charging (Raza et al., 2014), as it is shown on Figure 2-1. The battery gains popularity due to its characteristics and have greater performance compared to other rechargeable batteries, such as lead-acid and nickel-cadmium. The batteries have higher energy density (Anuphappharadorn et al., 2014; Aurbach et al., 2021; Gladysz & Chawla, 2015), lower self-discharge (Qiao & Wei, 2012), lower maintenance cost (Anuphappharadorn et al., 2014; Wang et al., 2012), and lower environmental impacts due to the materials that are less toxic when compared to its predecessors which contain substances such as cadmium, lead, and mercury (Patrizio, 2023; Wang et al., 2012).

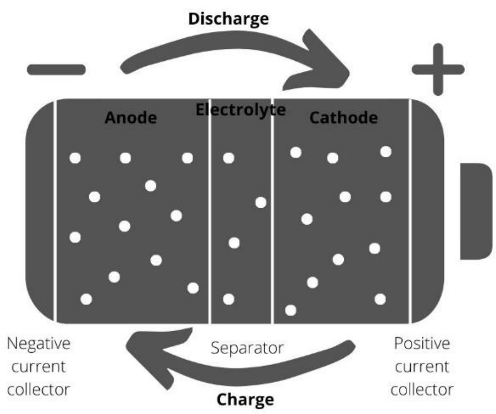

Figure 2-1. Schematic of a Lithium-ion Battery

Source: Author's own illustration based on Kushnir (2015); Raza et al. (2014); Urtubey and Heredia (2020).

Materials Need in Lithium-ion Battery

In contrast to other battery types, lithium-ion batteries exhibit greater diversity and complexity in their composition. Lithium-ion batteries have a variety of materials in each cell (see Table 2-1), in the form of powder and coating onto metal foil, which must be separated during recycling (Gaines, 2014). A lithium-ion battery pack is likely to have 100 or more individual cells that are connected into modules and are assembled into a pack with control circuitry attached to each cell (Gaines, 2014). Besides, a battery pack uses various thermal management system which the chemical compositions, especially the cathode varies among manufacturers. Battery function are also changing and may never be standardized (Gaines, 2014).

Table 2-1. Lithium-ion battery types and their materials

Components	**Lithium-ion Battery Types**				
	NMC	**NCA**	**LCO**	**LMO**	**LFP**
Active cathode materials	Cobalt Nickel Manganese Lithium Oxygen	Lithium Nickel Cobalt Aluminium Oxygen	Lithium Cobalt Oxygen	Manganese Lithium Oxygen	Iron Phosphorus Lithium
Anode	Graphite				
Collector	Copper and Aluminium				
Separator	Plastic				
Electrolyte	Electrolyte solution				
Casing	Plastic or metal (steel/aluminium)				

Source: Author's own elaboration derived from Kushnir (2015), Jacoby (2019) and Urtubey and Heredia (2020)

Creating a battery cell involves sourcing approximately 20 different materials from various global regions (Melin, 2019a), with raw materials making up 60% to 70% of the lithium-ion cell industry's costs (Pillot, 2018). For example, the cells of a typical 60-kilowatt-hour (kWh) battery, such as the one utilized in a Chevrolet Bolt, an electric vehicle manufactured and marketed by General Motors, consist of approximately 185 kilograms of minerals, excluding materials in the electrolyte, binder, separator, and battery pack casing (Bhutada, 2022). According to the International Energy Agency (2022), a battery in an electric vehicle requires six times more mineral inputs than an internal combustion engine vehicle.

Lithium-ion batteries have undergone some technological advancements aimed at improving their performance. Currently, there are five distinct lithium-ion battery types, including Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminium Oxide (NCA), Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), and Lithium Iron Phosphate (LFP) (see Table 2-1). However, the technological development has been further continued due to the demand for more advance battery performance. In the future, battery chemistries that are considered promising for surpassing current lithium-ion technology include lithium-metal anode, solid-state, sodium-ion, lithium-sulphur, and lithium-air batteries (Deng et al., 2017; Imanishi & Yamamoto, 2019; Nekahi et al., 2024; Wu et al., 2023; Xu et al., 2014).

The production of lithium-ion batteries begins with mining to obtain essential materials. Virgin materials used in current battery technologies include cobalt, lithium, nickel, manganese, graphite, aluminium, and copper, depending on the battery type (Urtubey & Heredia, 2020). The composition of the cathode is a key differentiating factor that distinguishes different battery types. For example, NMC batteries are made from nickel, manganese, cobalt, and lithium, while NCA batteries contain lithium, nickel, cobalt and aluminium (see Table 2-1). Each of these materials plays a crucial role in determining the overall quality and performance of the battery.

Lithium, the main cathode material in all lithium-ion battery types, is providing high energy density, allowing it to store a lot of energy while being lightweight, making it ideal for applications where both power and low weight are crucial, such as in electronic devices and electric vehicles (Goonan, 2012).

In addition to lithium, lithium-ion batteries use other materials for the cathode, such as *cobalt*, *nickel*, and *manganese*. *Cobalt* provides a vital function in keeping the battery stable and efficient, ensuring long-term performance, and significantly improving charging and discharging speed (Clemens, 2023). Even in nickel-rich cathode battery, such as NMC and NCA, small amount of cobalt is needed for thermal stability and cycle stability (Li & Lu, 2020). *Nickel* is also an important cathode material for lithium-ion batteries and it is predicted that the use of it will be increased in the future, especially to reduce cobalt (Breiter et al., 2022). The change into nickel is mainly driven by its ability to provide high energy capacity, high energy density and conductivity, which improve the battery performance (Nuhu et al., 2023). Additionally, the cost of using nickel is relatively low due to its structure, making it a promising alternative cathode material for lithium-ion batteries (Li et al., 2020). Another top candidate for future lithium-ion battery cathode material is *manganese* as this material can boost power or act as a stabilizer, making the batteries more efficient and last longer (Thackeray et al., 2018).

For the anode, the current lithium-ion batteries typically use *graphite* due to its ability to enhance energy density compared to earlier anode materials, such as soft and hard carbon (Asenbauer et al., 2020). Graphite is favoured for its low cost, low toxicity and abundance in availability (Insinna et al., 2023). However, current research efforts are exploring the replacement of graphite anodes with silicon to boost battery power capacity (Feyzi et al., 2024).

Lithium-ion batteries also use various other materials, including nickel, copper, aluminium, stainless steel, carbon, and composite materials to produce current collectors (Li, 2020). These components act as a bridge between the battery and the devices they power (Zhu et al., 2021). Among these materials, copper and aluminium are the most commonly used. Copper is typically selected for the anode side, while aluminium is used on the cathode side.

2.1.2 Lithium-ion Battery Lifecycle

The lifecycle of lithium-ion batteries encompasses multiple stages, including material extraction, cell and battery manufacturing, use, and end-of-life. This section will address the activities involved at each stage of the battery lifecycle.

Materials Extractions

This initial stage involves the mining of raw materials needed for battery production. The growing global demand for lithium-ion batteries has significantly increased the demand for key materials such as lithium, cobalt, nickel, manganese, and graphite. According to the US Geological Survey (2024), batteries were by far the largest end-user of lithium worldwide which accounted for 87% of lithium consumption in 2023. A study by Albemarle (2021) projected that demand for lithium used in electric vehicles (EVs) batteries alone could reach approximately 2.1 million metric tonnes by 2030.

The demand for cobalt is also expected to rise sharply. Statista (2023) forecasts that by 2030, battery applications will require around 237,000 metric tonnes of cobalt, with e-mobility batteries alone accounting for 176,000 metric tonnes. For nickel, the International Energy Agency (2023) estimates that demand in clean energy technologies could increase from 478,000 tonnes in 2023 to approximately 1.95 million tonnes by 2030, again largely driven by the growth in EV and battery production.

Manganese and graphite are also experiencing notable demand increases. Euro Manganese (n.d.) has indicated significant growth in the manganese market for lithium-ion batteries, projecting figures from 90,000 tonnes in 2021 to 1.1 million tonnes by 2031. Similarly, the demand for graphite in batteries is projected to increase from 133,000 metric tonnes in 2018 to nearly 700,000 metric tonnes by 2025 (DERA, 2020). Although this data does not clarify battery types, it is anticipated that the surge will primarily result from the expanding production of lithium-ion batteries (Barrera, 2019; European Carbon and Graphite Association, 2022).

Battery Cell and Pack Manufacturing

During the manufacturing stage, extracted materials are processed and assembled by combining individual cells into modules, which are then integrated into complete battery packs (Thompson et al., 2020; Urtubey & Heredia, 2020). Lithium-ion batteries exhibit a more complex structure than its predecessors, such as lead-acid batteries, consisting of a cathode, anode, separator, negative and positive collectors, electrolyte, battery management and monitoring systems, as well as optimization and cell integration (Kushnir, 2015; Urtubey & Heredia, 2020). In general, the lithium-ion battery manufacturing process involves three key phases: electrode manufacturing, cell assembly, and battery electrochemistry activation (formation/aging processes). Additionally, battery design occurs during this stage.

Electrode manufacturing typically involves six steps, encompassing slurry mixing (blending of electrode active and inactive materials), slurry coating on the current collector (aluminium foil for cathode and copper foil for the anode), solvent evaporation through drying, calendaring, slitting to match the cell design, and vacuum drying to eliminate excess water (Liu et al., 2021; Sharova et al., 2020).

Once the electrodes are prepared, the process proceeds to *cell assembly*. The electrodes, along with dried separators, are transported to the dry room where they are wound or stacked to construct the internal structure of a cell (Liu et al., 2021). Lithium-ion batteries typically come in three common cell designs: cylindrical, pouch, and prismatic. Winding is a common method employed for forming cylindrical and prismatic cells, while stacking is used in the production of pouch cells (Liu et al., 2021). Subsequently, the cell undergoes electrolyte filling and sealing processes.

The final step in the lithium-ion battery manufacturing stage is the *formation and aging process*. The formation procedure is designed to facilitate the creation of the solid electrolyte interface (SEI), preventing the irreversible consumption of electrolyte and safeguarding the anode from undesired side reactions (Liu et al., 2021; Mauler et al., 2021; Sharova et al., 2020). Simultaneously, the aging process is conducted to monitor the cell for any abnormal behaviour and prevent quality issues (Mauler et al., 2021).

Use

Once manufactured, batteries are distributed to manufacturers. Currently, lithium-ion batteries are utilized in a growing array of applications, driven primarily by three sectors: portable electronic devices, electric vehicles, and energy storage systems (Nitta et al., 2015). In portable electronics, lithium-ion batteries are essential components to power various electronic products, such as laptops, mobile phones, power tools, vaping devices, and children's toys. Presently, Lithium Cobalt Oxide (LCO) batteries stand out as the most common technology employed in portable electronic devices (Jaco Huisman et al., 2017).

In the electric vehicle sector, lithium-ion batteries are widely used because of long cycle life and high energy density offered by the batteries compared to their weight. Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LFP) are currently the most prevalent battery technologies. However, there is no single preferred option for choosing battery cell chemistry in electric vehicles (Romare & Dahllöf, 2017). For instance, companies like Tesla prefer using Lithium Nickel Cobalt Aluminium Oxide (NCA) in their cars.

In energy storage systems (ESS), the keys to wider battery deployment are longer cycle of life and lower costs (May et al., 2018), which lithium-ion batteries meet the need. Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LFP) are the most widely used lithium-ion batteries in ESS. In 2021, NMC held a dominant 70% market share, followed by LFP at 30% (Kamran, 2023). Nonetheless, it is anticipated that the use of LFP will increase and eventually become the leading battery technology in the stationary storage market (Holman, 2020).

In general, batteries in portable electronics have shorter lifespans than those in electric vehicles but accurately predicting when a battery will reach its end-of-life remains challenging. Some batteries may last much longer than expected. For example, Circular Energy Storage (n.d.) found that cells designed to last 3 to 10 years are sometimes used in equipment that operates for twice that duration, indicating that electric vehicle batteries, in particular, could remain functional for over 20 years.

End-of-Life

The end-of-life phase for lithium-ion batteries begins with the disposal of used or depleted units. Compared to other battery types, end-of-life pathways for lithium-ion batteries are more diverse. As outlined in Section 1.1, these pathways include remanufacturing, repurposing for second-life applications, and recycling. The choice of treatment method is largely determined by the battery's original application and remaining performance capacity. For example, lithium-ion batteries from consumer electronics are typically routed directly to recycling due to their small size and limited remaining capacity. In contrast, electric vehicle (EV) batteries often retain substantial residual capacity after their first use, making them suitable for remanufacturing or repurposing before ultimately undergoing recycling (Future Bridge, 2021).

It is projected that by 2030, approximately 11 million tonnes of lithium-ion batteries will have reached this stage (Leal et al., 2023). In parallel, it predicts a second-life battery market of 1 terrawatt-hour by 2030, with an estimated net market value of USD 45 billion for such applications through that year (Willuhn, 2019). On the recycling front, the International Council on Clean Transportation (ICCT) reports that roughly 1.2 million end-of-life electric vehicle (EV) batteries will require recycling annually by 2030 worldwide, with this figure expected to rise dramatically to 14 million by 2040 and 50 million by 2050 (Tankou et al., 2023). The global lithium-ion battery recycling market was valued at approximately USD 3.54 billion in 2023 and is forecasted to expand substantially, reaching nearly USD 24 billion by 2033 (BIS Research, 2024).

2.1.3 Environmental Issues of Lithium-ion Batteries

As it is outlined in Chapter 1, significant environmental concerns persist throughout the lifecycle of lithium-ion batteries. This section will outline various sustainability issues, including impacts on air, water, forest and land, greenhouse gas emissions, biodiversity, human health and society in each stage of battery lifecycle, from the material extraction to the end-of-life stage.

Material Extractions

Meeting the growing demand for lithium-ion batteries requires substantial quantities of materials, including lithium, cobalt, nickel, manganese, and graphite. As of now, the battery industry still relies heavily on virgin materials obtained through mining. The rising demand for materials needed for lithium-ion batteries has led to increased mining activities to obtain these resources, see Subsection 2.1.2. Mining activities present a range of complex social, economic, and environmental challenges. Issues such as air, water, and soil pollution, along with biodiversity loss, frequently emerge during the extraction of raw materials for lithium-ion battery production (Institute for Energy Research, 2020; Katwala, 2018; Whiteaker, 2021).

Most of the world's lithium is primarily sourced from the Lithium Triangle regions of Argentina, Bolivia, and Chile, encompassing more than half of the Earth's lithium supply. The problem is that the area is one of the driest places in the world, and lithium mining consumes as much as 65% of the region's water (Institute for Energy Research, 2023; Katwala, 2018). It is because a primary method for lithium extraction, known as brine extraction, involves significant water usage and the process also poses a risk of contaminating the water supply (Institute for Energy Research, 2023). About 2,273,000 litres of water are needed to produce a ton of lithium (Hirschlag, 2022; Katwala, 2018). Consequently, a surge in lithium demand has intensified water-related challenges, posing threats to ecosystems, wildlife, and the surrounding communities.

Cobalt is primarily mined from artisanal and small-scale, often informal operations in the Democratic Republic of Congo (DRC). Artisanal mines often neglect the environmental risks and cause air pollution, water contamination, biodiversity loss, and land degradation. These activities typically exploit marginal or small deposits which are unregulated, lack capital, have poor access to markets and support services, have low standards of health and safety and disregard any environmental standards (Buxton, 2013). Extraction from such artisanal mines has been increasing. As an illustration, the expansion of exposed rock areas in the DRC, believed to be associated with mining, has increased from 51.60 km^2 in 2014 to 76.32 km^2 in 2021 (Brown et al., 2022). Cobalt mine sites frequently contain sulphur, leading to the generation of sulfuric acid when exposed to air and water, thereby infiltrating rivers, streams, and impacting aquatic life (Institute for Energy Research, 2023).

Environmental issues have also emerged in several nickel mining regions, predominantly situated in Australia, Canada, Indonesia, Russia, and the Philippines (Opray, 2017). According to Ruehl and Dempsey (2023), at least 76,301 hectares-equivalent to the size of New York city-of tropical forests has been cleared with 329 nickel concessions in Indonesia which is driven by the high demand of lithium-ion batteries. The extraction and smelting processes of nickel ores can result in the emission of sulphur dioxide gas, the release of acid-containing iron waste, and the dispersion of dust containing toxic metals, thereby polluting rivers and the surrounding ecosystem (Opray, 2017).

The necessity for cathode materials in lithium-ion batteries is influenced by their technology, with many discussions emphasizing the need to replace cobalt and nickel for enhanced battery sustainability. One proposed solution involves adopting manganese or iron-based cathode materials (Laveda et al., 2016; Sanderson, 2021; Sharpe et al., 2020). These materials are favoured due to their abundant reserves, more ethical sourcing, and lower costs compared to cobalt and nickel. Therefore, employing manganese and iron is viewed as a solution to address sustainability issues in the material extraction for lithium-ion battery (He et al., 2021; Sanderson, 2021). Yet, the actual situation reveals that environmental concerns persist in both manganese and iron mining sites as well (Safarian, 2023; Taylor & Nkosi, 2022).

Manganese mines produced water with high concentrations of suspended solid particles and acidity, while the soil in these sites is identified as nutrient-deficient, potentially impacting soil productivity and fertility (Goswami et al., 2009; Huang et al., 2016; Li et al., 2007; Queiroz et al., 2021). Furthermore, an investigation by the Washington Post revealed that manganese mining workers in South Africa have suffered irreversible neurological damage due to exposure to manganese (Chason & Godfrey, 2023). Similarly, the situation in iron mining is equally concerning. A report by Costa (2022) indicated that iron mining in Brazil contributes to deforestation and threatens the livelihoods of indigenous communities.

While the sustainability discourse surrounding lithium-ion batteries has predominantly centred on production of cathode materials like nickel, cobalt, manganese, and lithium, it is essential to acknowledge that other battery components also contribute to environmental issues. For instance, graphite used in anode materials, as well as copper and aluminium in the current collector and steel in the battery casing, are also sourced from mining activities which can generate some environmental impacts.

Graphite mining in China pollute air and water threatening both the ecosystem and villagers who live near the mining sites (Whoriskey, 2016). Production of graphite also involves substantial energy consumption leading to the emission of greenhouse gases. Meanwhile, the production of copper occurs in countries, notably Chile, Peru, and the Democratic Republic of Congo (US Geological Survey, 2023), and they already recognized prevalent environmental issues, thereby heightening the associated risks. Issues like water supply shortage, water contamination, and poor air quality persist at the copper mining site, adversely impacting both local community and the surrounding environment (Poonia & Uteuova, 2021).

The surge in demand for aluminium is also having adverse effects on the environment and the inhabitants of the affected areas. Aluminium is primarily sourced from mining of bauxite ores. A study conducted by Dibattista et al. (2023) in Guinea, a key bauxite-producing region, revealed that the bauxite mining supply chain significantly contributes to environmental impacts, specifically in terms of water pollution and land degradation, as well as rising social and health issues.

In addition to environmental concerns, the increasing production of materials for lithium-ion batteries is giving rise to a range of socioeconomics and socio-political impacts, particularly in regions where mining activities are prevalent. These ramifications encompass community displacement, inadequate working conditions, poverty, violations of children's and indigenous rights, instances of corruption and bribery, human trafficking, issues of conflict minerals and other human rights-related risks (Amnesty International, 2019; Deberdt & Billon, 2021; Katwala, 2018). Besides, the presence of some materials, such as cobalt and nickel, is restricted to specific regions, leading to a significant supply vulnerability (European Commission & Joint Research Centre (JRC), n.d.-a).

Cell and Battery Manufacturing

The cell and battery manufacturing stage of lithium-ion batteries is a significant source of greenhouse gas (GHG) emissions, primarily due to the energy-intensive processes involved (Dai et al., 2019; Ellingsen et al., 2017; Kim et al., 2016; Sun et al., 2020; von Drachenfels et al., 2021). The production of battery materials, components, and cells requires vast amounts of electricity, often generated from fossil fuel-based energy sources, contributing to elevated carbon emissions (World Economic Forum, 2019). Manufacturing processes, such as electrode production, cell assembly, and thermal management, are also particularly energy-demanding and emit considerable amounts of CO_2 (Ambrose & Kendall, 2016; Ellingsen et al., 2013; Ellingsen et al., 2017; Peters et al., 2017; Romare & Dahllöf, 2017). Comparative analyses reveal that lithium-ion batteries have a higher climate impact during production than lead-acid batteries for fossil fuel vehicles, largely due to their more complex and energy-intensive manufacturing processes (Wall Street Journal, 2019).

Additionally, the manufacturing of lithium-ion batteries requires vast amounts of water. Water is used throughout various stages of production, from the cooling of machinery to the cleaning and rinsing of components (US Environmental Protection Agency, n.d.). In areas where water resources are already limited, the high demand for water in battery manufacturing can exacerbate environmental and social challenges.

The manufacturing process also generates a significant amount of waste, commonly referred to as battery manufacturing scraps. During the battery Research and Development (R&D) stage, significant amounts of scraps are generated during cathode material synthesis, cathode/anode electrode coating, battery fabrication, testing procedures, and especially throughout the optimization of scale-up processes (Yu et al., 2024). Oberhaus (2020) noted that, due to the complexity of lithium-ion batteries and the precision required in their production, a considerable portion of the output may fail quality control and become waste. Expanding on this, Yu et al. (2024) detailed that manufacturing scraps can include electrodes with defects in coating, calendaring, cutting, stacking, filling, or assembly; electrode trimmings and leftovers; as well as batteries that do not pass quality checks. Properly managing this waste is essential to reducing environmental harm, as improper disposal can contaminate soil, air, and water.

Use

Lithium-ion batteries can pose fire risks during the use stage, and managing such incidents can be challenging (Quraishi et al., 2023). Incident of fires caused by rechargeable batteries, including lithium-ion batteries have been steadily increasing in major cities like New York and San Francisco (Rao et al., 2023). A lithium-ion battery fire releases highly toxic, flammable gases, vapours, and smoke, posing potentially devastating impacts on local wildlife (Magtoto, 2025). Besides, greenhouse gas emissions can be produced due to the energy sources used to recharge the batteries, although the impact for this reason is indirect.

End-of-life

When it is time to dispose of lithium-ion batteries, it is crucial to prevent *improper disposal* or allowing spent batteries to end up in landfills untreated as these actions will generate various environmental issues. Due to their material composition, spent lithium-ion batteries have the potential to leach heavy metals into water supplies and soil that are toxic to plants and animals (Institute for Energy Research, 2023). While generally safe, the batteries can still pose fire hazards due to mechanical damage (e.g., crushing or collisions), electrical issues (e.g., short circuits), or overheating (Rao et al., 2023). Alarmingly, fire incidents involving these batteries are rising even at designated waste collection sites. The US Environmental Protection Agency (EPA) reported over 200 fires linked to lithium-ion batteries at waste facilities across the USA in 2021 (Crespo, 2024). Likewise, more than 1,200 battery fires occurred in bin lorries and waste sites across the UK in 2022, with lithium-ion batteries being a major factor in the rise of fire incidents (NFCC, 2024). These fire hazards not only pose serious threats to human health and the environment but also result in substantial economic costs. The damages in the UK alone are estimated at over £ 150 million annually (Eunomia, 2021).

Beyond improper disposal, environmental concerns also arise within battery waste management strategies, including remanufacturing, repurposing, and recycling. The process of *remanufacturing* lithium-ion batteries carries environmental risks, as the handling of degraded components can result in exposure to hazardous substances, and the process requires significant energy for testing and refurbishing, which potentially contributing to carbon emissions if powered by non-renewable sources (Neri et al., 2024; Xiong et al., 2020; Yu et al., 2024). The main issue with *repurposing* lithium-ion batteries lies in the variability of battery performance and chemistry, as degraded cells may cause operational inefficiencies, safety risks, and hazardous material release, while the transportation and repurposing process itself requires energy and resources that can lead to carbon emissions (Gu et al., 2024; IDTechEx, 2025; Kumar, n.d; Rufino Júnior et al., 2024). The *recycling* of lithium-ion batteries presents multiple environmental and safety challenges, including risks of fires and explosions, greenhouse gas emissions, high energy and water consumption, the release of hazardous materials, and the generation of waste residues requiring safe disposal, with the extent of these impacts varying by recycling method employed (Meegoda et al., 2024; Mrozik et al., 2021; Patel et al., 2024; Van Hoof et al., 2023).

2.2 An Overview of Battery Recycling System

The context of this research centres on the increasing demand for lithium-ion batteries driven by their pivotal role in enabling a low-carbon economy as it already mentioned in Chapter 1. However, an anomaly arises as this increased demand raises concerns about battery's sustainability as discussed in the Subsection 2.1.3. From an environmental perspective, the growing demand for batteries serves as critical enabler to reduce sustainability challenges, yet ensuring their sustainability also remains a critical challenge. Therefore, as highlighted in Section 1.1, solution must be pursued. One of which is the implementation of effective recycling practices. This section aims to provide an overview of battery recycling, discussing fundamental concepts, such as the purpose and significance of battery recycling and detailing the processes involved. The objective is to establish a common understanding of the general principles behind rechargeable battery recycling.

2.2.1 The Concept of Battery Recycling

Recycling is commonly understood as the reprocessing of waste materials into new products, materials, or other substances that can be reused or returned to the supply chain (Oberoi & Fritz, 2020; Worrell & Reuter, 2014b). Some studies have shown that recycling has proven to have some economic and environmental benefits, including slowing down the exhaustion of scarce resources, decreasing the emissions of pollutants in the environment, saving energy compared to mining, reducing the use of landfill space, as well as advancing the development of a more sustainable battery industry (Bernhart, 2019; Boyden et al., 2016; Church & Wuennenberg, 2019; Oberoi & Fritz, 2020; van Beukering et al., 2014). Therefore, this approach emerges as one of the most favourable end-of-life (EOL) strategies for managing obsolete products, particularly those containing valuable materials, such as batteries.

Recycling has long been a key component of battery waste management for rechargeable batteries, particularly lead-acid and nickel-cadmium types, due to their toxic contents and associated risks to human health and the environment if improperly handled (England, 2001; Prengaman & Mirza, 2017). However, as the industry shifts toward greater sustainability, the role of recycling has expanded beyond managing toxicity. It is now increasingly recognized as a means to enhance resource efficiency and extend material lifecycles through closed-loop systems (Dominguez, 2024; RMI, n.d.; Robertson-Fall, 2021).

Within the Circular Economy (CE) framework, recycling is one among several strategies that include refuse, rethink, reduce, re-use, repair, refurbish, remanufacture, repurpose, recycle, and recover (Potting et al., 2017). Among these, recycling is often considered a last resort, as it is generally less sustainable than strategies aimed at extending the lifespan of products and components (Future Bridge, 2021; Nhede, 2020), as discussed in Section 1.1. Nonetheless, recycling remains a critical component of circularity, particularly when extending their lifespan is no longer feasible and disposal is required. In fact, recycling has long been considered a key solution to addressing sustainability challenges within the battery industry. One of the primary reasons for this preference is that recycling facilitates the recovery and reuse of valuable materials while simultaneously reducing the demand for raw materials, decreasing waste, treating the hazardous substances and minimizing the environmental impact of batteries which are key sustainability challenges within the industry (Allwood, 2014; Jacoby, 2019; Worrell & Reuter, 2014a).

The shift toward circularity and a more sustainable battery industry has redefined the perception and strategic role of recycling. From an industry perspective, recycling offers a way to recover valuable materials, reducing reliance on primary resource extraction and mitigating the environmental, economic, and social risks linked to mining (Barber & Marshall, 2021; Mollah & Behdani, 2024). From a governmental standpoint, it is increasingly viewed as a strategic tool to enhance the resilience of domestic industries against supply chain disruptions caused by geopolitical tensions, trade restrictions, bottlenecks, or armed conflicts (Blenkinsop, 2024; IEA, 2024b). Consequently, recycling is now recognized not only as a waste management strategy or a means to achieve environmental and economic goals, but also as a critical pillar for securing alternative raw material sources and strengthening regional supply chain security.

2.2.2 Battery Recycling Process

As of now, battery recycling generally follows similar steps to metal recycling processes. It begins with the collection of waste, followed by material recovery processes, such as sorting, dismantling and extracting, before putting the recovered materials into the market.

Battery Collection

The recycling process begins when consumers dispose of batteries or battery-containing products at designated waste collection points. This marks the start of the collection stage, where batteries enter the recycling stream and are handled to minimize harm to human health and the environment. Effective collection systems are therefore critical, as they directly influence the volume of batteries recovered, which in turn affects both the potential for metal recovery and the overall cost-efficiency of recycling operations (Ayres et al., 2014; Thies et al., 2018).

The sources of waste batteries vary depending on their applications, which significantly influence both collection logistics and overall effectiveness. For instance, lead-acid batteries, widely used in automobiles, are typically collected through car scrapping services or battery replacement points (Quirijnen, 1999). In contrast, nickel-cadmium (Ni-Cd) batteries are generally classified into two categories: small consumer cells used in portable electronic devices and larger industrial batteries. This distinction affects their respective collection rates, as industrial Ni-Cd batteries tend to achieve higher collection efficiencies compared to consumer cells, which are frequently discarded with municipal waste or stored indefinitely after use (England et al., 2001). In addition to battery type and application, several other factors shape the effectiveness of collection systems. These include public compliance and consumer awareness, the robustness of legal and regulatory frameworks, the availability of financial resources, the density and accessibility of collection infrastructure, and the shared responsibilities among stakeholders involved in the battery waste management (EPBA, 2024a; Luidold & Antrekowitsch, 2014; Quirijnen, 1999).

Recognizing the significance of collection activities, many countries have implemented policies and regulatory measures to monitor and evaluate their effectiveness. For instance, the European Union (EU) employs the collection rate as a command-and-control policy instrument, which mandates that a minimum percentage of batteries be collected within a specified time frame (Eurostat, 2024). This metric is used to assess whether the EU's objectives concerning battery waste collection are being met and to ensure that waste is effectively redirected to appropriate recycling channels.

Material Recovery

Once batteries are collected, the material recovery process begins, typically starting with sorting based on battery chemistry and type. This step is essential for ensuring product quality, as most discarded batteries contain a mix of materials that must be separated before further processing (Graedel, 2011). Sorting can be conducted manually or automatically and knowing the source material (e.g., battery chemistry) is crucial to selecting an efficient process (Kushnir, 2015). Physical and mechanical separation techniques are commonly used in the early stages of recycling to isolate components for reuse, treatment, or safe disposal. These methods are also applied in other recycling industries to separate metals and plastics and to purify effluents. Additionally, batteries must be fully discharged to prevent safety hazards during downstream processes, especially in the case of rechargeable batteries like lithium-ion and nickel-cadmium.

After sorting and discharging, the recovery phase is initiated. As the European Battery Recycling Association (EBRA, n.d.) notes, battery recycling is highly complex and involves multiple steps, making it difficult to generalize. However, three primary recovery methods are commonly employed: pyrometallurgy, hydrometallurgy, and direct recycling.

Pyrometallurgy, as outlined by Chagnes et al. (2017), encompasses techniques such as smelting, combustion, pyrolysis, and molten salt processing, and is commonly used for metal recovery from waste electrical and electronic equipment (WEEE). These processes operate at elevated temperatures to extract or reduce metals, requiring substantial energy input, although still less than that required for primary metal production. An alternative approach is *hydrometallurgy*, which involves the use of mineral acid leaching followed by selective metal precipitation and/or solvent extraction (Chagnes et al., 2017). This method is particularly effective in processing low-grade and chemically complex material streams, offering greater selectivity and recovery efficiency for specific metals. The most recent development in battery recycling is *direct recycling*, which employs mechanical and solvent-based separation techniques to recover intact composite battery materials, such as active cathode materials, for direct reuse in new batteries (Dunn et al., 2012; Mrozik et al., 2021). This method is considered more environmentally friendly due to its lower energy consumption and reduced emissions, while also enabling the recovery of a broader range of components, including non-metallic materials (Patel et al., 2024). Nevertheless, the economic viability of direct recycling is contingent upon advancements that enable its implementation at an industrial scale.

After the recovery process, all extracted materials then undergo a purification process to eliminate impurities, ensuring the recovered materials meet specific quality standards for reuse.

The selection of processing techniques is generally determined by the type of metals being recovered, as each method has its own set of advantages and disadvantages. For instance, pyrometallurgy is effective for recovering nickel, cobalt, and copper, but less so for lithium and manganese (Bernhart, 2019). In some cases, multiple methods, such as pyro- and hydrometallurgy, may be combined (van Schaik & Reuter, 2014). Environmental factors also guide method selection, including carbon emissions, waste generation, and water use (Gaines, 2014). As Allwood (2014) emphasizes, recycling should only be pursued if it results in lower environmental impacts than alternatives such as landfilling or energy recovery.

Recycled Material Market

Once materials are recovered from batteries, their fate is determined by the recycled material market. These markets are vital for a circular economy, as they allow recyclables to re-enter the production value chain, reducing reliance on primary resources. For this to work effectively, the recycled material market must function efficiently.

The idea of a well-functioning recycled material market, much like in traditional commodity markets, is often implicitly associated with the concept of a competitive market, characterized by the absence of dominant players, a high volume of transactions, prices that reflect supply and demand, full transparency among participants, and the presence of standardized commodities or clearly segmented market structures (Castell-Rudenhausen et al., 2022). Although these ideal conditions are seldom fully realized in practice, they serve as important benchmarks for evaluating the functionality of recycled material markets.

Conversely, secondary material markets exhibit several characteristics that distinguish them from traditional commodity markets. These include their interaction with primary material markets through substitution effects, the possibility of negative prices for materials classified as 'waste,' the presence of asymmetrical or inadequate information, limited access to organized marketplaces, and the heterogeneity of traded materials (Carter, 2025; Castell-Rudenhausen et al., 2022). Additionally, these markets are often subject to substantial policy pressure to meet recycling and recovery targets, as part of broader efforts to advance a circular economy (Söderholm & Ekvall, 2020).

In the recycled material market from battery recycling, materials are typically categorized by type, such as lithium, cobalt, iron, manganese, nickel, and lead (Allied Market Research, 2023). Lead has long dominated this market, with the International Lead Association (n.d.) reporting that approximately 50% of global lead demand is met through recycling. The widespread use of nickel-cadmium batteries, especially in portable electronics, also led to the development of recovery processes for nickel and cadmium. More recently, the rapid expansion of lithium-ion battery use has driven innovation in recycling technologies tailored to these newer chemistries.

Ideally, recycled materials should be reintegrated into battery manufacturing, as securing a sustainable supply of critical raw materials is a key objective of battery recycling. However, recycled battery materials can also be utilized in other sectors such as automotive, construction, aerospace, and defense (Allied Market Research, 2023; Deloitte, 2015).

2.2.3 Factors Influencing Battery Recycling

As discussed in Subsection 2.2.2, the battery recycling process is influenced by a range of interconnected factors. For instance, at the collection stage, consumer behavior plays a critical role in returning spent batteries to designated points, while technical feasibility and economic considerations also shape the process. In the recycled materials market, factors such as market demand, regulatory frameworks, and access to reliable information affect its overall functionality. These examples illustrate that battery recycling is shaped by political, economic, social, and technical (PEST) dimensions (Goyal et al., 2023). This subsection explores each of these factors in greater depth across different stages of the recycling process, offering insights into the complexities, challenges, and opportunities within the battery recycling system.

Political Aspect

The political aspect of battery recycling refers to how governmental and institutional actions, policies, regulations, and political conditions influence the development of the battery recycling industry, market, or system (Ertz et al., 2023). Government intervention is widely seen as essential for advancing battery recycling efforts, with policy support playing a critical role in fostering green industries and promoting waste recovery systems (Erdem, 2022; Zhang et al., 2023). This political dimension encompasses legal frameworks, government policies, and geopolitical situation.

Legal frameworks establish responsibilities, standards, and enforcement mechanisms for battery collection, treatment, and disposal (Bird et al., 2022; Islam et al., 2025; Su et al., 2025). In parallel, policy instruments, such as subsidies, tax incentives, deposit-refund schemes, extended producer responsibility (EPR), and mandatory recycling targets, provide strategic direction and promote the growth of recycling infrastructure and markets (Zhang et al., 2022). Similar regulatory efforts exist in countries including China, the USA, Canada, South Korea, Japan, and Australia (China Ministry of Environmental Protection, 2003; Japan Ministry of the Environment, 2000; Ruether et al., 2021; Stanway, 2018; Su et al., 2025; Yang et al., 2021). Additionally, geopolitical considerations have increasingly become an important political driver and further shape the battery recycling agenda, especially because the supply of battery materials remains concentrated in a few regions. This geographic concentration raises concerns about resource security and supply chain vulnerability. In response, implementing circular economy strategies through battery recycling is increasingly viewed as a strategic measure to mitigate geopolitical risks, strengthen domestic resource resilience and address global competition for critical minerals (Bou, 2025; Jannesar Niri et al., 2024; Racu & Poliscanova, 2024).

Economic Aspect

From an economic perspective, the success of battery recycling is assessed by its ability to reduce environmental costs while delivering financial returns (Md Tasbirul Islam et al., 2022). The economic aspect thus refers to the conditions that determine whether recycling processes can be performed efficiently and profitably. Key factors include costs and revenues, market dynamics, material pricing, and financing mechanisms.

Lander et al. (2021) identify several cost components in lithium-ion battery recycling, including transportation, disassembly, and processing, which involve labour, materials, energy, and operational expenditures. Su et al. (2025) add that the complexity of battery chemistries and their classification as hazardous waste significantly increases handling and regulatory compliance costs. While revenue generation can come from various streams, including selling recovered materials, producers or recycling fee (Gonzales-Calienes et al., 2023; Naturvardsverket, 2025; Paristokierrätys, n.d.-b). When it comes to recovered materials price, they are dependent on the global metal market prices. Worrell and Reuter (2014a) and Maris, Aoussat, et al. (2014) stressed that the price of recycled materials must remain competitive with that of materials extracted from virgin ore in order to support the economic feasibility of recycling.

Market dynamics also play a vital role. The recycling market depends on a stable supply of end-of-life batteries and sustained demand for secondary raw materials. Studies by Thies et al. (2018), Kim et al. (2018), and van Schaik and Reuter (2014) emphasize that fluctuations in either supply or demand directly impact economic feasibility. Yet, battery manufacturers often hesitate to use recycled materials due to concerns over quality, reliability, and cost compared to primary materials (Maris, Froelich, et al., 2014). Strengthening market confidence in secondary materials is therefore essential to improving resource efficiency and enhancing the sustainability of the battery industry.

Finally, financing mechanisms are crucial in supporting battery recycling. Public and private funding, through grants, loans, or subsidies, help offset initial investment costs. In the EU and the US, governments actively support recycling initiatives through targeted funding programs (European Commission, 2020c; US Department of Energy, n.d.). Moreover, Extended Producer Responsibility (EPR) schemes are also widely used, shifting the financial and/or organizational responsibility for end-of-life battery management to producers (European Parliament, 2015; Hoarau & Lorang, 2022; Zhang et al., 2023; Zhu et al., 2020).

Social Aspect

When discussing recycling management, it is essential to consider the consumption phase, particularly how consumer behaviour influences the effectiveness and sustainability of recycling systems. Numerous studies have highlighted the critical role of consumer behaviour in determining the success of recycling initiatives, including battery recycling (Henao-Rodríguez et al., 2024; King & Boxall, 2019; Torkelis et al., 2024). However, such behaviour does not emerge in a vacuum, but it is shaped by various contextual and psychological factors (Torkelis et al., 2024).

Key influences on recycling behaviour include environmental awareness, attitudes, social norms, perceived behavioural control, and the visibility of recycling campaigns (Haj-Salem & Al-Hawari, 2021; Su et al., 2025; Wang et al., 2016; Zhang et al., 2021; Zhang et al., 2016). Additionally, socio-demographic variables (Meneses & Palacio, 2005; Vencatasawmy et al., 2000), financial incentives (Md Tasbirul Islam et al., 2022; Roca i Puigvert et al., 2020), availability of infrastructure (Perrin & Barton, 2001; Zhang et al., 2016), and access to clear information (Md Tasbirul Islam et al., 2022) significantly affect individuals' willingness and ability to engage in recycling.

Given the influence of these factors, promoting recycling behaviour requires systems that actively foster and support public participation. Ajzen (1991) suggests that encouraging pro-environmental actions like recycling demands a strategic integration of motivation, education, and accessible infrastructure. Empirical studies echo this, pointing to the importance of collaborative stakeholder efforts, targeted policy measures, economic incentives, environmental education, and user-friendly collection systems supported by timely and accessible information (Guo & Huang, 2023; Md Tasbirul Islam et al., 2022; Tang et al., 2023).

Furthermore, the concept of Social License to Operate (SLO), defined as the ongoing acceptance and approval of a project by the public and key stakeholders (Prno & Scott Slocombe, 2012), is becoming increasingly relevant to battery recycling within the broader sustainability discourse. While SLO has been extensively discussed in the mining sector, its application to recycling remains underexplored. However, growing public opposition to the siting and operation of recycling facilities highlights the need to consider SLO (CBS News, 2011; Cole, 2020; Shepherd, 2025), particularly given that batteries are classified as hazardous waste, which heightens public concern over the environmental and health risks associated with recycling activities.

Technical Aspect

Battery recycling involves a range of technical aspects aimed at recovering valuable materials from end-of-life batteries. Allwood (2014) noted that recycling is typically employed when it is technically feasible and when energy and emissions savings can be achieved compared to primary production. Technically feasible in the context of battery recycling refers to the ability of current technologies to efficiently and effectively recover valuable and critical materials from used batteries at high rates and purity. This ensures that the recovered materials are suitable for reuse in new batteries or other products while minimizing negative environmental impacts. These negative environmental impacts include carbon emissions, waste generation, water usage, and unsafe disposal of batteries (Gaines, 2014).

The technical feasibility of recycling encompasses several key components, including advanced recycling technologies, battery designs optimized for recyclability, well-developed recycling infrastructure, and efficient logistics systems (Gaines, 2014; Harper et al., 2019). A growing body of research has explored each of these components. For instance, various studies have investigated recycling methods (Harper et al., 2023; Lo Sardo et al., 2025; Sloop et al., 2020; Zanoletti et al., 2024), recycling technologies (Clyde et al., 2025; Feng et al., 2025; Han et al., 2025; Liu et al., 2025), and design for recycling (Lunde, 2021; Maris, Froelich, et al., 2014; Norgren et al., 2020; Scott et al., 2023; Thureborn & Yvell, 2022).

2.2.4 Analytical Framework: Battery Recycling System

As discussed in Subsection 2.2.1, the role of recycling for rechargeable batteries within circular economy frameworks has expanded beyond its initial focus on preventing hazardous materials from entering landfills. While the safe management of toxic substances remains a core objective, contemporary recycling practices increasingly emphasize the recovery of valuable materials to reduce dependence on primary raw resources. This shift reflects a broader commitment to resource efficiency and environmental sustainability. By extending the lifecycle of critical materials, battery recycling contributes to the development of a more resilient and sustainable battery industry, in alignment with the principles of a circular economy.

Cerdas et al. (2018) argue that recycling should not be viewed as an environmental goal in itself, but rather as a means to achieve broader environmental objectives. In this context, recycling is best understood as a system composed of interconnected components. As outlined in Subsection 2.2.2, the battery recycling process can be divided into three main stages: collection, material recovery, and the recycled material market. Subsection 2.2.3 further elaborates on how the performance of each stage is shaped by a range of political, economic, social, and technical factors.

The political dimension includes elements such as regulatory frameworks, policy incentives, and international agreements. Economic factors encompass material prices, market demand, cost structures, and financial support mechanisms. The social aspect includes consumer behavior, public awareness, demand for ethically sourced materials, and the social license to operate. Finally, technical factors involve recycling technologies and methods, the quality and composition of battery materials, and the availability of recycling infrastructure.

Together, these objectives, processes, and influencing factors constitute what is referred to in this thesis as the battery recycling system, which serves as the analytical framework for assessing lithium-ion battery recycling, the primary focus of this study.

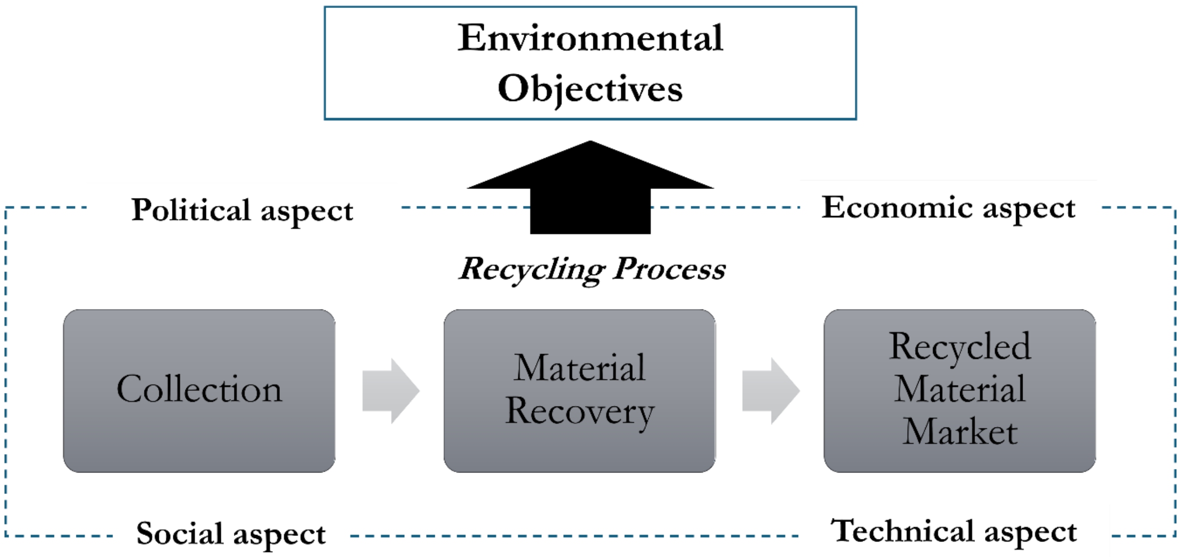

Figure 2-2. Battery Recycling System

Source: Author's own elaboration.

3 Methodology

This chapter provides a detailed overview of the research methodology employed in this study, encompassing the research design, specific methods used, and the data collection and analysis procedures. By elaborating on each component, this section aims to clarify how these methodologies choices align with the research objectives and facilitate answering the research questions. Particular attention is given to the rationale behind the selection of methods.

3.1 Research Design

This research adopted a qualitative research design to achieve its objective of exploring and developing a deeper understanding of lithium-ion battery recycling, with a particular focus on the European Union (EU), as outlined in Section 1.2. The research objective reflects the underlying philosophical assumptions that informed the overall design and methodological choices (Creswell, 2009). Achieving this objective requires addressing a multifaceted system that encompasses not only technical and regulatory structures but also the political, economic, and social dimensions that shape the recycling process, as discussed in Subsection 2.2.4. Given this complexity, qualitative research is particularly well-suited to the task, as it allows for in-depth examination of the meanings, processes, and stakeholder experiences associated with the topic.

Furthermore, qualitative design is appropriate for capturing emerging trends and debates, especially in rapidly evolving fields like battery recycling, where regulatory frameworks, technological capabilities, and market dynamics are still in flux. Its methodological flexibility allows for the adaptation of methods and procedures as the research progresses, and its capacity to capture rich, contextual data enables deeper insights into the interactions and underlying factors shaping the recycling landscape (Roudgarmi, 2011). Ultimately, qualitative design facilitates a holistic and nuanced exploration. As Creswell and Creswell (2018) emphasize, qualitative research excels in producing detailed textual descriptions of specific topics or phenomena. This approach aligns with the overall aim of contributing to develop more informed and grounded discussions on lithium-ion battery recycling within the EU context.

3.2 Research Method

This thesis employed document analysis as its primary research method. Document analysis entailed the systematic review and interpretation of documents to gain insights, enhance understanding, and develop empirical knowledge (Bowen, 2009). This method was particularly appropriate given that lithium-ion battery recycling in the European Union (EU) was still in its early stages, with many initiatives in planning or development phases. As such, it was challenging to construct a definitive picture of the present state of the system. Documents thus served as valuable tools for tracking changes over time, particularly when the events of interest spanned long time periods or involved multiple stakeholders, enabling the examination of periodic and final reports (where available) to assess how programs and organizations evolved (Bowen, 2009).

The selection of document analysis was also informed by the broad and complex scope of the research, which posed limitations for obtaining firsthand data through direct interviews. As Morgan (2022) noted, document analysis offered a practical and accessible approach, especially for researchers constrained by time, resources, or logistical challenges that precluded extensive fieldwork. Furthermore, it allowed for systematic comparison across different policies, institutions, and countries. Patton (2015) emphasized that any text-containing document could serve as a valid source for analysis. This versatility permitted the use of diverse sources, such as academic articles, policy documents, institutional reports, books, and news media, which collectively enriched the analysis.

3.3 Data Collection

This study employed document analysis, meaning the researcher did not engage directly with participants such as government officials, consumers, recycling companies, producers, or NGOs, but instead analysed a variety of existing textual sources. The involvement of these actors was therefore indirect, with their perspectives and contributions reflected through reports, policy documents, and other materials included in the document set.

Qualitative researchers are expected to use multiple sources of evidence to ensure convergence and corroboration of findings (Bowen, 2009). Data for this thesis were collected from both primary and secondary sources, all of which were document-based. Primary sources included original documents or direct results related specifically to the unit analysis of this research, while secondary sources comprised texts that analysed, interpreted, or discussed primary materials. All documents were sourced digitally, taking advantage of the accessibility and breadth of online platforms (Moser & Korstjens, 2018). While the study primarily adopted a qualitative approach, selected quantitative and mixed-method studies were also reviewed to support a more comprehensive understanding of the topic.

In selecting documents, the study adhered to four key criteria proposed by Flick (2018). *First*, authenticity, which refers to the genuineness and trustworthiness of the document. *Second*, credibility, which concerns the document's accuracy and its freedom from errors or misinformation. *Third*, representativeness, which assesses how typical or characteristic the document is of its category or type. *Finally*, meaning, which considers the relevance and significance of the document's content in relation to the research objectives. By applying these criteria, the study ensured methodological rigour and strengthened the validity of the insights derived from the data.

The research drew on a diverse body of documents, including peer-reviewed academic literature, grey literature, secondary sources, and news articles. These were retrieved through search engines and academic databases such as Google, Google Scholar, Scopus, and others. Primary sources, as listed in Table 3-1, consisted of documents directly addressing lithium-ion battery recycling in the EU. Secondary sources, shown in Table 3-2, encompassed broader perspectives on battery recycling systems, including global practices beyond the EU context.

During data collection, the research questions guided the selection of relevant literature through tailored search terms. For Research Question 1 (RQ1), terms included "lithium-ion battery collection in the EU," "lithium-ion battery recycling in the EU," and "lithium-ion battery recycled material market in the EU". Research Question 2 (RQ2) was addressed using terms such as "rationales behind battery recycling" and "concerns on battery recycling". For Research Question 3 (RQ3), the search focused on terms such as "lithium-ion battery collection challenges," "lithium-ion battery collection opportunities," "lithium-ion battery material recovery challenges," "lithium-ion battery material recovery opportunities," "recycled material market challenges," and "recycled material market opportunities."

The selection of data for this thesis is not confined to a specific timeframe, allowing for the inclusion of documents beyond recent publications. Instead, documents are chosen based on the relevance of their content to ensure a comprehensive exploration of the research topic, which is relatively new. Furthermore, older sources may still hold significant relevance today, and incorporating a diverse range of timeframes facilitates the identification of trends, enables comparisons, and enhances the understanding of how situations may have evolved over time.

Table 3-1. List of Primary Data Sources

Publishers	Type of documents	Number of documents
European Commission	Legal documents	4
	Policies	1
	Press Release	1
	Webpage	7
	Reports	10
	Graph	8
	News Article	3
European Agency (EEA, Eurostat, EBA, EPBA, JRC, ERP, ERMA, Horizon Europe)	Datasets	1
	News articles	1
	Books	1
	Datasets	2
	Reports	10
	Webpage	4
Countries Government	Legal documents	3
	Reports	1
	Webpage	2
Organization/companies	Reports	3
	Articles	18
	Webpage	2
	Audiofile	5
Others	Peer-reviewed journal	4
	Social Media Post	1
	Graph	1

Source: Author's own compilation.

Table 3-2. List of Secondary Data Sources

Publishers	Type of documents	Number of documents
Organization/companies	Articles	64
	Reports	20
	Audiofile	4
	Graph	8
Countries Government	Webpage	7
Others	Academic journal	95

Source: Author's own compilation.

3.4 Data Analysis

Following document collection, the data were analysed through a multi-step process as outlined by Bowen (2009), which included skimming (superficially examination), reading (thorough examination), and interpretation. This approach integrated elements of both content and thematic analysis. Content analysis in this study involved an initial review to extract relevant textual data, going beyond simple quantification. Documents were examined iteratively to identify passages that were meaningful and directly relevant to the central research questions, while excluding less pertinent content. Accordingly, predefined categories guided the analysis, including lithium-ion battery collection, material recovery, the recycled materials market, and the political, economic, social, and technical aspects of battery recycling. The conceptual framework presented in Subsection 2.2 served as both a theoretical reference and a basis for categorizing data.

In parallel, thematic analysis was conducted to identify patterns accross the data (Fereday & Muir-Cochrane, 2006), similar to the way interview or focus group transcripts are typically analysed. This approach enabled the identification of recurring themes, as presented in Finally, interpretation was guided by the conceptual framework discussed in Subsection 2.2, alongside the researcher's assumptions, commitments, and scholarly perspective, as suggested by Morgan (2022).

Table 3-3. Data Categories and Themes

, that contributed to answering the research questions. Finally, interpretation was guided by the conceptual framework discussed in Subsection 2.2, alongside the researcher's assumptions, commitments, and scholarly perspective, as suggested by Morgan (2022).

Table 3-3. Data Categories and Themes

Categories

	Collection	**Material Recovery**	**Recycled Material Market**
Political Aspect	Policies and Regulations		
Economic Aspect	Collection Cost and Financing Scheme	Material Feedstock	Quality and Quantity of Recycled Materials
		Recycling Cost and Financing Scheme	Market Demand for Recycled Materials
			Recycled Material Prices
Social Aspect	Consumer Awareness and Behaviours	Social License to Operate	Consumer Perception of Recycled Materials
Technical Aspect	Sources and Volume of Waste	Recycling Methods and Technologies	
	Collection Channels and Infrastructure	Recycling Infrastructures	

Themes

Categories

Themes

Source: Author's own elaboration.

4 Findings

This chapter aims to answers three research questions and presents the findings on the current state of lithium-ion battery recycling in the European Union (EU) (RQ1), explore the stakeholders' narratives regarding lithium-ion battery recycling (RQ2). In addition, it also highlights the challenges and opportunities associated with lithium-ion battery recycling within the region (RQ3).

4.1 State-of-the-art of Lithium-ion Battery Recycling in the EU

The lithium-ion battery market in the European Union (EU) is projected to experience significant growth, driven by the region's commitment to electrification and sustainable energy transitions. Various market research reports provide evidence supporting this upward trajectory. According to Knowledge Sourcing Intelligence LLP (2024) , the EU lithium-ion battery market was valued at approximately USD 21.45 billion in 2025 and is expected to reach USD 34.95 billion by 2030. Similarly, IMARC Group (2024) forecasts the market to grow from USD 13.6 billion in 2024 to USD 35.9 billion by 2033. In parallel, Persistent Market Research (2025) estimates an increase from USD 13.6 billion in 2025 to USD 30.7 billion by 2032. This anticipated expansion is largely underpinned by the EU's ambitious climate agenda, notably the European Green Deal (European Commission, n.d.-a), which seeks to reduce greenhouse gas emissions and accelerate the shift to clean energy sources.

A key factor driving this demand is the rapid adoption of electric vehicles (EVs). In the first five months of 2025 alone, the European EV market expanded by 27%, reaching 1.6 million units sold (Rho Motion, 2025). To accommodate the surging demand for lithium-ion batteries, more than 30 gigafactories are either planned or under development across the continent, aiming to bolster domestic production capacity and decrease dependence on Asian suppliers (Khan, 2021). Concurrently, the rapid growth of the EV market also enhances the potential for lithium-ion battery recycling, as the number of end-of-life batteries increases. According to Transport & Environment (T&E, 2024), a leading clean transport and energy advocacy organization, recycling spent battery cells and production scrap could provide up to 14% of the lithium, 16% of the nickel, 17% of the manganese, and 25% of the cobalt needed for EV production in Europe by 2030. In a related study, it projects that locally recycled battery materials could support the production of between 1.3 million and 2.4 million EVs by 2040, thereby potentially eliminating the need to open 12 new mines globally (Blenkinsop, 2024; Racu & Poliscanova, 2024).

To support the growing demand for lithium-ion batteries, as well as to establish a robust and sustainable battery industry, the EU introduced the most recent legislative framework: the EU Battery Regulation 2023/1542 which replaces and updates the previous Battery Directive EU Battery Directive 2006/66/EC to align with the current state of battery technologies and market developments. Among its key provisions is the introduction of mandatory battery recycling requirements, including for lithium-ion batteries. Notably, it not only sets recovery targets but also imposes stringent requirements for the inclusion of recycled materials in new batteries, marking a significant push for recycling (Peplow, 2023). To further enhance transparency and accountability within the battery value chain, the regulation requires manufacturers to disclose the carbon footprint of their batteries, promote low-emission recycling processes, and implement a digital battery passport to track material flow and lifecycle data.

Moreover, the EU has established a broader legislative and policy framework to regulate and stimulate the recycled materials market for batteries. Key initiatives include the Circular Economy Action Plan 2020 (European Commission, 2020b), Horizon Europe (European

Commission, 2020c) and the recently adopted EU Critical Raw Materials Regulation 2024/1252 (Critical Raw Materials Act). These policies aim to enhance sustainability, reduce dependency on raw material imports, and support the transition to a circular economy.

This section will delve deeper into the current state of the lithium-ion battery recycling system in the EU, with a particular focus on the three main technical stages: collection, material recovery, and the recycled materials market, following battery recycling process explained in Subsection 2.2.2. Each stage will be explored in detail, alongside a discussion of the various influencing factors, such as political, economic, technical, and social, that shape the EU's battery recycling system, as outlined in Subsection 2.2.3.

4.1.1 Lithium-ion Battery Disposal and Collection

The first stage of lithium-ion battery recycling involves the disposal and collection of spent batteries. An effective collection system is essential to ensure that used batteries are gathered safely and in an environmentally responsible manner. This not only facilitates their entry into the recycling process but, more importantly, prevents spent batteries from being improperly discarded or left untreated, which could pose significant environmental and safety risks. This subsection focuses on this critical initial phase and examines the key components that constitute an efficient collection system.

Policy and Regulations

Battery disposal and collection in the European Union (EU) is now governed by the EU Battery Regulation 2023/1542 concerning batteries and waste batteries. While EU Battery EU Battery Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators is now considered outdated, it remains relevant in understanding the evolution of the battery collection system in the EU, especially considering that some of the goals outlined in the new regulation will only be achieved in the years following the completion of this thesis. Examining the older Battery Directive is also useful for understanding the trends in collection practices during the period between the introduction of the EU Battery EU Battery Directive 2006/66/EC and the implementation of the EU Battery Regulation 2023/1542. Both laws place emphasis on the collection of all waste batteries generated within the region, addressing critical elements such as collection targets, collection schemes, and the financing mechanisms necessary to achieve the objectives.

The EU Battery Directive 2006/66/EC sets a minimum collection target of 45% for waste portable batteries by September 26, 2016. While the Directive also mentions other battery types (automotive, industrial, and accumulators), it did not establish specific collection targets for these. In contrast, the more recent EU Battery Regulation 2023/1542 provides detailed requirements for battery collection across five categories: waste portable batteries, light means of transport (LMT) batteries, starting, lighting, and ignition (SLI) batteries, industrial batteries, and electric vehicle (EV) batteries. The Regulation sets a 45% collection target for waste portable batteries by the end of 2023, which it will increase to 63% by 2027 and 73% by 2030. For LMT batteries, the collection targets are set at 51% by 2028 and 61% by 2031. However, the Regulation does not yet specify collection targets for waste SLI, industrial, or electric vehicle batteries.

According to the European Portable Battery Association (EPBA, 2024a), the new Regulation builds upon the foundational principles to enhance the effectiveness and efficiency of the collection and recycling systems. It aims to create a level playing field for all Extended Producer Responsibility (EPR) schemes while fostering a viable market for secondary raw materials. Moreover, the Regulation acknowledges the complexity of portable battery collection, considering factors such as consumer awareness, legal frameworks, density of collection points, variety of collection streams, the shared responsibilities of all stakeholders involved in the collection process.

Although the EU has established policies and regulations that are applicable across all member states, their implementation ultimately falls under the jurisdiction of each individual country (European Commission, 2018, n.d.-b). Member states retain the sovereignty to determine how EU directives and regulations are transposed and enforced within their national contexts (EUR-Lex, n.d.). As a result, the practical application of these regulations can vary significantly between countries. For instance, a report by the European Portable Battery Association (EPBA, 2024b) identified Austria and Switzerland as having specific national measures targeting lithium batteries. In Austria, the Waste Treatment Ordinance 2017 requires the removal of lithium batteries from waste electrical and electronic equipment (WEEE) at collection points, provided that end-users can detach them, and mandates the separate collection of lithium batteries exceeding 500 grams. In Switzerland, collection practices have been adapted to reflect the longer lifespan of lithium-ion batteries by differentiating collection rates between lithium and non-lithium battery types (EPBA, 2024b).

Collection Cost and Financing Scheme

Samarukha (2020) estimates that the collection and transportation costs of spent lithium-ion batteries in certain EU member states range from €0.01 to €5.12 per ton-kilometre, depending on factors such as distance, vehicle type, and whether the waste is classified as hazardous or non-hazardous. Although comprehensive and consistent data on collection costs across the EU are lacking, existing studies indicate that the overall cost of collecting lithium-ion batteries is relatively high. This is primarily attributed to transportation expenses and stringent safety requirements, which together account for a significant portion of total recycling costs (Kavanagh, 2021; Rallo et al., 2022; Rizos & Urban, 2024; Slattery et al., 2021).

The financial mechanisms supporting lithium-ion battery collection in the EU are primarily based on the Extended Producer Responsibility (EPR) model as mandated in both The EU Battery Directive 2006/66/EC and The EU Battery Regulation 2023/1542. In this framework, producers bear financial responsibility for the collection, treatment, and recycling of the batteries they place on the market. These obligations are fulfilled either through participation in collective compliance schemes or by establishing individual systems. The EPR model funds the collection infrastructure through differentiated fee structures based on battery types. For example, the European Recycling Platform (ERP, 2024) reports that in Austria, lithium-ion batteries are subject to higher fees due to the specific challenges they pose, including the need for separate collection, specialized handling, and dedicated recycling processes. Beyond the EPR system, additional financial support mechanisms, such as EU funding programs, public-private partnerships, and market-driven incentives, contribute to the development of efficient collection systems and regulatory compliance (European Commission, 2020c; European Investment Bank, 2024; Gospodinova, 2021; Stena Recycling, 2021). Moreover, deposit-return schemes are being considered as a complementary financing mechanism and are encouraged for evaluation under the EU Battery Regulation 2023/1542.

Consumer Awareness and Behaviours

Increasing public participation in battery collection in the European Union (EU) centres on enhancing awareness and engagement in responsible recycling practices, as well as improving the accessibility of recycling infrastructure. As mentioned by Albertsen et al. (2021), while most take-back systems operate under mandatory producer responsibility legislation, the system still relies on consumers voluntarily returning batteries to producers. Since the collection process begins with consumers disposing of their batteries, ensuring public involvement at this stage is critical, especially because participation is entirely voluntary.

Consumers in the EU are generally characterized by relatively high levels of environmental awareness and positive attitudes toward recycling (Eurobarometer, 2024; European Environment Agency, 2024a, 2024b). Several studies suggest that while a significant share of EU citizens are willing to return used batteries to designated collection points, as reflected in reported collection rates, consumer participation is also shaped by contextual factors such as the proximity of collection infrastructure and the effectiveness of communication strategies (Acuti et al., 2023; Lizin et al., 2017; Paristokierrätys, n.d.-a; Science for Environment Policy, 2023; Tijm et al., 2021). However, despite these encouraging trends, various behavioural barriers continue to undermine the effectiveness of battery collection. A key issue is the common tendency among consumers to hoard used batteries or battery-powered portable electronic devices, delaying their return to collection systems (Melin, 2019b; Sorrel, 2007; Velázquez-Martínez et al., 2019). Furthermore, improper disposal remains a persistent challenge. The European Environment Agency (EEA, 2019) has identified the mixing of used batteries with other waste streams, particularly within waste electrical and electronic equipment (WEEE), as a major obstacle to improving collection rates. Mrozik et al. (2021) and Melin (2019b) show that such batteries are often discarded in residual waste or recycling streams due to inadequate labeling, poor consumer awareness, and insufficient communication about disposal options. Molina (2022a) highlights how the co-collection of lithium-ion batteries with other chemistries further complicates downstream sorting and reduces material recovery efficiency. Notably, such improper disposal practices have also contributed to a rising number of fire incidents at collection and waste handling facilities across Europe (Hayler, 2024).

Sources and Volume of Waste

Both the EU Battery Directive 2006/66/EC and the EU Battery Regulation 2023/1542 categorize batteries based on their application (e.g., portable, industrial, and automotive batteries) rather than their chemical composition. In the EU Battery Regulation 2023/1542, automotive batteries are further classified as waste batteries from Light Means of Transport (LMT), Starting-Lighting-Ignition (SLI), and electric vehicles (EVs). However, neither legal framework provides specific guidance on the collection of lithium-ion batteries. To address the sources and volumes of lithium-ion battery waste in the EU, this study adopts the categorization outlined in the EU Battery Regulation 2023/1542.

Regarding the volume of waste, it is projected that EV batteries will become the dominant source of lithium-ion battery waste, as EVs increasingly constitute the main application for lithium-ion batteries. However, Peplow (2023) notes that the current supply of spent batteries remains limited due to the relatively recent adoption of EVs, meaning many batteries are still in use and have not yet reached their end-of-life. Significant growth in battery waste is expected around 2030, as many batteries approach the end of their first life (Allen, 2023; Marthaler et al., 2022). This timeline may even extend further, as some studies suggest that advances in battery technology and user behaviour could prolong battery lifespan beyond initial expectations (Herbert, 2024). Additionally, spent EV batteries may be reintegrated into the value chain for secondary applications, such as stationary storage, delaying their entry into the recycling stream (Cortesão, 2024; Stena Recycling, 2025). Batteries used in industrial applications, particularly energy storage systems (ESS), are also expected to have a similar lifespan to EV batteries (Powerlink Energy, n.d.). Consequently, comprehensive data on actual collection rates for these categories remain scarce. Nonetheless, it is projected that by 2030, approximately 111,000 tonnes (equivalent to 25 GWh) of end-of-life EV batteries will arise within the EU (Directorate-General for Mobility and Transport, 2022).

In contrast, portable batteries have shorter lifespans, which means they become waste and enter the collection system more quickly. In addition, Boyden et al. (2016) suggested that data on portable batteries is more readily available, partly because they are commonly used in electronic and electrical equipment, and waste from such equipment (WEEE) is one of the fastest-growing waste streams. According to Eurostat (2024), approximately 111,000 tonnes of used portable batteries were collected for recycling in the EU in 2022. The European Portable Battery Association (EPBA, 2024b) reports that by 2022, only Luxembourg and Norway were near consistently meeting the 63% collection target for portable batteries set for 2027. However, these figures do not specify how many lithium-ion batteries were collected. It can only be assumed that a portion of the collected portable batteries are lithium-ion, given that this battery type is now the most common in portable electronic devices (Boyden et al., 2016).

Collection Channels and Infrastructure

According to Article 59(1a) of the EU Battery Regulation 2023/1542, producers of portable batteries are required to establish take-back and collection systems for waste portable batteries. Similar obligations apply to producers of batteries used in light means of transport (LMT) batteries, starting-lighting-ignition (SLI) batteries, industrial batteries, and electric vehicle (EV) batteries, as specified in Articles 60 and 61. In addition, manufacturers and importers are responsible for ensuring the availability and proper functioning of collection systems for all types of waste batteries. These provisions reflect the implementation of the Extended Producer Responsibility (EPR) principle.

In the EU, the responsibility for setting up collection systems may be fulfilled either individually by producers or collectively through membership in Producer Responsibility Organizations (PROs). These systems are often developed in cooperation with authorized dealers, retailers, and electronics and automotive service centres (Reuters, 2024). Partnerships may also be formed with municipal infrastructure, managed by local authorities, including recycling centres, hazardous waste facilities, and curb side pickup services for household battery waste (Bergfald et al., 2024; El-Kretsen, n.d.). Specialized recycling companies further reinforce the collection network, particularly for the collection and handling of industrial and automotive battery waste (Stena Recycling, 2024).

In the context of lithium-ion battery collection, the battery's application significantly influences the type of the collection channels. For portable lithium-ion batteries, the collection system is relatively well-established. Consumers are typically provided with accessible drop-off points at retail outlets that sell batteries or battery-powered products, as well as at municipal collection points, where batteries can be returned free of charge (Mrozik et al., 2021). In the EU, collection efforts primarily target portable lithium-ion batteries or those embedded in portable devices such as laptops, mobile phones, and micromobility vehicles, as these are the most likely to have reached end-of-life (Molina, 2022a). Consequently, the collection of these batteries is largely integrated into the existing Waste Electrical and Electronic Equipment (WEEE) collection systems (EPBA, 2024b).

In contrast, the collection infrastructure of lithium-ion batteries used in electric vehicles and industrial batteries remains relatively underdeveloped (Albertsen et al., 2021). Large-format batteries from electric vehicles and industrial uses are generally retrieved through reverse logistics systems operated by original equipment manufacturers (OEMs), car dismantlers, municipal facilities, or designated industrial waste collection sites (Albertsen et al., 2021). Moreover, a project done by the EU-funded Battereverse documented not all Member States have yet established national collection schemes for EV batteries, resulting in inconsistencies in collection practices and capabilities across the Union (Battereverse, n.d.).

Moreover, emerging EU initiatives promoting second-use applications, such as battery repurposing and remanufacturing, present new pathways for used batteries that diverge from traditional recycling. While offering extended utility and environmental benefits, these second-life applications can also complicate and reshape the structure and logistics of existing collection channels (Dahlström, 2023). The EU Battery Regulation (2023/1542) stipulates that repurposed and remanufactured batteries must be clearly labelled and accompanied by documentation that enables their identification and monitoring throughout their extended lifecycle. Once these batteries reach the end of their second life, they are to be directed to recycling facilities through designated collection schemes. In the EU, the logistics of collecting batteries after repurposing or remanufacturing are still evolving through initiatives like BatteReverse (Battereverse, n.d.), yet structured collection schemes are increasingly being established through projects such as Recirculate, an EU-funded initiative powered by a consortium of 11 partners from 8 countries dedicated to transforming battery reuse across Europe (Recirculate, n.d.-b). Additionally, collaborations among industry actors along the battery value chain are increasingly emerging to support these efforts (EVBoosters, 2024; Stena Recycling, 2025).

4.1.2 Material Recovery of Lithium-ion Batteries

The material recovery process for spent lithium-ion batteries in the EU follows a similar framework to that of other battery types, including sorting, dismantling, recovery, and purification of materials, as discussed in Subsection 2.2.2. However, the outcomes can vary significantly due to several influencing factors, such as the quality and composition of the feedstock, the infrastructure in place, the chosen recycling methods, economic considerations, and the types of materials being recovered. This subsection aims to examine the key components that define and shape the material recovery stage.

Policy and Regulations

Article 70 of the EU Battery Regulation 2023/1542 regulates the treatment of waste batteries, prohibiting their disposal or use to energy recovery operations. This provision mandates that collected waste batteries must undergo appropriate recycling processes. To support this, the Regulation establishes specific recycling efficiency and material recovery targets in Article 71(2). These targets apply to various battery chemistries, including lead-acid, lithium-based, and nickel-cadmium, and other waste batteries.

The recycling efficiency targets for lithium-ion batteries are set in Part B of Annex XII of the EU Battery Regulation 2023/1542. Lithium-ion batteries are classified under lithium-based batteries, with the EU aiming for a recycling efficiency rate of 65% by the end of 2025 and 70% by 2030. As the new target is to be met by 2025, available recycling efficiency data still follows the EU Battery Directive 2006/66/EC, where lithium-ion batteries are categorized with other batteries, and the recycling efficiency target is set at 50%. According to Eurostat (2024), all EU countries met this 50% target in 2022.

Under the EU Battery Regulation 2023/1542, material recovery targets are outlined in Part C of Annex XII, focusing on five key materials: cobalt, copper, lead, lithium, and nickel. Four of these materials, cobalt, copper, lithium, and nickel, are commonly found in lithium-ion batteries. By the end of 2027, the EU aims to recover at least 90% of cobalt, 90% of copper, 50% of lithium, and 90% of nickel. These targets will increase by 2031 to 95% for cobalt, 95% for copper, 80% for lithium, and 95% for nickel. The previous EU Battery Directive did not set material recovery rates, so actual recovery data is currently unavailable, with the first recovery targets due in 2027.

Material Feedstock

The growing number of gigafactories in European Union (EU) will generate substantial production scrap, which will serve as a major feedstock in the near term (Navarro et al., 2022; Parker, 2021; Racu & Poliscanova, 2024). Currently, only a small fraction of spent lithium-ion batteries contributes to recycling, but this share is expected to rise significantly in the coming decade as more batteries, especially from electric vehicles, reach the end of their life (Slattery et al., 2024). End-of-life batteries are anticipated to account for 72% of the recycling feedstock by 2035, rising further to 88% by 2040 (Racu & Poliscanova, 2024).

The material feedstock for lithium-ion battery recycling plants coming from the batteries in the EU is most likely composed of all battery chemistries that are placed on the EU market. European Commission and Joint Research Centre (JRC) (n.d.-c) published forecasted data on the number of batteries placed on the EU market, categorized by their chemistries. The data includes nine different battery chemistries, four of which are lithium-ion batteries: Lithium Cobalt Manganese (LCO), Lithium Iron Phosphate (LFP), Lithium Manganese Oxide (LMO), and Nickel Manganese Cobalt (NMC). While these chemistries differ, their applications are largely similar, as they are used in portable devices, electric vehicles, and industrial applications (European Commission & Joint Research Centre (JRC), n.d.-b). Data on waste volumes generated by different lithium-ion battery chemistries in the EU is available but varies, and it is important to acknowledge the inherent uncertainties due to the predictive nature of these estimates (European Commission & Joint Research Centre (JRC), n.d.-c; Jaco Huisman et al., 2017; ProSUM project, n.d.).

For electric vehicles, Harper et al. (2019) and Hottenroth et al. (2018) note that the most common cathode materials used in the EU are NMC and LFP. However, data published by European Commission and Joint Research Centre (JRC) (n.d.-b) indicates that NMC batteries dominate the EU market over LFP batteries. According to The Wall Street Journal (2023), the EU's preference for NMC batteries is aligned with its strategy to lead the electric vehicle market. By prioritizing the recycling of materials from NMC batteries, the EU aims to position itself as a leader in high-performance EV technology. NMC batteries, known for enabling longer-range EVs, are crucial for accelerating the transition to electric mobility and competing with markets like the USA and China, which have different battery preferences.

One of the most recent reports published by Transport and Environment (T&E), a European non-governmental organization (NGO) focused on promoting sustainable transportation policies, argues that although NMC chemistries currently dominate battery demand in Europe, the mix of battery chemistries is expected to shift in the coming years (Racu & Poliscanova, 2024). Moreover, the report emphasized that emerging nickel-based chemistries, with higher manganese content and iron-based chemistries are expected to gain market share. Finally, sodium-ion batteries, still in their early stages, are projected to account for around 2% to 6% of demand, primarily in energy storage systems and smaller electric vehicles (Racu & Poliscanova, 2024). The changes of battery chemistries will likely affect the future material feedstock of recycling process.

Recycling Cost and Financing Scheme

Recycling lithium-ion batteries in the European Union (EU) involves a variety of technological and financial considerations. According to Bruno and Fiore (2022), among the different processing methods, the combination of pyrometallurgical (high temperature) and hydrometallurgical (chemical) treatments results in the highest costs, amounting to approximately €230 per ton of batteries processed, while hydrometallurgy as a standalone process has been identified as the most cost-effective option, with significantly lower costs reported at around €92 per ton.

Extended Producer Responsibility (EPR) schemes and the sale of recovered materials form the financial backbone of battery recycling in the EU (EU Battery Regulation 2023/1542; Tankou et al., 2023). These mechanisms are instrumental in offsetting the operational costs associated with recycling and in improving the overall economic feasibility of material recovery. Bruno and Fiore (2022, 2023) provide two distinct approaches to calculating recycling revenues: one based on income per ton of processed batteries, and the other on income by type of recovered metal. According to their analysis, the combined pyrometallurgical and hydrometallurgical processes yielded the highest revenue at €1,242 per ton of batteries, followed closely by hydrometallurgy at €1,200 per ton, while pyrometallurgy alone generated lower returns of around €1,006 per ton (Bruno & Fiore, 2022). In terms of material-specific revenue, the recovery of 22.6 kilotons of metals through battery recycling was projected to generate total income of €53.6 million. This figure includes an estimated €27.7 million from copper, €18.8 million from cobalt, €3.4 million from lithium, and €2.9 million from aluminium (Bruno & Fiore, 2023).

Social License to Operate

In the European Union (EU), the establishment of lithium-ion battery recycling facilities generally benefits from a supportive policy framework, as outlined earlier under the Subsections Policy and Regulations. Nevertheless, despite this favourable regulatory context, the implementation of such projects continues to encounter social resistance in several member states. Notable cases have been reported in Germany (Amelang, 2024b; Bodnár, 2024) and Hungary (Inotai, 2023), where proposed recycling plants faced strong public opposition due to concerns related to environmental, health, and safety risks. In some cases, these concerns have resulted in significant delays, the suspension of planned investments, or even the cancellation of projects. The Social License to Operate (SLO) thus remains a critical component in the successful deployment and scaling of lithium-ion battery recycling infrastructure, even within the EU, where environmental regulations are generally strict.

Recycling Methods and Technologies

Recycling methods in the European Union (EU) is a multi-stage process, starting with sorting and dismantling, and then followed by material recovery process. According to Peplow (2023), battery recyclers in EU mainly prioritize recovering materials from battery cathodes like lithium, cobalt, and nickel, while ensuring environmental and safety compliance.

During the *sorting* stage, spent lithium-ion batteries are sorted based on chemistry, size, and condition aiming to optimize the efficiency of the subsequent recycling stages (Bhar et al., 2023; Hossain et al., 2023; Werner et al., 2020). The batteries undergo an initial inspection to identify any units that are damaged or pose safety hazards, such as those at risk of thermal runaway (e.g., overcharging, short-circuiting). Depending on their chemistry, size, and condition, the batteries are categorized using manual or automated methods. Advanced technologies, such as optical scanners and automated identification systems (Evergreen, 2022), are increasingly used to differentiate between lithium cobalt oxide (LCO), nickel-manganese-cobalt (NMC), and lithium iron phosphate (LFP) batteries.

After sorting, batteries are sent to *dismantling* facilities where larger packs, like those from electric vehicles, are broken down into modules and cells (Kay et al., 2022). This process separates key components such as casings, electrodes, and electrolytes, with some materials like aluminium and copper being directly recycled (Vieceli et al., 2018). Batteries retain energy and contain hazardous substances. So, batteries are discharged before disassembly to reduce risks. While dismantling remains labour-intensive, some facilities are adopting robotic and semi-automated systems for greater efficiency (Free4Lib, n.d.; Kuka, n.d.; Recirculate, n.d.-a).

Once dismantled, the separated materials undergo *pre-processing*. This involves shredding the battery components into a mixture known as "black mass" (Carfrae, 2025). Black mass from lithium-ion batteries contains valuable metals such as lithium, cobalt, nickel, and manganese. Additional steps, such as screening and sieving, are employed to separate coarse materials like plastics and aluminium from finer, metal-rich powders (Bhar et al., 2023). Pre-processing is typically conducted by specialized recycling companies with expertise in handling lithium-ion batteries.

The final stage of the recycling process is the recovery of materials from the black mass. Peplow (2023) argued that the most common methods in the EU are hydrometallurgy and pyrometallurgy. Pyrometallurgy involves high-temperature smelting to extract metals like cobalt, nickel, and copper, while hydrometallurgy is a chemical-based method uses solvents to extract valuable metals with greater precision, including lithium, as already discussed in Subsection 2.2.2. Besides, other studies are currently underway to explore the potential of adopting direct recycling as an alternative technique which considered more effective and efficient compared to the other methods.

In the EU, recycling methods are chosen by companies based on their expertise and infrastructure, meaning that there is no single method to recover the materials from the spent lithium-ion batteries in the region. Umicore, one of the largest recyclers, uses a combination of pyrometallurgy and hydrometallurgy, recovering over 95% of nickel, copper, and cobalt, and over 70% of lithium (Umicore, 2023). Other companies, such as Li-Cycle Germany, Fortum Battery Recycling, and Revolt Ett, primarily use hydrometallurgy, claiming recovery rates exceeding 95% for cobalt, manganese, nickel, and lithium from black mass (Oberhaus, 2020).

Recycling Infrastructures

Molina (2022a) highlighted that over 35 lithium-ion battery recycling projects are currently in progress or planned across the EU. According to the International Energy Agency (2024), the EU's total recycling capacity is projected to exceed 2.5 million metric tonnes or equivalent to 1,550 GWh by 2030. Some existing companies also continue expanding their recycling facilities (S&P Global Commodity Insights, 2023). One of the largest initiatives is led by Umicore, which has been operating a 7,000 tonnes battery recycling plant since 2011 and aims to establish a facility with a capacity of 150,000 tonnes facility in the EU by 2026 (Umicore, 2023).

4.1.3 Recycled Materials Market

Secondary raw material markets play a crucial role, ensuring the timely circulation of high-quality recycled materials in the economy while reducing dependence on natural resource extraction. While some markets have been well-established and contribute significantly to the circular economy, others continue to face barriers to further development, even when supported by robust European Union (EU) and national waste and recycling policies. This section aims to explores the lithium-ion batterie recycled material market situation in the EU.

Policy and Regulations

Recovered materials from recycling processes are reintegrated into the market, supported by the EU's circular economy framework. Key policy instruments supporting this development include the EU Battery Regulation 2023/1542, the EU Critical Raw Materials Regulation 2024/1252 (Critical Raw Materials Act), and the Circular Economy Plan 2020 (European Commission, 2020b). The EU Battery Regulation 2023/1542 establishes mandatory minimum thresholds for the use of recycled content in batteries, requiring that by 2031, new batteries must contain at least 16% recycled cobalt and 6% recycled nickel and lithium. These targets are set to increase significantly beyond 2036. The regulation is intended to promote the integration of secondary raw materials into battery manufacturing. In parallel, the EU Critical Raw Materials Regulation 2024/1252 prohibits the export of black mass outside the EU. Additionally, black mass has recently been classified by the European Commission as hazardous waste under the EU Waste Shipment Regulation (Regulation (EU) 2024/1157) and restricting its export to non-OECD countries, reinforcing efforts to retain valuable materials within the EU's circular economy and support the development of domestic recycling capacity (Directorate-General for Environment, 2023; Linnenkoper, 2025; Resource.co, 2025).

Quality and Quantity of Recycled Materials

Recycled materials recovered from lithium-ion battery recycling in the European Union (EU) must meet stringent quality standards to be considered suitable for reuse in battery manufacturing and other applications. For example, lithium-ion batteries require a high purity chemical product in the form of nickel sulphate (Shi et al., 2022). As recycling technologies mature, several processes, including pyrometallurgical, hydrometallurgical, and direct recycling, have demonstrated the capability to recover critical materials such as lithium, cobalt, nickel, and manganese at purities comparable to those of primary raw materials (Tembo et al., 2024). Umicore, a Belgium battery recycler, claimed that their companies are able to produce recycled cobalt and nickel with purity levels of 95% or higher which making them suitable for use in new cathode active materials (Umicore, n.d.). Lohum, an Indian-EU recycling firm operating in Europe, reports that its proprietary processes recover battery raw materials with performance and purity on par with virgin mined metals, including 99.5% lithium carbonate, cobalt sulphate and nickel sulphate (Lohum, n.d.).

A study by the EU Joint Research Centre (n.d.) projects steady growth in the EU's supply of battery raw materials from secondary sources. Recycled lithium is expected to account for 3% of supply by 2025, 5% by 2030, and 9% by 2040. Recycled cobalt could meet 24% of EU demand by 2025, rising to 32% by 2030 and 51% by 2040. Nickel recycling is projected to provide 8% of supply by 2025, 23% by 2030, and 42% by 2040. While current lithium-ion batteries also contain iron and are expected to increasingly use manganese and graphite, there are no regulatory targets for recovering these materials or mandating their use in new batteries. Nonetheless, recycled manganese could meet 10% of demand by 2025, 17% by 2030, and 23% by 2040, while recycled graphite is projected to supply only 1% by 2025, 2% by 2030, and 3% by 2040.

Market Demand for Recycled Materials

The market potential for recycled materials from lithium-ion battery recycling in the European Union (EU) is driven by the increasing demand in the battery industry, particularly for manufacturing lithium-ion batteries used in electric vehicles (EVs) and renewable energy storage systems (ESS) (Navarro et al., 2022; Strategy&, n.d.). For this thesis, the market demand for recycled materials will be limited to four minerals that are commonly found in lithium-ion batteries and have the recycled targets which are nickel, cobalt, and lithium, as outlined in Subsection 4.1.2. A study about market demand from battery manufacturing will be the main part of discussion in this subsection, but other potential markets will also be discussed. While specific projections for the demand of recycled materials are limited, the material is typically examined from the supply side, emphasizing the extent to which recycled material can contribute to overall market supply, rather than estimating how much of it will be specifically demanded by end-users (see the subsections *Quality and Quantity of Recycled Materials*).

Nickel plays a critical role in both the stainless-steel and lithium-ion battery industries. Nickel demand is largely driven by the stainless-steel industry, which accounts for approximately 70% of global primary nickel consumption (Roskill et al., 2021). However, the lithium-ion battery sector, particularly for electric vehicles (EVs), is projected to experience the fastest growth among all end-use sectors. In the EU, this trend is reinforced by the increasing adoption of nickel-rich cathode chemistries in lithium-ion batteries, which are well-suited to the high energy density requirements of EVs. According to Roskill et al. (2021), Europe's demand for nickel in batteries is projected to increase dramatically, from 17 kilotons (kt) in 2020 to 304 kt in 2030 and 560 kt by 2040. However, this landscape is expected to diversify over time as the demand for recycled nickel in the battery sector will depend heavily on the evolution of battery chemistries, with non-nickel chemistries such as lithium iron phosphate (LFP) gaining market share in certain applications (IEA, 2025; Kane, 2022; Kavanagh, 2023; Shah, 2025).

Lithium demand for batteries is foreseen to grow fivefold in 2030 and have a 14-fold rise in 2040 compared to the 2020 level. According to European Commission and Joint Research Centre (JRC) (n.d.-a), lithium demand for battery materials will increase to 727 kilotons (kt), 1,536 kt, and 4,015 kt by 2025, 2030, and 2040 respectively from 291 kt by 2020. In the EU, lithium are used in various industries, including batteries and product containing batteries, glass and ceramics, products made of aluminium alloys, lubricating greases, electronics and pharmaceutical products (Deloitte, 2015). Among these industries, the glass and ceramics industries have historically been significant users of lithium. With the booming electric vehicle and energy storage system, these industries have been increasingly the main user of lithium in the EU (European Lithium, n.d.).

In the increasing penetration of EVs and ESS, *cobalt* consumption will be boosted by the usage of lithium-ion batteries, in particular Nickel-Manganese-Cobalt (NMC) and Nickel-Cobalt-Aluminium (NCA) chemistries, which cobalt as cathode material (Pavel et al., 2018). In the EU, cobalt demand will amount to 53,500 tonnes in 2025, increasing in 2030 to 108,000 tonnes in average circumstances (Pavel et al., 2018). The potential amounts of recycled cobalt generated by end-of-life vehicles deployed in the EU is estimated at 500 tonnes in 2025 and may amount to 5,500 tonnes in 2030. In 2030, recycling could provide for around 10% of European consumption in the EVs sector. In the EU, end-use sectors of cobalt is batteries, superalloys, hard metals, pigments, and catalysts (Deloitte, 2015).

Due to the early-stage development of the industry in the EU, collaborations between battery manufacturers, recyclers, and raw material suppliers have emerged with aiming to stabilize the market. Some alliances created by multiple players, such as the Renault-Veolia-Solvay, Valmet-Fortum-Nornickel-BASF, and Volkswagen-Northvolt-Hydro are other notable examples (Navarro et al., 2022). This collaboration is crucial especially for battery manufacturers that are committed to producing greener batteries by integrating recycled materials. For example, Northvolt Ett, a battery manufacturer based in northern Sweden, plans to lower its carbon footprint by utilizing renewable energy and sourcing 50% of its raw materials from recycled batteries by 2030 (Peplow, 2023). This collaboration also ensures that materials recovered from end-of-life (EOL) batteries are reused directly in new EV batteries produced by the same company, rather than being released into the open market.

Recycled Material Prices

The recycling process is expected to enable the recovery of valuable metals such as lithium, nickel, and cobalt. The market value of these recovered materials plays a critical role in the overall economics of the recycling system, as revenue from their sale constitutes one of the primary funding sources for recycling operations. Within the EU, recovered materials from lithium-ion battery recycling are typically traded in two main forms: black mass and refined materials (Research and Markets, 2025; Reutner, 2024; S&P Global Commodity Insights, 2023).

The value of black mass is influenced by a range of factors, including the chemistry of the input batteries, global demand for critical metals, fluctuations in commodity prices, regional processing capacity, and transportation costs (Allen, 2024; Perry, 2023). For example, black mass derived from battery chemistries with higher cobalt content commands higher prices, whereas material from lithium iron phosphate (LFP) batteries yields lower value due to its limited content of economically valuable metals (Allen, 2024). Whilst refined materials obtained from lithium-ion battery recycling refer to high-purity metal compounds extracted from black mass, such as lithium carbonate or lithium hydroxide, nickel sulphate, and cobalt sulphate (Rinne et al., 2025; Saleem et al., 2023). These refined products have higher market value than black mass as these materials generally meet the quality standards required for new battery production.

In the EU, the prices of both black mass and refined materials have recently declined due to falling market values of lithium, nickel, and cobalt, which have subsequently reduced profit margins for recycling operations (Gherasim & Michel, 2024; Holman & Day, 2024; Zhao, 2024). As of mid-2024, the price of black mass in the EU has experienced a decline, reflecting broader downward trends in global battery metal markets. The assessed price for nickel-cobalt black mass in late November 2024 was approximately USD 1,879 per ton (EX Works Europe), down from a peak of USD 2,265 per ton earlier in the year, based on a minimum composition of 3% lithium, 5% cobalt, and 12% nickel (S&P Global Commodity Insights, 2024). Similarly, refined materials recovered through recycling have also faced continued price pressure in the EU. As reported by Laskowski and Jodha (2025), the price of battery-grade lithium carbonate, fell to approximately USD 10,555 per tonne CIF (cost, insurance, freight) in early 2025, down from over USD 17,700 per tonne in December 2023, while lithium hydroxide experienced a similar decline, reaching around USD 9,590 per tonne CIF.

Consumer Attitudes to Recycled Materials

Consumer perceptions of recycled materials derived from lithium-ion battery recycling in the EU are generally favorable, driven by increasing environmental awareness, concerns about ethical sourcing, and a growing preference for sustainable consumption practices (Stena Recycling, 2022). However, despite this positive perception, consumer willingness to pay a premium for batteries containing recycled materials remains limited (Day, 2024). This gap between environmental values and actual purchasing behavior poses a challenge for the market uptake of recycled materials.

4.2 Discourses on Lithium-ion Battery Recycling: Navigating Rationales and Concerns

The discourse surrounding battery recycling is shaped by a complex interplay of perceived benefits and recognized barriers. As outlined in Subsection 2.2.1, battery recycling is increasingly positioned as both an environmental imperative and a strategic opportunity for enhancing resource security, particularly in the context of the transition to a low-carbon economy. However, due to various systemic factors as discussed in Subsection 2.2.2 and 2.2.3, battery recycling continues to encounter technical, economic, and regulatory challenges, which have drawn critical scrutiny.

This subsection explores the contrasting perspectives on lithium-ion battery recycling within the European Union (EU), highlighting how various actors, including industry stakeholders, policymakers, researchers, and environmental advocates, frame both its importance and its limitations. By analysing these discourses, the subsection aims to uncover the underlying values, assumptions, and tensions that shape how lithium-ion battery recycling is understood and pursued. In addition, it aims to provide a balanced examination of the different viewpoints and thus can set the stage for discussing the future of lithium-ion battery recycling.

4.2.1 Perceived Rationales

One key argument in support of lithium-ion battery recycling in the European Union (EU) is its potential to *mitigate environmental degradation linked to both primary resource extraction and battery waste generation,* as outlined in Subsection 2.1.3. Stakeholders contend that recycling plays a critical role in preventing the release of hazardous substances into the environment, while also reducing the cumulative ecological burden associated with mining activities and the disposal of end-of-life batteries (European Commission, 2019, 2020a; Hartmut Stahl et al., 2018a, 2018b). Supporting this perspective, Transport & Environment (T&E) estimates that battery recycling could save approximately 0.2 million tonnes of lithium ore by 2030 and 0.8 million tonnes by 2040, thereby contributing to reduced carbon emissions and aligning with the EU's climate objectives (Racu & Poliscanova, 2024). Similarly, Tankou et al. (2023) project that recycling could reduce the annual demand for raw materials, such as cobalt, lithium, manganese, and nickel, by 3% in 2030, 11% in 2040, and 28% in 2050.

Another central rationale is the anticipated risk of resource depletion and material bottlenecks. Shan (2023) warns of a potential shortfall in lithium carbonate as early as 2025, while other forecasts suggest shortages by 2030. In this context, recycling is regarded as *a vital strategy for ensuring long-term material availability*. Given the strategic importance of lithium-ion batteries for the EU's transition toward a low-carbon economy, stakeholders warn that continued reliance on primary resources may hinder progress. According to Peplow (2023), EU industry actors and policymakers increasingly view recycling as a strategic measure to secure access to critical raw materials. Racu and Poliscanova (2024) further note that as battery demand escalates, recycling end-of-life batteries will become an essential secondary source of materials.

Moreover, stakeholders highlight that expanding recycling capacity can *reduce the EU's dependency on imported materials*, which exposes the region to supply chain vulnerabilities such as geopolitical tensions and trade disruptions. Molina (2022b) underscores that most raw materials essential for the energy transition are sourced externally, making the EU's battery supply chain less resilient. The European Commission (2020b), through the Circular Economy Action Plan 2020, has emphasized that establishing a robust domestic recycling industry would help ensure a stable supply of raw materials, reduce exposure to price volatility, and strengthen the EU's strategic autonomy. In alignment with this, Blenkinsop (2024), Navarro et al. (2022), Molina (2022b) argue that scaling up recycling infrastructure is essential for preventing the outflow of strategic materials to non-EU markets and reinforcing the EU's self-sufficiency amidst global market disruptions.

Stakeholders also underscore the *alignment of lithium-ion battery recycling with key EU regulatory and climate policy frameworks*. Recycling is an integral component of recent legislative initiatives, including the EU Battery Regulation 2023/1542 and the Critical Raw Materials Act (Regulation 2024/1252), which stipulate minimum recovery rates and mandate environmentally sound recycling practices. These policies aim to ensure that recycling contributes meaningfully to the EU's broader climate strategy, particularly the objective of achieving net-zero emissions by 2050 (European Commission, n.d.-a).

Finally, *economic considerations* also play a significant role in stakeholder support for recycling. Recycling is perceived as a driver of economic growth, with the potential to generate new revenue streams, create jobs across collection, processing, and research sectors, and enhance the EU's competitiveness in the global battery market (ISRI, 2021; Molina, 2022a; Tellus Institute & Sound Resource Management, 2021). Empirical studies (Bruno & Fiore, 2023; Strategy&, n.d.) have quantified the job creation and economic value added by recycling, reinforcing its potential to contribute to EU economic resilience and industrial leadership.

In summary, stakeholders perceive lithium-ion battery recycling as a multifaceted solution that supports environmental protection, resource security, economic development, and regulatory compliance. Recycling is seen as central to advancing the EU's sustainability agenda, enhancing circularity, and reinforcing supply chain resilience. By recovering valuable materials from end-of-life batteries, recycling helps reduce the negative impacts of mining, lowers dependence on imports, and ensures a more stable and autonomous battery ecosystem in the EU.

4.2.2 Recognized Concerns

One of the primary concerns raised by stakeholders regarding lithium-ion battery recycling in the European Union (EU) relates to *economic, technological, and policy-related limitations*. While the EU has set ambitious recycling targets, such as recovering 90% of cobalt and nickel and 35% of lithium by 2026, stakeholders' express skepticism about the achievability of these goals given current technological and market constraints (Blenkinsop, 2024; Simon, 2021; Willuhn, 2020). In particular, they question the economic viability of recycling operations within the EU due to high operational and capital costs, limited financial capacity, the relatively low volume of end-of-life batteries restricting economies of scale, and the still underdeveloped nature of the EU's recycling market (Allen, 2023; S&P Global Commodity Insights, 2024). Technological barriers further compound these challenges, including insufficient recycling infrastructure, limited access to advanced and efficient recycling technologies, and inadequate product design for recyclability that hinders recyclability (Albertsen et al., 2021; Battereverse, n.d.; Molina, 2022b). Moreover, disparities in regulatory enforcement across member states , as well as mandatory risk fragmenting implementation efforts and may undermine the effectiveness of the EU's overall recycling strategy (Directorate-General for Environment, 2018; Hancock, 2025).

Environmental concerns have also emerged, with some stakeholders cautioning against an *over-reliance on recycling as a singular solution to resource scarcity and sustainability challenges*. They argue that the environmental benefits of lithium-ion battery recycling are sometimes overstated, potentially diverting attention and investment away from other critical strategies such as remanufacturing, reuse, and material efficiency (Dahlström, 2023; Zhou et al., 2024). According to Wood Mackenzie (2021), the supply of secondary materials from recycling alone will not be sufficient to bridge the anticipated shortfall in key battery materials such as lithium, nickel, and cobalt by 2030. While numerous studies highlight the potential environmental gains from recycling, other research points to its limitations, as discussed in Subsection 2.1.3 (Kemfert, 2017; Meegoda et al., 2024; Mrozik et al., 2021; Patel et al., 2024; Van Hoof et al., 2023).

In conclusion, stakeholder perspectives highlight a range of economic, technological, policy-related, and environmental concerns associated with lithium-ion battery recycling in the EU. These insights contribute to a more nuanced understanding of the limitations of current practices, as discussed in Subsection 4.2.1, and raise critical questions about the role of recycling in achieving the EU's sustainability and resource security objectives.

4.3 Opportunities and Challenges of Lithium-ion Battery Recycling

Understanding the opportunities and challenges of lithium-ion battery recycling in the European Union (EU) is essential for guiding sustainable and strategic decision-making in the transition to a circular economy. This section aims to provide a nuanced understanding of these dynamics not only highlights where progress is possible but also identifies the structural and systemic issues that must be addressed to make recycling a viable long-term solution. Analysis will be done in each step of recycling process, revealing opportunities and challenges of political, economic, social, and technical aspects.

4.3.1 Opportunities

Opportunities of lithium-ion battery recycling refer to the favorable conditions, enabling factors, and supportive mechanisms, such as regulatory frameworks, technological innovation, market demand, and environmental incentives, that facilitate the development, scaling, and integration of recycling systems within the battery value chain. These opportunities are critical for implementing and expanding recycling initiatives in alignment with the European Union's broader objectives related to resource efficiency, circular economy, and climate neutrality. This subsection aims to explore opportunities of lithium-ion battery recycling that are available in the EU.

Collection

Within the European Union (EU), the collection of lithium-ion battery presents several *political opportunities* that can facilitate the development of an effective recycling system. As discussed in Subsection 4.1.1, the EU Battery Regulation 2023/1542 mandates the collection and recycling of spent batteries, establishing specific targets for collection rates and material recovery. Complementary policies such as the Circular Economy Action Plan and Extended Producer Responsibility (EPR) schemes further reinforce this mandate by promoting sustainable product design and robust collection infrastructure (European Commission, 2020b). Moreover, the EU's broader sustainability agenda creates a strong political framework for expanding collection systems, underpinned by political will of cross-sector collaboration among policymakers, industry actors, academia, and civil society (Bergfald et al., 2024; El-Kretsen, n.d.; Reuters, 2024; Stena Recycling, 2024).

From an *economic perspective*, the rapid growth in electric vehicle (EV) adoption and the expansion of energy storage systems (ESS) are expected to generate a significant volume of end-of-life (EOL) batteries in the coming years (Allen, 2023; Marthaler et al., 2022). This emerging feedstock presents substantial economic opportunities for the recycling industry. In addition, the EU is facilitated by various financing scheme to enhance the viability of collection systems, including the EPR, market incentives, EU funding programs, and public-private partnerships (ERP, 2024; EU Battery Regulation 2023/1542; European Investment Bank, 2024; Gospodinova, 2021; Stena Recycling, 2021).

Social opportunities are also emerging, driven by increasing public awareness and pro-environmental behaviour (Acuti et al., 2023; Lizin et al., 2017; Paristokierrätys, n.d.-a; Science for Environment Policy, 2023; Tijm et al., 2021). This upward trend reflects growing environmental consciousness and consumer willingness to engage with collection schemes.

From *technical perspective*, the EU can benefit from mature and efficient collection systems of other type of batteries to establish efficient collection of spent lithium-ion batteries (Hartmut Stahl et al., 2018b). As discussed in Subsection 4.1.1, portable battery collection is also well-established, supported by a wide network of municipal drop-off points, retailers, and automotive dealerships (Bergfald et al., 2024; El-Kretsen, n.d.; Reuters, 2024). These established systems provide a valuable foundation for scaling up the collection of lithium-ion batteries from EVs, ESS, and consumer electronics.

Material Recovery

The European Union (EU) offers a *political foundation* that presents significant opportunities for advancing lithium-ion battery material recovery. Central to this effort is the EU Battery Regulation 2023/1542, which sets binding recycling efficiency thresholds and material recovery targets, as discussed in Subsection 4.1.2. These measures align with the EU's strategic objectives to reduce reliance on imported raw materials and to foster a circular battery value chain. Moreover, they serve as compliance incentives and catalysts for innovation, as reflected in stakeholder perspectives in Subsection 4.2.1. The regulation's design-for-disassembly provisions further reinforce recovery efforts by requiring manufacturers to ensure the removability of batteries, particularly in portable devices and light means of transport (LMT), to facilitate more efficient material extraction (European Parliament, 2022). Collectively, these instruments establish a proactive policy landscape that supports long-term strategic planning and enhances investor confidence in the battery recycling sector.

Economically, the recovery of materials from lithium-ion batteries presents substantial opportunities driven by the increasing volume of end-of-life (EOL) batteries and production scrap, a result of rapid growth in electric vehicles (EVs), energy storage systems (ESS), and portable electronics (Navarro et al., 2022; Parker, 2021; Racu & Poliscanova, 2024; Slattery et al., 2024). This trend positions the EU to benefit economically from the recovery of valuable secondary raw materials, such as lithium, cobalt, nickel, and graphite, which are essential for battery production and are subject to fluctuating global supply and pricing. Furthermore, the EU supported by financing scheme to support the financial sustainability of the recovery system (EU Battery Regulation 2023/1542). Steward et al. (2019) note that reducing the cost of lithium-ion batteries has become a key focus of ongoing research and development.

From a *social perspective*, widespread public support presents a significant opportunity for the development of lithium-ion battery recycling facilities and encouraging broader participation in recycling activities (Eurobarometer, 2024; European Environment Agency, 2024a, 2024b).

Technically, the EU is increasingly well-equipped to lead in battery material recovery due to its advancing capabilities in recycling technologies and the steady development of supporting infrastructure (Evergreen, 2022; Free4Lib, n.d.; International Energy Agency, 2024; Kuka, n.d.; Molina, 2022b; Peplow, 2023; Recirculate, n.d.-a; S&P Global Commodity Insights, 2023). These advancements enhance the EU's capacity to meet both environmental objectives and growing supply chain demands.

Recycled Material Market

From a *political standpoint*, the European Union (EU) provides a highly supportive regulatory framework that creates significant opportunities for the development of the lithium-ion battery recycled materials market. Key legislative instruments, including the EU Battery Regulation 2023/1542 which mandates minimum levels of recycled content in new batteries, as well as the Circular Economy Action Plan (European Commission, 2020b) and the EU Critical Raw Materials Regulation 2024/1252 (Critical Raw Materials Act) which collectively foster domestic recycling, strengthen supply chain resilience, and reduce reliance on imported raw materials.

Economically, the market is supported by a strong and growing demand for recycled materials (Joint Research Centre, n.d.; Navarro et al., 2022; Peplow, 2023; Strategy&, n.d.), driven in part by the expansion of battery manufacturing and the rapid adoption of electric vehicles and energy storage system.

From a *social perspective*, the market benefits from increasing consumer interest in sustainable and ethically sourced products, which supports demand for recycled inputs and enhances the marketability of products containing secondary raw materials (Stena Recycling, 2022).

Technically, the EU is well-positioned to lead in this space, owing to its advancing capabilities in producing high-purity secondary materials suitable for use in new battery applications (Shi et al., 2022; Tembo et al., 2024; Umicore, n.d.). Furthermore, the growing volume of end-of-life batteries provides a reliable and scalable feedstock, which is essential for the long-term economic viability of recycling operations and continued investment in infrastructure, as elaborated in Subsection 4.1.3.

4.3.2 Challenges

The challenges surrounding lithium-ion battery recycling in the European Union (EU) span multiple dimensions that hinder the efficient collection, processing, and reintegration of end-of-life batteries into the circular value chain. This subsection aims to explore the key barriers to the development and scaling of recycling systems within the EU context. These challenges not only compromise the overall effectiveness of recycling efforts but also pose obstacles to achieving the EU's broader environmental and circular economy objectives.

Collection

Despite the overarching legislative framework established by the European Union, most notably the Battery Regulation (EU) 2023/1542, the implementation of lithium-ion battery collection systems remains uneven across Member States, posing a significant *political challenge*. The effectiveness of national collection schemes varies due to disparities in institutional capacity and regulatory enforcement. While countries such as Germany, Sweden, and Belgium have developed efficient systems characterized by high consumer participation and reliable reporting mechanisms, others continue to face systemic barriers, including lack of infrastructure development, insufficient funding, limited public awareness, and fragmented responsibilities among regulatory authorities, producers, and waste management actors (EPBA, 2024b; European Commission, 2018, n.d.-b).

From an *economic* perspective, high costs represent a significant barrier to the effective collection of lithium-ion batteries in the EU (Onstad, 2024b). Although various financial support schemes are available, their design and implementation vary across member states, resulting in uneven financial capacities and creating disparities in collection system performance (EPBA, 2024b; European Environment Agency, 2023).

Socially, lithium-ion battery collection is hampered by behavioral and informational barriers. Improper disposal and hoarding are widespread issues, particularly for small-format batteries embedded in products such as power banks, e-cigarettes, and cordless electronics (EEA, 2019; Melin, 2019b; Molina, 2022b; Mrozik et al., 2021; Sorrel, 2007; Velázquez-Martínez et al., 2019).

Additionally, the EU faces a range of *technical challenges* in improving lithium-ion battery collection rates. Amelang (2024a) notes that the extended lifespan of lithium-ion batteries in electronics and electric vehicles slows the rate of immediate availability of spent batteries. Additionally, disparities in infrastructure development across Member States and battery categories undermine system efficiency, as highlighted in Subsection 4.1.2. The EU also experiences significant leakage of end-of-life batteries to non-EU countries, particularly China, which offer more established recycling capabilities and favorable economic conditions (EPBA, 2024b; Peplow, 2023). Complicating matters further is the difficulty in tracking battery flows due to broad and inconsistent classification systems, especially the industrial battery category, which obscure data and hinder strategic planning (Albertsen et al., 2021). Some scholars argue that reported low collection rates may be partially attributable to data limitations rather than actual performance, as lithium-ion batteries are often aggregated with other chemistries in statistical reporting. Even for lead-acid batteries, long considered a success story, questions persist over the accuracy of collection metrics, which are often based on estimates (BlyBatteriRetur, n.d.; EPBA, 2024c; Landbell SagisEPR, 2024). Finally, safety concerns, particularly the risk of fire and explosion from damaged or degraded batteries, remain a critical technical barrier to both collection and transport, as discussed in Subsection 2.1.3.

Material Recovery

Despite the European Union's proactive regulatory approach, several *political challenges* continue to hinder the effective recovery of lithium-ion battery materials. As highlighted in Subsection 4.2.2, ongoing debates persist regarding whether current recovery targets appropriately balance environmental objectives and industrial feasibility (Allen, 2023; Blenkinsop, 2024; S&P Global Commodity Insights, 2024; Simon, 2021; Willuhn, 2020). Moreover, tensions have emerged between the EU's strategic aim of securing critical raw materials and industry calls for more flexible implementation timelines that would allow for innovation and industrial scaling (Hodgson & Hancock, 2025).

From an *economic perspective*, the high operational costs associated with recovery processes and the limited economies of scale present substantial obstacles (Onstad, 2024b). Advanced recycling techniques, such as hydrometallurgy and direct recycling, remain significantly more expensive than extracting virgin materials, primarily due to complex disassembly requirements and energy- and labor-intensive operations (IEA, 2022). Additionally, the current limited supply of end-of-life batteries, particularly from electric vehicles, constrains processing throughput and contributes to elevated per-unit costs. The substantial capital investment required to establish modern recycling infrastructure poses further economic challenges, particularly for small and medium-sized enterprises (Eunomia, 2021). Moreover, shifts in battery chemistries, such as the reduced use of cobalt and nickel, introduce long-term risks to the profitability of recovery operations that rely on the extraction of high-value metals (Kurdve et al., 2019; Mayyas et al., 2019).

Social acceptance also represents a critical barrier to material recovery. While there is general public support for the principles of recycling, local opposition frequently arises due to concerns over emissions, hazardous waste, and potential health risks associated with recycling facilities (Amelang, 2024b; Bodnár, 2024; Inotai, 2023). As discussed in Subsection 4.1.2, such concerns have resulted in delayed permit approvals and, in some cases, the rejection of proposed facilities, thereby obstructing the development of necessary infrastructure.

From a *technical standpoint*, the heterogeneity of lithium-ion battery designs and chemistries presents significant challenges for sorting, disassembly, and material recovery, as outlined in Subsection 2.1.1. A key limitation is the lack of design-for-recycling principles in current battery production, with many batteries constructed without consideration for end-of-life processing (Norgren et al., 2020; Thompson et al., 2020). For example, Stena Recycling (n.d.) highlights that certain battery models are so extensively glued and limited access to battery-specific data, which hampers safe and efficient handling. While the forthcoming EU battery passport is expected to enhance data transparency, its implementation and efficacy remain uncertain.

Furthermore, no existing recycling technology can currently recover all critical materials with high efficiency (Dobó et al., 2023; Md T. Islam et al., 2022; Ma et al., 2021). For example, pyrometallurgical processes are effective at recovering nickel, cobalt, and copper, but struggle with lithium, aluminium, and manganese (Bernhart, 2019; Oberhaus, 2020). Hybrid approaches combining pyro- and hydrometallurgy offer improved recovery rates but at the cost of increased complexity and operational expenses (Oberhaus, 2020). Direct recycling, while promising higher material yields and lower environmental impacts, faces substantial design-related challenges and remains largely confined to laboratory-scale applications (Hirschlag, 2022; Oberhaus, 2020). Compounding these issues are safety concerns, particularly the risk of fires during handling and processing, which further complicate recovery operations (Meegoda et al., 2024; Mrozik et al., 2021; Patel et al., 2024).

Recycled Material Market

From a *political perspective*, the recycled materials market in the EU faces several significant challenges. While regulatory frameworks seek to strengthen the market by enhancing competitiveness and operational efficiency, most notably through mandatory recycled content targets as outlined in Subsection 4.1.3, the lack of harmonization across member states in terms of rules, standards, capacities, and data collection continues to impede market functionality (Giosuè et al., 2021; Rizos & Urban, 2024). Moreover, stakeholders have expressed concerns regarding the feasibility of meeting these regulatory targets, citing existing structural limitations within the EU that ultimately undermine the effectiveness of the Union's broader recycling strategy, as analyzed in Subsection 4.2.2 (Albertsen et al., 2021; Directorate-General for Environment, 2018; Hancock, 2025).

Economically, the competitiveness of recycled materials market in the EU is constrained by multiple factors. Recycled materials are frequently more expensive than both virgin materials and imported recycled alternatives (European Commission, 2020b; Onstad, 2024b; Racu & Poliscanova, 2024). This price gap is exacerbated by the failure to internalize the environmental and social costs of virgin material extraction (The Faraday Institution, 2020). Moreover, instability in supply and demand presents ongoing challenges, as the availability of recyclable lithium-ion batteries and the demand for their recovered materials are closely linked to broader trends, such as the pace of electric vehicle adoption across the EU (Dempsey et al., 2024; Onstad, 2024a). Price volatility of raw materials further threatens the economic viability of recycling operations, as declining prices can significantly erode profit margins (Gherasim & Michel, 2024; Holman & Day, 2024; Laskowski & Jodha, 2025; S&P Global Commodity Insights, 2024; Zhao, 2024). Additionally, the majority of EU recycling facilities remain at pilot or demonstration scale, limiting cost efficiency and scalability (Navarro et al., 2022). Delays in the deployment of planned gigafactories have further hindered the establishment of a comprehensive recycling infrastructure (Racu & Poliscanova, 2024).

From a *social perspective*, limited consumer willingness to pay a premium for products containing recycled materials represents a significant barrier, despite growing positive perceptions of such materials and increasing societal expectations for businesses to incorporate recycled content into their products (Day, 2024; Stena Recycling, 2022).

5 Discussions

This chapter aims to discuss the research findings presented in Chapter 4, ranging from the current state of the art of lithium-ion battery recycling in the European Union (EU), the key rationales and concerns articulated by stakeholders, as well as the opportunities and challenges of lithium-ion battery recycling in the EU. The discussion is also grounded in the conceptual framework outlined in Chapter 2. Through this discussion, the chapter seeks to provide a critical and integrative analysis of how technical, political, economic, and social dimensions interact to shape the development of lithium-ion battery recycling in the European context. By synthesizing empirical insights with theoretical perspectives, the chapter aims to deepen the understanding of the enabling conditions and systemic barriers that influence the transition towards a circular and sustainable battery value chain in the EU.

5.1 The EU's Lithium-ion Battery Recycling Landscape

The European Union (EU) considers lithium-ion batteries a strategic industry central to its broader climate and industrial policies. These batteries are vital for enabling the decarbonisation of transport and energy systems, particularly through their application in electric vehicles (EVs), grid storage, and portable electronics. In this context, lithium-ion battery recycling has emerged as a cornerstone for advancing sustainability, resource efficiency, and circularity in the EU's battery value chain. The EU's lithium-ion battery recycling landscape reflects a strategically coordinated effort driven by ambitious policies, economic incentives, societal demands, and technological innovation, yet it still faces challenges related to infrastructure, public engagement, and technical complexity that must be addressed to achieve a truly circular battery value chain.

5.1.1 Political

The European Union (EU) offers a highly conducive political environment for the advancement of lithium-ion battery recycling. This supportive context is rooted in the EU's strategic climate and industrial goals, particularly its commitment to achieving climate neutrality by 2050 and ensuring a resilient and competitive battery value chain. A cornerstone of this policy landscape is the EU Battery Regulation (2023/1542), which establishes binding requirements across the entire battery life cycle, from design and labelling to collection, reuse, and recycling. The regulation sets mandatory recycling efficiencies, recovery targets for critical raw materials such as lithium, cobalt, and nickel, and introduces obligations for the incorporation of recycled content in new batteries.

Complementary legislative instruments further strengthen this framework. For instance, the Critical Raw Materials Act (EU Regulation 2024/1252) aims to reduce the EU's dependency on third-country imports by promoting the sustainable sourcing and recycling of strategic materials. Similarly, the Circular Economy Action Plan (European Commission, 2020b) reinforces resource efficiency and waste reduction across sectors, including batteries. These policies reflect the EU's integrated approach to fostering a circular battery economy.

This robust regulatory framework presents significant political opportunities for scaling up lithium-ion battery recycling across the EU. By offering legal certainty and clearly defined compliance obligations, these instruments serve as enabling mechanisms that align stakeholder interests and incentivize investment, innovation, and coordination. The establishment of recycling targets and traceability requirements fosters accountability while facilitating collaboration among key actors, including producers, recyclers, policymakers, and consumers. Moreover, the regulations have garnered broad support from industry associations and environmental non-governmental organizations, which recognize their long-term economic, environmental, and strategic benefits. In this context, the EU's political commitment and regulatory coherence provide fertile ground for advancing a circular and integrated battery recycling system.

However, despite these political strengths, several challenges persist in the implementation of lithium-ion battery recycling policies at the Member State level. Although the overarching objectives and legal frameworks are harmonized at the Union level, national-level implementation remains uneven. Disparities in transposition, institutional capacity, enforcement mechanisms, and stakeholder engagement create inconsistencies across the region. For example, the performance of Extended Producer Responsibility (EPR) schemes, the effectiveness of public awareness campaigns, and the clarity of waste classification procedures vary significantly among Member States. While some countries have developed mature waste management infrastructures and comprehensive battery collection systems, others lag behind due to limited regulatory oversight and insufficient infrastructure. This asymmetry undermines the overall effectiveness of the EU's battery recycling strategy and hampers cross-border collaboration and material flow.

These political challenges constrain the EU's ability to establish a coherent and integrated recycling system. Without greater consistency in implementation, enhanced institutional capacity, and stronger coordination across Member States, the effectiveness of EU-level regulations risks being diluted. Addressing this fragmentation is essential to ensure that the EU's ambitions for a circular and sustainable battery value chain are not only legislated but also effectively operationalized at both national and local levels.

5.1.2 Economic

As the European Union (EU) advances its climate neutrality objectives, particularly within the energy and transport sectors, the demand for batteries is expected to increase significantly. This surge in battery usage underscores the urgency of effective and sustainable end-of-life management, thereby fostering favorable conditions for the emergence of a competitive and innovation-oriented recycling market. Key anticipated economic benefits include reduced dependence on imported critical raw materials, improved trade balances, enhanced resource efficiency, and strengthened strategic autonomy over essential materials.

To realize these goals, the EU actively supports lithium-ion battery recycling through targeted investments in technology development, infrastructure expansion, and market creation. Public and private funding, channeled through initiatives such as the European Battery Alliance, the Innovation Fund, and Horizon Europe, has been instrumental in establishing recycling technologies and facilities across Member States. These investments not only reflect growing market confidence but also highlight the strategic importance of battery recycling within the EU's broader green transition and resource security agenda. In parallel, the increasing volume of end-of-life batteries provides a growing and valuable input stream. Economic returns can also be generated through EPR schemes and the resale of recovered metals.

Despite these positive developments, several persistent economic challenges hinder the establishment of a sustainable and efficient recycling system. One of the most significant barriers is the high cost of recycling, which makes secondary raw materials less economically attractive compared to primary alternatives. Virgin materials, often sourced from global mining operations, tend to benefit from subsidies, fewer regulatory constraints, and lower labor costs. These factors contribute to the continued market dominance of primary materials and limit the commercial viability of recycled ones.

Further complicating the economic outlook is the ongoing shift in battery chemistries. As producers increasingly adopt lower-value chemistries such as lithium iron phosphate (LFP), the profitability of recycling diminishes. Unlike higher-value variants such as NMC (Nickel Manganese Cobalt) or NCA (Nickel Cobalt Aluminium), LFP batteries contain fewer critical metals, reducing the economic incentive to invest in their recovery.

On the supply side, while future projections suggest a substantial availability of recyclable materials, current input volumes remain constrained. Factors such as varying battery lifespans, immature collection systems, technological limitations in recycling processes, and the relatively nascent stage of the electric vehicle market all contribute to this shortfall (see Subsection 4.3.2). These inconsistencies in material flows create operational risks for recycling facilities, including the underutilization of processing capacity.

On the demand side, the market for secondary materials such as lithium, cobalt, and nickel remains underdeveloped. To support a robust circular economy, these materials must be cost-competitive, high-quality, and available at scale. Smaller recycling enterprises often face high per-unit costs and limited access to capital for scaling up advanced recovery technologies. Moreover, the limited maturity of the EU's battery manufacturing sector, coupled with shifting battery chemistries, has dampened manufacturers' willingness to adopt recycled inputs. Achieving economies of scale depends not only on technological innovation but also on systemic enablers such as design-for-recycling principles, efficient collection logistics, harmonized cross-border trade regulations, and conducive policy frameworks.

Market inefficiencies are further exacerbated by limited transparency and restricted data access. The recycling sector remains fragmented, with much information considered proprietary. This lack of data sharing inhibits collaboration, impedes the development of coherent policies, and constrains the growth of a standardized secondary materials market. Moreover, recycled materials are often perceived as niche products, and the absence of widely accepted quality standards further undermines their market integration.

In summary, the economic landscape of lithium-ion battery recycling in the EU is characterized by a combination of strong enabling factors and persistent structural barriers. While significant progress has been made in mobilizing investment and expanding infrastructure, challenges related to cost competitiveness, market development, supply reliability, and policy coordination remain. Overcoming these obstacles requires a systemic approach that aligns economic realities with the EU's circular economy and climate objectives. Encouragingly, such barriers are not unique to battery recycling but are common to many emerging secondary materials markets (Biddle, 1993; Woodring, 2020). As Biddle (1993) suggests, these challenges can be addressed through targeted regulation, stakeholder engagement, innovative business models, and technological advancements that ensure access to high-quality, low-contamination feedstocks. A strategic and coordinated response to these dynamics will be essential for unlocking the full economic potential of lithium-ion battery recycling in the European Union.

5.1.3 Social

The transition toward a circular battery economy is increasingly driven by public concern for ethical and environmentally responsible sourcing. Consumers and civil society actors are demanding greater transparency in supply chains and a reduction in the social and environmental harms associated with primary resource extraction, particularly in regions with weak labor and environmental protections. In this context, recycled materials are progressively viewed as a more ethical and sustainable alternative to virgin raw materials.

The social dimensions of lithium-ion battery recycling in the EU encompass a variety of interconnected factors, including consumer awareness, recycling behavior, public demand for products containing recycled materials, and the sector's social license to operate. These elements collectively influence the social acceptability, participation rates, and long-term viability of recycling systems. Importantly, the development of the recycling sector presents significant social opportunities, particularly in light of growing environmental consciousness and heightened expectations for ethical resource management. European citizens have shown strong support for climate action and sustainable consumption, creating a favorable social environment for the expansion of battery recycling, especially when these efforts are framed within broader narratives of sustainability and circularity.

Public concern over the negative social and environmental impacts of raw material extraction, including human rights abuses, child labor, and ecological degradation, has intensified the call for ethically sourced materials. Recycling lithium-ion batteries within the EU addresses these concerns by reducing reliance on primary extraction from high-risk regions and aligning with the EU's broader commitments to fairness, transparency, and environmental stewardship. As such, battery recycling is increasingly perceived as a legitimate and socially aligned practice. This evolving "social license to operate" plays a critical role in fostering policy support, enhancing corporate legitimacy, and attracting private investment.

Nonetheless, several persistent social challenges constrain the sector's development, particularly in relation to consumer behavior and public perceptions of recycling operations. One of the major barriers is the improper disposal and hoarding of batteries, which restrict the availability of recyclable materials and undermine circular resource flows (see Subsection 4.1.1). Public knowledge regarding appropriate disposal practices remains limited, and incentive structures for battery return are often inadequate or inconsistently implemented across Member States.

Maintaining a social license to operate also presents ongoing challenges for recyclers and manufacturers. Community resistance frequently arises from concerns over potential environmental and health impacts, particularly regarding air and water pollution associated with recycling processes. These fears are often amplified by inadequate communication from industry actors and policymakers about environmental safeguards, operational safety standards, and the broader societal benefits of recycling. Where transparency is lacking, public mistrust may persist, even when facilities comply with rigorous environmental regulations.

Inconsistencies in the enforcement of environmental standards across EU Member States further complicate public perceptions. In regions with historical legacies of industrial pollution or weak regulatory oversight, communities may exhibit heightened skepticism toward new waste-processing infrastructure, regardless of its technological or environmental merits. Such perceptions, often rooted in past experiences and governance gaps, can pose significant obstacles to the expansion of recycling capacity.

These challenges underscore the importance of community engagement, transparency, and trust-building in the development of recycling infrastructure. To foster public acceptance, industry and policymakers must prioritize inclusive stakeholder consultation, embed participatory decision-making processes, and adhere to principles of environmental justice. Empirical studies suggest that early and meaningful community involvement, combined with transparent environmental impact assessments and the delivery of tangible local benefits, such as employment opportunities or infrastructure investments, can significantly enhance social acceptance (Jenkins et al., 2018). Moreover, harmonizing environmental regulations and strengthening enforcement mechanisms across the EU are essential steps toward building public trust and ensuring consistent adherence to high operational standards.

5.1.4 Technical

From a technical standpoint, the EU has made notable progress in advancing lithium-ion battery recycling through the development of innovative technologies and infrastructure. EU-funded research and innovation programs have played a pivotal role in overcoming technical barriers and improving recycling efficiency. Collaborative efforts among industry actors, research institutions, and public authorities have further supported the emergence of a more integrated and technologically advanced battery ecosystem.

The ongoing expansion and modernization of recycling facilities across Member States are contributing to increased processing capacity and operational efficiency. Technological advancements have significantly enhanced material recovery rates, with some facilities achieving efficiencies of up to 90% for critical raw materials such as lithium, cobalt, and nickel. These improvements align with the objectives of the EU Battery Regulation 2023/1542, reinforcing regulatory compliance while advancing circularity and resource efficiency goals. Furthermore, the growing volume of end-of-life batteries, driven by the proliferation of portable electronics and the rapid adoption of electric vehicles (EVs), provides a steadily expanding feedstock for recycling operations. In more mature segments, such as portable electronics, well-established collection systems offer a strong foundation for scaling up recycling activities. Collectively, these developments support the EU's strategic ambitions to enhance resource recovery, reduce dependence on primary raw materials, and foster resilient and sustainable battery value chains.

Despite these advancements, several systemic technical challenges persist. A key limitation is the lack of comprehensive, reliable, and harmonized data across the EU. Robust data collection and reporting mechanisms are essential for monitoring progress, guiding policy development, and supporting efficient market operations. However, the current data landscape remains fragmented, impeding stakeholders' ability to identify bottlenecks and respond to emerging issues effectively.

Collection infrastructure presents another major constraint. Many Member States lack well-coordinated, safe, and accessible systems for the timely collection of spent lithium-ion batteries, particularly from consumer electronics and EVs. Limited public awareness, weak incentives for battery return, and the insufficient availability of collection points undermine system performance. Given the hazardous and chemically complex nature of lithium-ion batteries, existing infrastructure is often ill-suited to manage the growing volume of end-of-life batteries. Safety considerations are particularly critical, as incidents involving fires and other accidents linked to improper handling and storage of battery waste have become increasingly frequent.

Moreover, although the EU has invested in developing recycling infrastructure, many existing facilities are not adequately equipped to process the wide variety of lithium-ion battery chemistries currently in use. No single recycling technology is yet capable of optimizing the recovery of all valuable materials. Additionally, the emergence of next-generation chemistries, such as solid-state and sodium-ion batteries, introduces additional complexity, necessitating further adaptations in processing techniques and regulatory oversight. Recyclers face a double challenge: they must keep up with changing regulations while also upgrading their technology, both of which require major financial and operational investments.

Design for Recycling (DfR) is widely recognized as a key enabler of circular battery systems. However, its practical implementation remains limited. Battery manufacturers tend to prioritize performance parameters such as energy density, lifespan, and safety over end-of-life considerations. As a result, DfR is often viewed as an additional cost rather than a strategic design principle. This misalignment hampers the development of batteries that are easier to disassemble and recycle, thereby constraining the scalability and efficiency of recycling operations.

In summary, the technical landscape of lithium-ion battery recycling in the EU is marked by considerable progress alongside persistent systemic barriers. Unlocking the full potential of the sector will require coordinated and long-term strategies aimed at strengthening data infrastructure, improving safe and accessible collection systems, investing in advanced and adaptable recycling technologies, and embedding DfR principles throughout the battery value chain. Particular attention must also be paid to enhancing recovery rates for under-recycled chemistries, such as lithium cobalt oxide (LCO), which remains prevalent in consumer electronics.

5.2 Stakeholders Views on Lithium-ion Battery Recycling in the EU

The findings presented in Section 4.2 reveal two primary perspectives on the establishment of lithium-ion battery recycling within the European Union (EU). As outlined in Subsection 4.2.1, proponents emphasize the potential environmental, economic, and social benefits associated with developing a robust recycling system. For stakeholders in key industries, such as battery manufacturing and automotive production, recycling has become an integral component of strategic planning. These actors argue that integrating battery recycling into production processes, where critical materials such as lithium, cobalt, and nickel are recovered and reused in a closed-loop system, can reduce dependence on mining, decrease the demand for newly extracted resources, and mitigate associated environmental impacts.

In addition to industrial motivations, geopolitical considerations have further reinforced the importance of domestic recycling capabilities. The EU's limited access to primary raw materials and its reliance on imports from third countries heighten its vulnerability to external supply chain disruptions. In this context, policymakers increasingly view lithium-ion battery recycling as a strategic imperative to enhance resource security, reduce exposure to geopolitical risks, and strengthen the EU's autonomy in critical raw materials.

However, despite these rationales, some stakeholders' express scepticism regarding the feasibility and effectiveness of current recycling initiatives. Their concerns centre on several structural limitations within the EU, including the economic viability of recycling operations, the technical challenges of recovering certain materials, and uncertainties related to market development. Critics caution that overemphasis on recycling could inadvertently sideline other sustainable end-of-life strategies, such as remanufacturing and repurposing.

Others argue that achieving a sustainable battery industry is contingent on optimizing lithium-ion battery recycling to ensure processes are efficient, cost-effective, and environmentally sound. This includes deploying advanced technologies capable of recovering high percentages of valuable materials while minimizing energy consumption, emissions, and the risks associated with handling hazardous substances like electrolytes and heavy metals. Additionally, they emphasize the importance of establishing reliable markets for recycled materials, addressing economies of scale, and ensuring that recycling operations adhere to principles of fairness, safety, and environmental responsibility.

While perspectives differ, there is a general consensus among stakeholders that lithium-ion battery recycling plays a critical role in shaping the future of a sustainable battery industry. Supporters advocate for its integration as a core circularity strategy, whereas critics highlight the necessary conditions and systemic improvements required to ensure its long-term success. Ultimately, the EU's objective of fostering both sustainable recycling practices and a resilient battery value chain should inform policy development, strategic planning, and stakeholder engagement across the sector.

5.3 Understanding the Opportunities and Challenges

Based on the analysis presented in Section 5.1 and 5.2, it is evident that the recycling strategy for lithium-ion batteries in the European Union (EU) faces both significant challenges and promising opportunities. This section aims to provide a comprehensive discussion of the key issues encountered at each stage of the recycling process, namely, battery collection, material recovery, and the recycled materials market within the EU. The political, economic, social, and technical dimensions of each stage will be critically examined, with particular attention to how these factors collectively influence the achievement of the EU's ambitious recycling targets.

5.3.1 Collection

An effective lithium-ion battery collection system in the EU ideally relies on proper consumer disposal practices. This includes timely disposal of batteries once they reach end-of-life, adherence to regulations prohibiting the mixing of batteries with other waste streams, and use of designated collection points. At these collection points, safe and compliant storage is essential, requiring adequate funding and infrastructure. To facilitate this process, all EU Member States should maintain sufficiently accessible and well-coordinated collection systems to support the safe and efficient disposal of spent lithium-ion batteries.

The EU benefits from a robust regulatory framework, including policies promoting extended producer responsibility (EPR), economic incentives, and a gradually expanding collection infrastructure. These elements provide a strong foundation for improving battery collection. However, further development is needed to address emerging complexities. For instance, collection pathways must adapt to account for delayed returns and the increasing diversity of battery sources, especially as second-life applications become more prevalent. This evolving landscape highlights the need for integrated and transparent collection systems that can trace battery flows across multiple life stages while ensuring compliance with EPR obligations.

Despite all the advancements, a major challenge of low consumer awareness and inconsistent disposal behaviour remains. Public understanding of proper disposal practices is limited, reducing the effectiveness of collection systems. Therefore, enhancing consumer education and engagement is critical to improving return rates and supporting the overall success of battery recycling initiatives.

5.3.2 Material Recovery

All lithium-ion batteries entering the recycling process undergo sorting, dismantling, and subsequent material recovery. The EU benefits from strong political and societal support for advancing material recovery efforts, underpinned by ambitious policy frameworks such as the EU Battery Regulation 2023/1542. Technically, the EU possesses considerable expertise and capability in recovering critical raw materials, such as lithium, cobalt, and nickel, with several advanced facilities demonstrating high recovery efficiencies. However, despite these strengths, the recovery process remains limited in scale and faces significant economic challenges.

One of the primary barriers is the limited economic viability of recovery processes under current market conditions. While some battery chemistries are technically recyclable, the costs associated with recovering certain materials often outweigh their market value, especially when dealing with evolving and more complex chemistries. The rapid diversification of battery types complicates the recovery process, requiring flexible and adaptive technologies that are not always economically feasible at present. Consequently, scaling up material recovery in a cost-effective and sustainable manner remains a key challenge for the EU's battery recycling ecosystem.

5.3.3 Recycled Material Market

The recycled materials market for lithium-ion batteries in the EU is currently in an emerging phase. While there is strong political support and growing social acceptance for the use of recycled materials, the market remains underdeveloped due to several structural and temporal constraints. For example, one limitation is the current scarcity of spent lithium-ion batteries available for processing. Since substantial volumes of batteries, particularly from electric vehicles, are expected to reach end-of-life predominantly after 2030, the existing supply of recyclable materials is limited. This feedstock constraint hinders the short-term development of a fully functional and economically viable recycled materials market. Additionally, key enabling factors such as advanced recycling technologies and adequate infrastructure are still evolving, requiring further investment and innovation.

Despite these challenges, the outlook for the sector remains promising. Projections suggest that the EU will possess many of the essential components needed to support a mature and resilient recycled materials market in the coming decades. In the interim, however, it is crucial for the EU to continue strengthening its lithium-ion battery recycling ecosystem. This includes investing in scalable technologies, developing efficient collection and processing systems, and fostering collaboration across the value chain to prepare for the anticipated surge in available end-of-life batteries.

5.4 Limitations

This thesis has several limitations. First, it relies exclusively on written documents as the primary source of data. Given that lithium-ion battery recycling in the European Union (EU) is an emerging field, the information contained in these documents may quickly become outdated and may not fully capture the most recent developments. Additionally, although all selected documents pertain to lithium-ion battery recycling, they differ in scope, purpose, and institutional origin. As a result, the data may not encompass all relevant dimensions or provide a fully comprehensive representation of the industry's current state.

Furthermore, the study adopts a broad, holistic perspective aimed at offering an overarching understanding of lithium-ion battery recycling in the EU. While this approach facilitates a general overview, it may limit the depth of analysis in specific technical, regulatory, or country-level contexts. Lastly, as the research focuses specifically on the EU, its findings may not be directly applicable to other geographic contexts or fully representative of the situation in individual member states.

6 Conclusions and Area of Future Research

This chapter presents the conclusions of the research whereas all research questions will be answered, as well as some areas for the future research are proposed.

6.1 Conclusions

RQ 1: *How does the state-of-the-art of lithium-ion battery recycling within the European Union look like?*

The development of lithium-ion battery recycling within the European Union (EU) is in an emerging yet promising phase. Politically, the sector is supported by a comprehensive regulatory framework aligned with the EU's broader climate objectives, including the transition to a circular economy and the goal of climate neutrality by 2050. Additionally, the development enjoys broad support from stakeholders across the EU who recognize the long-term strategic, economic, and environmental benefits of sustainable battery recycling. Economically, the EU is investing in the development of recycling technologies, infrastructure, and markets to stimulate growth in the sector. Socially, rising environmental awareness and increased expectations for ethical and responsible resource management further contribute to a favorable context for development. Technologically, significant advances are being made in innovative recycling methods and supporting infrastructure.

However, several challenges persist. Politically, fragmentation among member states, reflected in varying capacities for regulatory transposition, enforcement, and stakeholder engagement, creates uneven implementation. Economically, issues such as cost competitiveness, limited market development, feedstock uncertainty, and a lack of coordinated policy instruments constrain progress. Socially, improper consumer disposal practices, battery hoarding, and public skepticism toward recycling operations remain barriers. Technically, the lack of harmonized, reliable data, alongside insufficiently coordinated and accessible collection systems, impedes the efficient processing of the diverse range of battery chemistries currently in circulation.

In summary, while the EU's lithium-ion battery recycling sector is still at a relatively early stage, it demonstrates meaningful progress across political, economic, social, and technical dimensions, positioning it for further development and long-term impact.

RQ 2: *What are the perceived rationales and concerns for lithium-ion battery recycling?*

Two primary perspectives shape the discourse on the establishment of lithium-ion battery recycling within the European Union (EU). Proponents view it as a critical strategy for advancing circular economy principles, mitigating environmental impacts, and enhancing resource security. Conversely, critics underscore the technical, economic, and systemic barriers that must be addressed to ensure the long-term viability and effectiveness of recycling efforts. Despite these differing viewpoints, there is broad consensus among stakeholders that lithium-ion battery recycling is fundamental to the development of a sustainable battery industry. Moving forward, the EU's commitment to fostering both sustainable recycling practices and a resilient battery value chain should inform policy development, strategic planning, and cross-sectoral collaboration.

RQ 3: *What are stated opportunities and challenges of lithium-ion battery recycling?*

Lithium-ion battery recycling in the European Union (EU) holds significant potential to contribute to the region's environmental and climate goals. However, its development is shaped by a complex set of opportunities and challenges that emerge across different stages of the recycling process. While the opportunities act as key enablers for advancing the sector, the challenges can hinder progress if left unaddressed.

At the collection stage, the system benefits from favorable political frameworks, increasing economic interest, and ongoing technical advancements. Nevertheless, social factors, such as consumer awareness, participation, and disposal behavior, remain underdeveloped and require targeted interventions.

In the material recovery stage, strong political support, societal endorsement, and rapid technological improvements provide a solid foundation. However, the economic viability of recovery processes remains a critical barrier, particularly in light of fluctuating material prices and changing battery chemistries.

Finally, the recycled materials market in the EU is still in its early stages. While it is supported by political will and future projections of increased battery waste volumes, it currently faces structural limitations, including insufficient feedstock and infrastructure. With sustained investment and ecosystem development, the market is expected to mature in the coming years.

In summary, both opportunities and challenges are present across all stages of the lithium-ion battery recycling process. The EU possesses many of the key foundational elements required to advance this sector. While certain barriers persist, the current landscape suggests that opportunities outweigh the challenges. Nevertheless, a coordinated effort across political, economic, social, and technological dimensions is essential to address the remaining obstacles. Such an integrated approach is particularly critical if the EU aims to ensure that battery recycling contributes meaningfully to its sustainability targets and the broader energy transition.

6.2 Area of Future Research

Future research on lithium-ion battery recycling should focus on several key areas to enhance sustainability. First, more investigation is needed into the upstream stages of the battery lifecycle, particularly on how to prevent waste as it is the main goal of circular economy. Additionally, improving consumer participation through better collection schemes, incentives, and convenient return points is crucial to increasing recycling rates. Research into advanced recycling technologies is essential to handle the complexity of modern batteries, improve material recovery, and reduce environmental impacts. The secondary material market should be explored especially to include material with low value. Furthermore, studying the economic and policy frameworks, such as subsidies, extended producer responsibility (EPR), and regulations, can support scaling up recycling efforts. Lastly, integrating remanufacturing and repurposing with recycling could further enhance sustainability by reusing batteries in secondary applications before recycling. Addressing these areas will help the EU transition to a circular battery economy, improving the sustainability of lithium-ion batteries and minimizing environmental impacts.

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