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Activities and Structures in Circular Electric Vehicle Battery Supply Chains

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Department of Technology Management and Economics

CHALMERS UNIVERSITY OF TECHNOLOGY

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Abstract

The transition to electric mobility has created an urgent need to reconsider the management of electric vehicle (EV) batteries after their first life. As numbers increase, questions arise regarding battery collection, treatment, and potential pathways for reuse, repurposing, and recycling. Circular strategies can extend battery lifespan and retain material value; however, their implementation requires significant changes to existing supply chain structures. Research on circular battery supply chains remains fragmented, providing a limited understanding of how activities, actors, and flows are structured and coordinated to enable circular pathways. Furthermore, insufficient insight exists into how these structures may evolve in the future. Therefore, the purpose of this thesis is to understand the activities and likely future structures in circular EV battery supply chains.

This thesis comprises three studies that investigate circular EV battery supply chains. Study 1 synthesises existing knowledge through a systematic literature review on activities for circular EV battery supply chains. Study 2 employs semi-structured interviews to identify current actors, activities, flows, and industry perspectives on future developments. Study 3 applies a Delphi study to explore future-oriented perspectives.

The findings reveal the emergence of new actors and responsibilities within the EV battery sector. Seven crucial aspects influencing the development of circular EV battery supply chains were identified, including collection models, ownership, control and data governance, actor diversity, logistics alignment, and economic and regulatory interdependencies across circular pathways. The results highlight tensions between regulatory objectives, such as recycling targets, and repurposing strategies. Battery collection is identified as a critical enabler for scalability; yet collection remains underexplored in the literature and challenging to implement in practice.

This thesis advances theoretical understanding of circular EV battery supply chains by identifying supply chain activities, actors, flows, and structural requirements, and by connecting these elements across circular strategy pathways. Furthermore, it provides practical insights for managers and decision-makers seeking to design and adapt supply chain structures in alignment with current practices and likely future developments.

Keywords: Electric vehicle batteries, Circular supply chain, Supply chain Structures, Circular strategies

List of appended papers

Paper I: Lopes, T. O., van Loon, P., Fallahi, S. and Johansson, M. (2025). Supply chain considerations for circular electric vehicle batteries: a Systematic literature review. *Submitted to an academic journal.*

Author contribution: All authors contributed to the conceptualisation of the study. Data collection was led by Lopes, with support from van Loon and Fallahi. Data analysis and writing of results was conducted by Lopes, van Loon, and Fallahi. All authors participated in the review and editing of the final version.

Paper II: Shafi, S., Lopes, T. O., Altuntas Vural, C. and van Loon, P. (2025). Circular electric vehicle batteries: Integrating the circular supply chain and logistics perspectives.

The appended version was presented at the 32nd Annual European Operations Management Association Conference, June 15-18, 2025, Milan, Italy.

Author contribution: All authors contributed to the conceptualisation of the paper. Data collection was conducted by all the authors. Lopes coded and analysed the interviews data on supply chain considerations while Shafi coded and analysed the logistics considerations. Altuntas Vural wrote the frame of reference. The findings and discussion sections were developed by Shafi and Lopes. All authors participated in the reviewing and editing of the paper.

Paper III: van Loon, P., Lopes, T. O., Fallahi, S., Johansson, M. and von der Gracht, H. A. (2024). Future scenarios and driving forces for circular electric vehicle batteries: a Delphi-study.

The appended version was presented at the 31st Annual European Operations Management Association Conference, July 1-3, 2024, Barcelona, Spain.

Author contribution: van Loon led the conceptualisation, planning and framing of the study, with all authors contributing to the research design. Data collection was carried out by all the authors. Lopes conducted the data analysis together with van Loon and led the development of the discussion. Lopes, van Loon and Fallahi contributed to the writing of the manuscript. All authors were involved in reviewing and editing the paper.

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Tayana Ortix Lopes
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Table of Contents

List of figures

List of tables

Abbreviations

AI	Artificial intelligence
BI	Business intelligence
CE	Circular economy
CLSC	Closed-loop supply chain
CO_2	Carbon dioxide
CSC	Circular supply chain
CSCM	Circular supply chain management
DfD	Design for disassembly
EOL	End-of-life
EPR	Extended producer responsibility
EV	Electric vehicle
IP	Intellectual property
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
ML	Machine learning
OEM	Original equipment manufacturer
OLSC	Open-loop supply chain
SC	Supply chain
SCM	Supply chain management
SCS	Supply chain structure
SLR	Systematic literature review
SOC	State of charge
SOH	State of health
VR	Virtual reality

1 Introduction

This chapter introduces the thesis by positioning electric vehicle batteries within circular supply chains and outlining the challenges of transitioning from linear to circular models. It provides background on battery configurations and circular strategies, including reuse, repurposing, and recycling, before defining the research problem. The chapter then presents the purpose of the thesis and the two research questions that guide the study and concludes by outlining the structure of the thesis.

1.1 Background

The transportation sector is among the largest contributors to global carbon dioxide (CO_2) emissions (European Environment Agency, 2022). In response to increasing environmental concerns, both governments and industries have prioritised the transition toward more sustainable mobility solutions, notably through the electrification of transport systems. Electric vehicles (EVs) have become central to this transformation, supported by regulatory frameworks, industrial innovation, and consumer demand. However, the adoption of EVs brings new challenges, particularly related to the management of lithium-ion (LIB) batteries throughout their lifecycle (Shqairat et al., 2024; Wrålsen et al., 2021).

EV batteries have a limited operational lifespan. Once their capacity degrades to approximately 70-80%, they are no longer considered suitable for automotive use (Börner et al., 2022; Bülow and Meisen, 2023; Hill et al., 2019). This threshold signals the end of their first life, necessitating removal from vehicles and raising critical supply chain management questions regarding their collection, treatment, and potential pathways for reuse, repurposing and recycling (Barman et al., 2023; Koroma et al., 2022; Rajaeifar et al., 2022). With global EV sales surpassing 17 million units in 2024, representing a year-over-year growth of more than 25% from 2023 (IEA, 2025), the volume of batteries reaching end-of-life (EOL) is expected to continue to increase significantly in the coming years (Circle Energy Storage, 2022).

EV batteries contain critical raw materials such as lithium, cobalt, nickel and manganese (Baars et al., 2021; Raj et al., 2022; Ziemann et al., 2018), many of which are sourced from geopolitically concentrated regions (Barman et al., 2023; Narang et al., 2023). The rising scarcity and price volatility of these materials expose EV battery supply chains to significant risks (Sun et al., 2018). The growing demand for these materials, coupled with supply chain vulnerabilities, has intensified interest in recycling, reuse and repurposing (Ahuja et al., 2020).

Three primary pathways for circularity have emerged: (1) recycling batteries to recover materials for new battery production (Kamran et al., 2021; Kastanaki and Giannis, 2023; Nurdiawati and Agrawal, 2022; Schulz-Mönninghoff et al., 2023; Xu et al., 2020), (2) repurposing batteries with residual capacity for secondary applications (e.g., stationary energy storage) (Altuntas Vural et al., 2024; Bobba et al., 2018; Kamath et al., 2023; Olsson et al., 2018; Shahjalal et al., 2022), and (3) refurbishing and remanufacturing batteries for reuse in EVs (Glöser-Chahoud et al., 2021; Kampker et al., 2021; Neri et al., 2024). Each pathway presents unique supply chain challenges (Hossain et al., 2019), including reverse logistics (Rajaeifar et al., 2022; Rosenberg et al., 2023; Tadaros et al., 2022), quality assessment, traceability (Nurdiawati and Agrawal, 2022) value chain coordination (Wesselkämper and von Delft, 2024) and compliance with emerging battery regulations (Shqairat et al., 2024).

In response to these challenges, the European Union has established regulatory frameworks such as the Extended Producer Responsibility (EPR) directive and the EU Battery Regulation (EU, 2023), requiring original equipment manufacturers (OEMs) to ensure the responsible collection, treatment and reintegration of used batteries (Shqairat et al., 2024). These regulations underscore the need for circular supply chains (CSCs) that support material recovery, repurposing, and reuse within Europe (Shqairat et al., 2024).

The challenges have placed increasing pressure on manufacturers, suppliers and other industry stakeholders to redesign their supply chains in accordance with circular economy (CE) principles (Bressanelli et al., 2019; Ellen MacArthur Foundation, 2020; Lieder and Rashid, 2016; McKinsey, 2015). CSCs aim to extend product lifecycles, reduce dependency on virgin raw materials, and eliminate waste through restorative and regenerative processes (Batista et al., 2018; Farooque et al., 2019). In the EV battery context, supply chains must be reconfigured to incorporate reverse flows, for instance, by returning used products into the value chain through reuse, repurposing or recycling (Kurdve et al., 2019; Richa et al., 2017a). This model contrasts sharply with traditional linear supply chains, which follow a one-way path from raw material extraction to product disposal (Govindan and Hasanagic, 2018). However, firms face barriers to implement this CSC model for EV batteries, including high capital investment, lack of supply chain visibility, technological uncertainties and the need for coordination among diverse stakeholders (Wesselkämper and von Delft, 2024).

Although the literature has increasingly addressed technical aspects, including the design and processing of batteries for recycling and repurposing (Al-Alawi et al., 2022; Iqbal et al., 2023; Slattery et al., 2021), the integration of these strategies into CSC structures, remains underdeveloped (Chirumalla et al., 2024; Slattery et al., 2024). The literature remains fragmented across disciplines and few studies provide a holistic view of how circular EV battery supply chains can be strategically designed and managed (Zhu et al., 2025).

1.2 Problem statement

The transition to electric mobility brings with it an urgent need to rethink how EV batteries are managed after their first life. These batteries, while no longer suitable for vehicles, retain significant residual value (Hu et al., 2022) and pose environmental and safety risks if not handled properly. CE strategies such as reuse, repurposing and recycling offer promising pathways to extract this remaining value, extend battery lifespan and reduce the environmental footprint of battery production (Hossain et al., 2019; Richa et al., 2017b). However, enabling these strategies requires considerable changes to existing supply chain structures and operations (Bressanelli et al., 2019).

At the core of this complexity is the lack of supply chain knowledge tailored to circular EV battery systems. Unlike traditional linear supply chains, circular EV battery supply chains must accommodate a reverse logistics flow that includes collection (Slattery et al., 2021; Yazdekhasti et al., 2022), testing and diagnosing (Ramirez-Meyers et al., 2023), sorting (Raj et al., 2022), disassembly (Rosenberg et al., 2022), remanufacturing (Neri et al., 2024), repurposing (Altuntas Vural et al., 2024) and recycling (Xu et al., 2020). These activities are technically and logistically demanding, as they require reliable assessment of battery state of health (SOH), safety status, state-of-charge (SOC), and residual value to determine suitability for second-life applications (E. Martinez-Laserna et al., 2018) or material recovery. Additionally, the transportation of EOL batteries involves regulatory challenges due to their classification as hazardous goods, given the chemical risks and fire hazards involved (Skeete et al., 2020). Structurally, these factors introduce substantial uncertainty regarding the timing, volume and quality of returned batteries, necessitating supply chain structures capable of coordinating multiple actors and circular strategies across interconnected loops (Amir et al., 2023; Choudhary et al., 2025; Guide et al., 2006).

Multiple questions remain unanswered, including decisions on who will collect used batteries, which actors will be responsible for their transportation and processing, how access to used batteries will be regulated and monitored, what criteria determine whether a battery should be reused, repurposed or recycled, and which supply chain structures can support these decisions enabling batteries to be reintroduced into the market in a way that ensures consumer acceptance.

Moreover, current supply chains are not fully prepared to manage the scale, variability and uncertainty associated with EOL batteries (De Lima and Seuring, 2023; Rufino Júnior et al., 2023). EV batteries differ significantly in chemistry, format, and design across manufacturers, often driven by proprietary technologies. This lack of standardisation poses challenges for reverse logistics, disassembly and reuse processes. While standardisation has been proposed as a solution (Xu et al., 2020; Ziemann et al., 2018) competitive pressures and intellectual property (IP) concerns hinder its implementation (Nurdiawati and Agrawal, 2022) underscoring the need for supply chain structures that prioritise flexibility and adaptability in response to technological change and uncertainty (Chi et al., 2009; Brandao and Godinho Filho, 2024).

Limited visibility and traceability in battery flows adds further uncertainty. Although OEMs are typically mandated to collect used batteries under EPR directive (Zhang et al., 2021) and EU Battery Regulation (2023/1542) (Shqairat et al., 2024), not all EOL batteries are returned through formal channels (Gong et al., 2022). This fragmentation creates space for new actors such as third-party collectors, recyclers, and logistics providers, to participate in the circular ecosystem (Kurdve et al., 2019; Li, 2022). As a result, responsibility, control and value distribution along the supply chain become increasingly dispersed, posing coordination challenges among stakeholders (Chirumalla et al., 2022; Rufino Júnior et al., 2023; Slattery et al., 2024).

Technological innovations such as Battery Passport and blockchain for traceability, offer potential to improve transparency (Wu et al., 2020) and coordination across actors (Bräuer et al., 2020). Nevertheless, their successful implementation depends on a thorough understanding of the supply chain structure and data-sharing mechanisms. Without alignment on information standards, process integration and inter-organisational collaboration, these tools risk becoming underutilised (Bräuer et al., 2020).

Internal firm-level operations also require significant adaptation. Battery repurposing and recycling processes necessitate specialised infrastructure for testing, diagnosing, sorting and disassembly (Kampker et al., 2023; Rosenberg et al., 2022). Automation may enhance efficiency, but decisions about where and how to implement automation must balance cost, safety and processing time (Beghi et al., 2023; Hertel et al., 2024; Kaarlela et al., 2024). Importantly, the evolving nature of battery technologies means that supply chain structures must be flexible and continuously updated to reflect the latest product designs and material compositions (Hansen et al., 2025).

From a theoretical perspective, EV battery circularity encompasses both closed-loop and open-loop supply chain models (Zhu et al., 2025). In closed-loop systems, used batteries are returned to the OEM and reprocessed within the same industry (Alamerew and Brissaud, 2020; Chizaryfard et al., 2022; Genovese et al., 2017; Li et al., 2021). In contrast, open-loop systems enable batteries or their recovered materials to be used in other sectors, such as grid services, EV charging stations or the construction sector (Altuntas Vural et al., 2024; De Lima and Seuring, 2023; Etxandi-Santolaya et al., 2023; Kalverkamp and Young, 2019). Even though the CSC literature increasingly recognises the importance of integrating multiple loops (Farooque et al., 2019), existing supply chain frameworks remain largely linear and reactive, prioritising recovery for profitability rather than the intentional design of supply chain structures that enable full-loop circularity (Amir et al., 2023).

Despite growing academic interest in CSCs (Kreye, 2025), systematic understanding of how CSC principles can be operationalised in the context of EV batteries remains limited (Zhu et al., 2025). Specifically, limited knowledge exists on how supply chain structures, considering the configuration of activities, actors and flows, can be designed to support circular battery flows (Rufino Júnior et al., 2023; Barman et al., 2023; Schulz-Mönninghoff et al., 2023; Slattery et al., 2024). Addressing this gap is essential for advancing knowledge of CSCs and supporting the practical implementation of circular EV battery supply chains.

1.3 Purpose and research questions

As the transition to electrified mobility accelerates, the environmental and economic sustainability of EV batteries has emerged as a critical concern (Hill et al., 2019). CSCs offer a promising approach to mitigating the environmental footprint of EV batteries by extending product lifetimes through reuse and repurposing, and enabling material recovery through recycling. However, despite growing academic interest in CE principles, there remains a limited understanding of how supply chain activities and structures can be effectively configured to support circular EV battery flows (Chirumalla et al., 2024; Zhu et al., 2025). Therefore, the purpose of this thesis is to understand the activities and likely future structures in circular EV battery supply chains.

The first research question is motivated by the need to synthesise knowledge on the activities that enable circular flows for EV batteries (Barman et al., 2023; Schulz-Mönninghoff et al., 2023; Slattery et al., 2024). The development of economically viable and environmentally sustainable supply chains depends on a detailed understanding of the activities that constitute these circular systems and the interdependencies among them (Gebhardt et al., 2022). In the case of CSCs, activities such as collection, testing and diagnosing, sorting, disassembly, remanufacturing, repurposing and recycling, are not performed by a single organisation but involve a diverse set of actors across multiple stages (Toorajipour et al., 2024). This complexity requires careful coordination and integration (Wesselkämper and von Delft, 2024), a challenge that has been recognised in the literature and evident in practice (Bonsu, 2020). Moreover, uncertainty in the volume and timing of returned batteries, potential mismatches between returned battery quality and the requirements for reuse or repurposing (Beaudet et al., 2020), and evolving regulatory frameworks (Shqairat et al., 2024) introduce additional complexity that makes supply chain planning and execution more difficult.

Although CSCs are a growing field of research, studies addressing their application to EV batteries remain fragmented (Zhu et al., 2025), limiting a comprehensive understanding of both implementation and implications (De Angelis et al., 2018). There is a lack of knowledge regarding how activities are currently structured, their specific characteristics, and how they can be aligned to enable circular flows (Barman et al., 2023). The discussions in the literature often focus on isolated aspects of the supply chain and lack integration into a coherent, end-to-end perspective (Albertsen, 2020; Koroma et al., 2022; Neri et al., 2024). Consequently, the literature has yet to comprehensively map and assess the full range of activities necessary to support circularity in EV battery supply chains (Bauer et al., 2015; Gebhardt et al., 2022; Sopha et al., 2022). Therefore, the first research question seeks to consolidate existing knowledge in order to identify current gaps, challenges and opportunities for developing circular EV battery supply chains.

RQ1: What do we know about supply chain activities for circular EV batteries?

Building on the understanding of activities from RQ1, the second research question explores how supply chain structures for circular EV batteries are currently configured and how they might evolve in the future. While understanding the activities involved in a circular EV battery supply chain is essential, the transition to circularity requires rethinking how actors, processes and flows are organised. This includes identifying the prevailing patterns of reverse material flows, as well as the roles and responsibilities of actors (Chirumalla et al., 2022; Toorajipour et al., 2024) which underpin the movement and transformation of used batteries throughout the supply chain.

A clear understanding of existing supply chain structures allows researchers and practitioners to identify inefficiencies, bottlenecks and coordination challenges that hinder the transition toward circularity (Yea et al., 2025). Furthermore, assessing current configurations provides a baseline for comprehending how supply chains can be redesigned (Bressanelli et al., 2019) or improved to accommodate increased volumes of EOL batteries, respond to regulatory requirements such as the EU battery regulation, and meet the economic and environmental demands of circular systems (Wesselkämper and von Delft, 2024). By combining theoretical insights with empirical evidence from industry experts and practitioners, the second research question aims to identify current supply chain structures and explores how they may evolve through reuse, repurposing and recycling pathways.

RQ2: What are the supply chain structures for circular EV batteries today and their likely future developments?

Therefore, by addressing these two interrelated research questions, this study contributes to bridging the gap between fragmented academic discussions and the practical challenges of implementing circular EV battery supply chains. The findings advance theoretical understanding by systematically identifying supply chain activities, actors, flows and structural requirements for circular EV batteries. They also provide guidance for researchers and industry practitioners in developing integrated, coordinated, and future-oriented CSCs that deliver environmental benefits while generating long-term economic and strategic value for stakeholders across the battery value chain.

1.4 Outline of the thesis

This thesis is organised into seven chapters, each building toward a comprehensive understanding of CSCs for EV batteries. Chapter 1 introduces the topic, presenting the problem statement, research motivation and justification, followed by the research purpose and questions. Chapter 2 provides a theoretical foundation, reviewing literature on supply chain structures, and circular supply chain and its structures, identifying key concepts and existing research gaps. Chapter 3 outlines the methodology, detailing the research design, data collection and analysis methods and quality considerations.

Chapter 4 summarises the three appended academic papers, highlighting their relevance to the overall research purpose and questions. Chapter 5 presents the main findings, first addressing the supply chain activities involved in circular EV battery systems, then exploring current supply chain structures and likely future developments. Chapter 6 offers a critical discussion of these findings in relation to the literature, emphasising implications for both theory and practice in the design of circular supply chains. Finally, Chapter 7 concludes the thesis by summarising key contributions, outlining theoretical and practical implications, acknowledging limitations and suggesting directions for future research. A full list of references follows.

2 Theoretical background

This chapter presents the key concepts and theories guiding the research conducted in this thesis. It outlines and connects relevant literature on the Circular Economy, Circular Supply Chains, Supply Chain Structures and Circular Supply Chain Structures to establish a coherent theoretical background. Through this synthesis, the chapter provides the conceptual basis for analysing circular supply chains structures and positions the research within existing academic literature.

2.1 Circular Economy

For decades, global supply chains have operated under a linear model, commonly summarised as take, make, dispose - where products are produced, consumed, and ultimately discarded. This model has significantly contributed to resource depletion, environmental degradation, and socio-economic imbalances (Ellen MacArthur Foundation, 2013). In response, the concept of the CE has emerged as an alternative economic system aimed at addressing socio-economic challenges (Sehnem et al., 2019).

The most well-known CE definition is presented by Ellen MacArthur Foundation (2013, p. 7) as "an industrial economy that is restorative or regenerative by intention and design". Restorative processes include reuse, refurbishment, remanufacturing, redistribution, and recycling, while regenerative practices involve the valorisation of organic waste through methods such as biochemical extraction and anaerobic digestion (Ellen MacArthur Foundation, 2013). Complementing this view, the European Environment Agency (EEA, 2016) identifies five defining characteristics of CE: 1) reducing natural resource use, 2) promoting renewable and recyclable materials, 3) mitigating CO_2 emissions, 4) minimising material losses, and 5) retaining products and components within the economy for as long as possible.

A central principle of CE is the decoupling of economic growth from resource consumption and environmental impact (UNEP, 2018). Achieving this goal requires systemic redesign of products and processes to enable durability, disassembly and closed-loop material flows (Ellen MacArthur Foundation, 2013). Accordingly, CE implementation entails adopting innovative strategies such as eco-design, product-as-a-service models and extended product life cycles (Farooque et al., 2019; Kirchherr et al., 2017; Kjaer et al., 2019; Montag, 2022; Pigosso et al., 2013). These strategies demand the involvement, integration and collaboration of multiple stakeholders across the value chain, making CSCs critical for CE implementation (Geissdoerfer et al., 2018; Masi et al., 2018; Massari et al., 2023).

Although rooted in fields such as ecological economics, industrial ecology and cleaner production (Ghisellini et al., 2016; Korhonen et al., 2018), CE has only recently started to receive greater attention in business, influenced by regulatory, environmental and market pressures favouring resource efficiency (De Angelis et al., 2018). Growing societal expectations and the depletion of non-renewable resources are pressuring firms to replace linear models with circular strategies to remain competitive (De Angelis et al., 2018; Jain et al., 2018). This shift raises critical questions about the challenges firms encounter in sustaining competitiveness while redesigning supply chains to align with circular principles (De Lima and Seuring, 2023; Howard et al., 2019). Yet, the integration of CE principles into business models remains limited (Liakos et al., 2019), as it requires significant redesign of product development and EOL management systems (De Angelis et al., 2018).

While regulatory measures and heightened environmental awareness amplify the pressure for change, most firms continue to struggle with fundamental shifts in value creation, delivery and capture (Lüdeke-Freund et al., 2019; Masi et al., 2018). Manufacturing companies play a pivotal role in this transition, given their influence on material choices, product design, business models, and supply chain configurations (Lieder and Rashid, 2016). However, many firms remain cautious about transforming their existing business models without jeopardising profitability or competitive advantage (van Loon et al., 2018). Current industrial systems are largely unprepared for full-scale transition, requiring advances in financing mechanisms, product and operational redesign, regulatory development for circularity and shifts in consumer behaviour (van Loon et al., 2018; Van Wassenhove, 2019).

Consequently, companies and governments face the challenge of redesigning linear supply chains into CSCs (Rasi et al., 2023). Evidence of economic benefits will be critical to encourage investments in circular strategies (Ghisellini et al., 2016; Lieder and Rashid, 2016; Wang et al., 2025). Effective CE implementation depends on CSCs capable of managing reverse flows, which involve acquiring end-of-life products, sorting them by type and quality, and directing them to suitable processes such as reuse, remanufacturing, or recycling (Gunasekara et al., 2023). Nevertheless, the complexity of these reverse flows introduces new operational and strategic challenges, emphasising the need for comprehensive models and decision-making frameworks to manage them efficiently (Gunasekara et al., 2023).

2.2 Circular Supply Chain

Building on the principles of the CE, CSCs represent a strategic reconfiguration of traditional supply chains to enable the circulation of materials, products, and information. Unlike linear supply chains, CSCs integrate forward and reverse logistics to retain resources within the economic system for as long as possible through recovery processes such as reuse, refurbishment, remanufacturing, repurposing and recycling (Batista et al., 2018). A defining characteristic of CSCs is their emphasis on resource efficiency and value preservation throughout the entire product lifecycle (Batista et al., 2018).

Scholars have refined this concept through definitions that include coordinated value creation, extended product lifecycles and stakeholder collaboration across industries. For instance, Batista et al. (2018, p. 446) describe CSCs as "*the coordinated forward and* *reverse supply chains via purposeful business ecosystem integration for value creation from products, services, by-products and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organisations"*. Farooque et al. (2019) expand on this view by emphasising two core CE principles: the regenerative and restorative nature of cycles and the pursuit of a zero-waste vision. Their definition positions circular supply chain management (CSCM) as "*the integration of circular thinking into the management of the supply chain and its surrounding industrial and natural ecosystems. It systematically restores technical materials and regenerates biological materials toward a zero-waste vision through system-wide innovation in business models and supply chain functions from product/service design to end-of-life and waste management, involving all stakeholders across the lifecycle including parts/product manufacturers, service providers, consumers and users"* (Farooque et al. 2019, p. 884). This definition highlights the systemic integration of CE thinking into all supply chain functions, stressing collaboration across organisational boundaries, innovation in business models, and stakeholder engagement throughout the lifecycle. Unlike earlier approaches such as reverse logistics, green supply chains and sustainable supply chain management, which address sustainability in supply chains to varying degrees (Ahi and Searcy, 2015), CSCM advances a vision of systemic circularity by embedding restorative and regenerative cycles that support a non-waste economy (Farooque et al., 2019).

To distinguish CSCs from related concepts, it is important to clarify the role of closed-loop and open-loop supply chains. A closed-loop supply chain (CLSC) integrates forward and reverse flows, whereby returned products are recovered by the OEM for repairing, remanufacturing or recycling (Genovese et al., 2017; Guide and Van Wassenhove, 2009; Souza, 2013). CLSCs are a well-established subfield of supply chain management, closely linked to remanufacturing studies, with profitability as a key driver (Guide and Van Wassenhove, 2009; Lieder and Rashid, 2016). Contrary to traditional supply chains, CLSCs account not only for demand uncertainty but also for the uncertainty associated with product returns from customers (MahmoumGonbadi et al., 2021).

In contrast, open-loop supply chains (OLSCs) extend value creation across different industries or sectors by enabling returned products or by-products from one chain to serve as inputs for another (Berlin et al., 2022; Kalverkamp and Young, 2019). Kalverkamp and Young (2019, p. 581) define OLSC as a "*system that maximizes value creation over the entire life cycle of a product including (re-) design, where the control and operation of the system, particularly reverse logistics and the remanufacturing process, is conducted by a diversity of business actors other than the OEM"*. By extending resource utilisation beyond OEM boundaries, OLSCs generate cascading flows that supports CSCs.

In practice, CSCs expand their scope by combining closed-loop and open-loop configurations to maximise resource efficiency (Batista et al., 2018; Farooque et al., 2019). This broader integration supports systemic ecosystem management by coordinating restorative flows across multiple value networks. For example, agreements that allow third-party remanufacturers to use components from returned OEM products can help meet demand without requiring a fully dedicated sales system (Kalverkamp and Young, 2019). Similarly, opening the loop enables CSC actors to collaborate beyond the original supply chain, therefore capturing residual value from product returns and facilitating resource recovery across industries (Gunasekara et al., 2023).

The above definition is illustrated in Figure 1, where a circular supply chain is compared with linear and closed-loop supply chains.

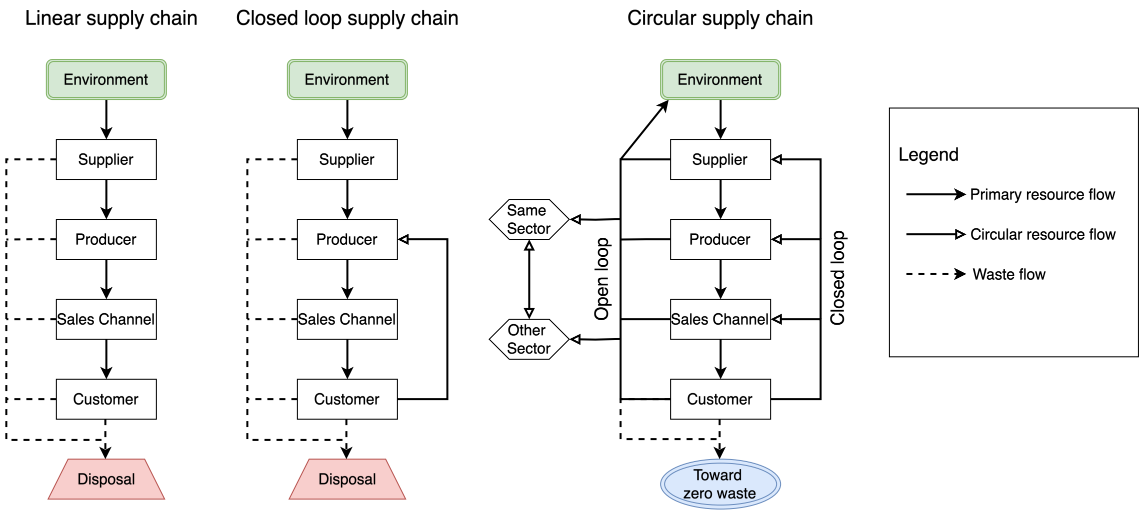

Figure 1. Linear, closed-loop and circular supply chains (Farooque et al., 2019)

2.3 Supply Chain Structures

In today´s global market, supply chains constitute a key source of competitive advantage by adding value to products and services and influencing how firms compete (Seuring and Müller, 2008). Supply chains comprise multiple elements that define their structure and functioning. Three core elements are commonly highlighted: (1) network structure, referring to the actors and their relationships; (2) business processes, representing the activities that generate customer value; and (3) management components, encompassing culture, leadership, and planning practices (Lambert and Cooper, 2001). Complementing this view, supply chains can also be categorised into four interrelated aspects: processes and activities, flows, technologies and systems and actors, highlighting the inherent complexity of modern supply chains (Fabbe-Costes and Jahre, 2008).

Supply chain management (SCM) is defined as the systemic and strategic coordination of business functions and tactics within and across firms to enhance long-term performance (Mentzer et al., 2001). This coordination occurs internally, requiring trust, commitment and effective risk management, and externally, involving relationship management, redistribution of functions, and structuring inter-organisational networks (Mentzer et al., 2001). SCM may also be understood as the management of relationships across a firm's network of suppliers, logistics, marketing and related systems facilitating forward and reverse flows to maximising efficiency, profitability and customer satisfaction (Stock and Boyer, 2009). Effective SCM requires careful decisions regarding which members to connect, which processes to integrate and the degree of integration pursued (Lambert and Cooper, 2001).

Understanding supply chain structure (SCS) is fundamental to effective SCM. SCS refers to the pattern of relationships among participating entities, including their geographic scope and governance mechanisms (Choi et al., 2001; Stock et al., 2000). It encompasses the processes that coordinate and control the objectives and activities of independent organisational units (Hur et al., 2004). The design of a firm´s SCS strongly influences the nature of supply chain activities, as well as its efficiency, effectiveness and inter-firm relationships (Chi et al., 2009). Consequently, structures must align with competitive priorities such as cost, quality, flexibility, speed and innovation and must adapt to changing business conditions, including fluctuating demand, supply uncertainty, technological shifts and competitive intensity (Chi et al., 2009; Fine, 1998, as cited in Chi et al., 2009).

Industry characteristics further influence SCSs. Comparative research in the automotive, semiconductor and tyre industries identifies factors such as customer demand characteristics (e.g., sales volume, forecasting and availability expectations), product and process complexity, organisational policies and competitive dynamics as key structural drivers (Hur et al., 2004). Understanding and managing supply chains further requires attention to the dynamic movement and interactions of flows, with managerial decisions regarding participant interaction, distribution channel organisation and technology determining the operational configuration of the chain, from simple arrangements to complex networks, making flexibility essential (Brandao and Godinho Filho, 2024).

Mapping supply chains provides practical insights for structural improvement. Because different internal processes may link to different external partners, distinct network structures can exist within a single firm (Lambert and Copper, 2001). For instance, a firm may collaborate closely with one supplier in product development while engaging multiple suppliers in demand management. Mapping individual processes and integrating them into a comprehensive supply chain map enables the identification of critical segments and support value optimisation (Hur et al., 2004).

However, existing research on SCSs is predominantly rooted in linear models, emphasising one-way material flows and EOL disposal, which limits its ability to guide the transition to CSCs. Therefore, additional literature explicitly addressing CSCs structures is required for this thesis.

2.4 Circular Supply Chain Structures

Transforming linear supply chains into CSCs represents a complex endeavour due to their multi-functional nature and the diverse activities and processes involved (Choudhary et al., 2025; Guide and Van Wassenhove, 2009). In contrast to traditional linear supply chains, CSCs must simultaneously manage reverse flows of returned products, which are often less structured and subject to uncertainty regarding timing, volume, residual value and feasible reprocessing options (Amir et al., 2023; Choudhary et al., 2025; Guide et al., 2006). These challenges demand a critical re-examination of the structural foundations of supply chains, as transitioning from linear to CSCs requires substantial changes in strategy, structure and governance (De Angelis et al., 2018). These changes entail modifications in flows, focus, scale and scope, besides significant moves in supply chain relationships, ownership models and procurement practices (Idem). Consequently, the development of CSCs should be understood not as a technical adjustment but rather as a systemic reconfiguration that essentially restructures how supply chains operate.

Recent bibliometric evidence identifies SCS and stakeholder management as central and rapidly expanding areas of investigation within CSCM. Research on supply chain design has increased by 41%, with structural considerations representing 42% of the reviewed sample, indicating that circular configurations are receiving growing academic attention (Garcia-Buendia et al., 2024). Hence, this trend highlights increasing academic recognition of structure as an important enabler of CSC transition.

CSC structures are characterised by multiple closed- and open-loop systems designed to transform waste and EOL products into resources through circular practices (MahmoumGonbadi et al., 2021; Massari et al., 2024). These loops may operate within a single sector or extend across industries, creating diverse and complex interdependencies between supply chain actors (Kreye, 2025). Distinctions also exist between inner loops, where resources circulate close to the firm they originate from and outer loops, where resources circulate across longer cycles and broader industrial systems (Batista et al., 2018; Montag, 2022). As loop systems expand and interact, interdependencies arise based on access to information needed to identify new value-creation opportunities, technological capabilities and skills required to implement CE strategies, and by-products that can be converted to secondary raw materials (Kirchherr et al., 2017; Massari et al., 2024). Therefore, CSC structures become layered and dynamic, influenced by the interaction of multiple supply chains.

Constructing CSCs is inherently complex due to uncertainties arising within organisations and across supply chain relationships. Enhancing circularity requires addressing challenges related to product characteristics, manufacturing processes, supply chain configuration, infrastructure and high dependence on customers as suppliers (de Lima et al., 2024). These challenges often necessitate redesigned products, restructured operations and supply chains, and the integration of new actors to enable reverse flows (Idem). CSCs therefore require the intentional integration of value propositions, product design, and supply chain structures to enable effective loop closure (Amir et al., 2023). However, existing supply chain frameworks remain predominantly linear and reactive, prioritising recovery for profitability rather than adopting a systemic perspective on value creation and retention, which limits their capability for full-loop closure (Idem). Emerging proposals advocate CSC structures based on circular value propositions, proactive recovery strategies, and collaboration mechanisms that reduce uncertainty and support full circularity (Amir et al., 2023; Fussone et al., 2025).

CSC structures essentially depend on activities that enable the return and recovery of products. Research on return acquisition, sorting and disposition processes has gained importance, as these decisions are fundamental to managing uncertainty and facilitating resource recirculation in CSCs. Key decision areas include (1) returns forecasting, which concerns methods for estimating the quantity, quality and timing of returned products; (2) acquisition effort, referring to the time, cost and resources required to secure returns; (3) channel selection, which consider the decision from which supply chain actors collect the returns, therefore influencing variability; (4) sorting (at or after the acquisition), that reduces quality uncertainty and allocates returns to appropriate recovery operations; and (5) disposition, which determines the most valuable recovery pathways (Gunasekara et al., 2023). These decisions jointly influence uncertainty management and recovery value in CSCs.

In summary, CSC structures are complex and dynamic systems characterised by interconnected material loops, diverse stakeholders, and strong interdependencies. The complexity of CSC structures occurs not only from integrating forward and reverse flows but also from the need to coordinate multiple supply chains, manage uncertainty and balance environmental and economic performance. Despite growing academic attention, substantial gaps remain in understanding how these structures can be effectively designed, coordinated and controlled to manage uncertainty and address performance trade-offs. Therefore, this thesis advances knowledge of CSC structures by exploring them in the empirical context of EV batteries.

3 Methodology

This chapter outlines the methodological approach adopted in this thesis, describing how the research questions are addressed through the overall research process and design. It describes the methods employed in the three studies, including their data collection and analysis procedures. The chapter concludes with a discussion of research quality and ethical considerations to ensure the rigour and trustworthiness of the findings.

3.1 Research process

The research presented in this thesis is connected to two projects. The first project, *High Performing Circular Battery Flows*, is funded by the Swedish Energy Agency and runs from May 2021 to December 2025. The project examines circular battery flows, with a focus on reuse, repurposing, recycling, and the reintegration of recovered materials into new battery production. The research is carried out by a multidisciplinary team consisting of two senior researchers and one doctoral student from the Division of Supply and Operations Management, Department of Technology Management and Economics at Chalmers University of Technology, together with one senior researcher from the Research Institutes of Sweden.

The second project, *Circularity for EV Batteries: Integrating the Circular Supply Chain and Logistics Perspectives*, is funded by the Chalmers Transport Area of Advance/ SFO Transport and runs from January 2024 to December 2025. This project aims to integrate supply chain and logistics perspectives to enhance the reuse, repurposing and recycling of EV batteries. Its objectives include identifying the actors and activities involved in establishing circular EV battery supply chains and examining how logistics services can facilitate efficient material and information flows within these SCSs. The project established a collaboration between two senior researchers and two doctoral students from the Division of Supply and Operations Management, Department of Technology Management and Economics at Chalmers University of Technology.

Study 1, a Systematic Literature Review (SLR), was conducted between June 2022 and August 2025 as part of the *High Performing Circular Battery Flows* project. The study aimed to develop a comprehensive understanding of existing knowledge on how supply chains can enable and accelerate the circularity of EV batteries. To guide the review, the following research question was formulated: How are supply chain perspectives in relation to the circular performance of EV batteries across reuse, second-life, and recycling strategies discussed in literature?

I contributed to the execution of Study 1, the SLR, by conducting the literature search, screening studies according to predefined inclusion and exclusion criteria and synthesising the findings. The initial data collection was carried out in June 2022 and covered peer-reviewed publications from 1993 to June 2022. However, given the growing volume of research on EV batteries, the research team decided to update the review to include publications from July 2022 to March 2024. In total, 564 papers were identified after duplicate removal, and 119 papers met the criteria for inclusion in the review. The manuscript was finalised and submitted to an international journal in August 2025.

Study 2, an Interview study, was conducted from March 2024 in relation to the *Circularity for EV Batteries: Integrating the Circular Supply Chain and Logistics Perspectives* project. The study aimed to identify the structures of CSCs for EV batteries and the logistics services required to support reuse, repurposing and recycling. To guide the research, the following research question was formulated: How are circular supply chain structures and supporting logistics service systems designed to enable reuse, repurposing and recycling of EV batteries?

Study 2 comprised 14 interviews conducted between May 2023 and November 2024. The interviews focused on current actors involved in the circular EV battery supply chain to characterise existing CSC structures, including actor roles, activities, material and information flows, and logistics service perspectives in the European market.

I contributed to Study 2 by participating in data collection and analysis of interviews from a supply chain perspective. Interview transcripts were coded using NVivo 15, followed by further analysis in Microsoft Excel. Another PhD student and I initiated the coding process with predefined categories, such as actors, activities, and structures, while allowing additional categories to emerge inductively. Emerging themes were subsequently organised and coded systematically. In this process, both the PhD student and I independently coded a subset of transcripts, with me focusing on supply chain aspects and another PhD student focusing on the logistics perspective. The coded results were then aligned to integrate both perspectives.

Insights from the analysis of Study 2 formed the basis of a full paper submitted to the 2025 EurOMA Conference and included as an appendix to this licentiate thesis. I contributed to drafting the introduction, the findings related to the treatment phase and circular strategies for EV batteries after first-life, and discussion on existing circular supply chain structures.

Study 3, a Delphi Study, was conducted from April 2023 as part of the *High Performing Circular Battery Flows* project. The study aimed to outline likely future supply chain scenarios for EV batteries after their first life in vehicles. Through a Delphi expert survey, the study examined various aspects including collection, reuse, repurposing and recycling and assessed areas of consensus and divergence among experts regarding the implications of these scenarios.

Study 3 followed three main phases: preparation, data collection, and analysis. I contributed by participating in 6 interviews with industrial experts involved in various stages of the EV battery supply chain. Together with the research team, I participated in refining the Delphi statements, including adjustments made following a pre-test with external experts. I also assisted in identifying and contacting experts and inviting them to participate in the Delphi survey on the SurveyLet platform. In addition, I led together with a senior researcher a follow-up online meeting with participants after the first round to present preliminary results and facilitate discussion of the initial findings.

Insights from the analysis of Study 3 formed the basis of a full paper submitted to the 2024 EurOMA Conference and included as an appendix to this licentiate thesis. I contributed to drafting the introduction, presenting the findings, comprising basic descriptive statistics and qualitative insights for each of the 12 statements, as well as developing the discussion and conclusion of the paper. I also conducted the overall refinement of the manuscript for submission.

Figure 2 provides an overview of the research process, outlining the key milestones from the start of the PhD in June 2022, including the conducted studies and the development of the papers integrated into this licentiate thesis.

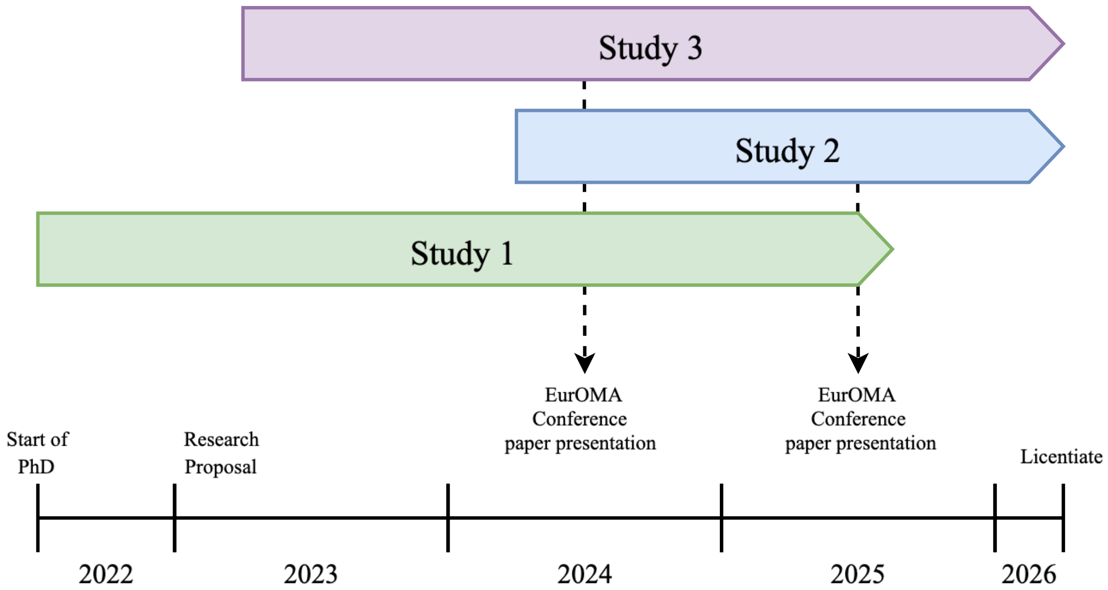

Figure 2. Research process timeline and milestones

Overall, the three studies together support the findings and discussion presented in this thesis. Study 1 provided a comprehensive academic groundwork by synthesising existing knowledge on circular EV battery supply chains and identifying key gaps in the literature. These insights informed the design of Study 2, including the development of a focused interview guide, and the formulation of statements employed in Study 3. Study 2 offered a practice-oriented perspective by identifying how industrial actors currently design and manage EV battery supply chains, including their approaches to prepare for future battery demand and handle used batteries within circular flows. It also identified factors practitioners consider critical for future developments to circular EV battery supply chain structures. Finally, Study 3 provided an expert-based outlook on likely future supply chain scenarios, with observed areas of consensus and divergence strengthening the overall analysis and supporting the development of a map of likely future supply chain structures for circular EV batteries. Together, the three studies provide an integrated academic and empirical perspective for the findings and discussions in this licentiate thesis.

3.2 Research design

The research conducted in this thesis adopted an exploratory and descriptive qualitative design, which was well suited to investigating an emerging and rapidly evolving phenomenon such as circular EV battery supply chains. The circularity of EV batteries constitutes a multifaceted and insufficiently understood area, characterised by evolving actors, roles and activities influenced by technological, regulatory changes and market uncertainties. Under such conditions, qualitative methods were particularly appropriate, as they enabled in-depth examination of processes, meanings and interactions that are difficult to capture through quantitative methods (Bryman and Bell, 2015).

The exploratory nature of the research reflected the fragmented state of prior knowledge and the lack of established theoretical frameworks in the field of CSC, especially in the context of EV batteries. Exploratory research is valuable when concepts are still evolving, and industry practices are not yet established (Saunders et al., 2019; Stebbins, 2001). In this thesis, exploration facilitated the identification of emerging themes and supported the development of new perspectives on how circular supply chain structures were understood, designed, and anticipated by different actors.

At the same time, the research fulfilled a descriptive purpose by systematically capturing the current state of knowledge and practice. Descriptive qualitative research contributes by detailing key characteristics of a phenomenon and identifying patterns that support concept formation (Creswell, 2014). In this thesis, description was central to outlining how circular EV battery supply chains were discussed in the literature (Study 1), documenting existing actors, activities and flows in industry practice (Study 2) and synthesising expert perspectives on future developments (Study 3). These descriptive insights provided an essential empirical foundation that contextualised and strengthened the exploratory findings.

A qualitative approach was particularly suitable for achieving the purpose of this thesis, as it enabled an in-depth understanding of how actors interpreted their roles, made decisions and interacted within a specific context (Bryman and Bell, 2015). Understanding how circular EV battery supply chain structures emerge and exploring likely future scenarios required methods that preserved contextual importance and allowed for inductive and interpretative analysis. Although this thesis did not aim to test causal relationships, it offered interpretative explanations of why certain structures or future pathways appeared more likely than others, therefore contributing to advancing knowledge in this evolving field.

The thesis comprised three qualitative studies, which together formed an iterative and cumulative research design. Study 1 established a theoretical foundation through an SLR, synthesising existing knowledge and identifying research gaps. Study 2 employed semi-structured interviews to identify current industrial practices and a future view of circular EV battery supply chains, enabling inductive theme development. Study 3 focused the analysis on future-oriented perspectives through a Delphi study, drawing on expert reasoning and identifying areas of consensus and divergence. This multi-method qualitative design reflected the value of method triangulation, enhancing the credibility and depth of the findings (Saunders et al., 2019). Figure 3 provides an overview of the studies and papers connecting them to the research questions and research purpose.

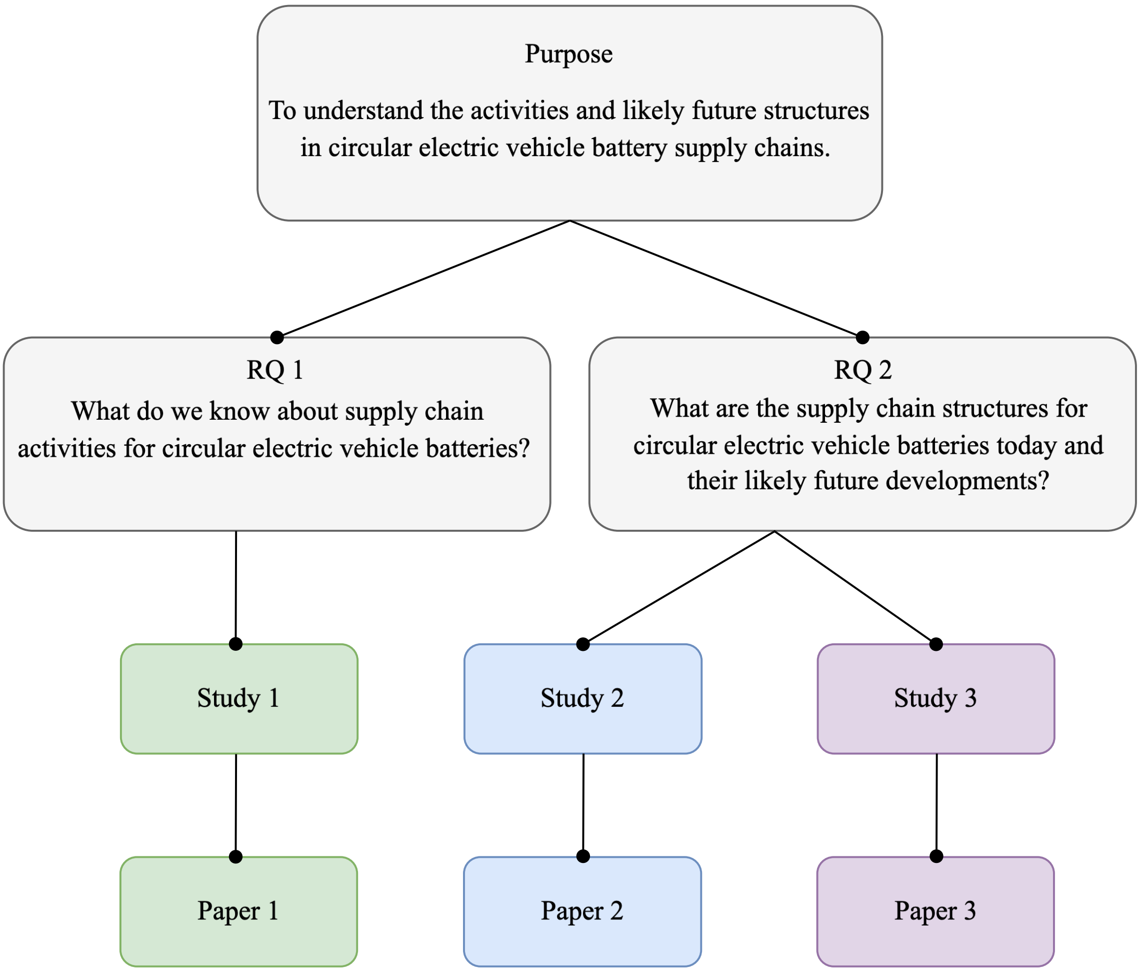

Figure 3. Overview of research purpose, research questions, studies and papers

In summary, the exploratory-descriptive qualitative research design adopted in this thesis was well aligned with the developmental stage of circular EV battery supply chains. It offered the methodological flexibility required to investigate a complex and evolving phenomenon, supported detailed descriptions of current and likely future supply chain structures, and enabled the development of interpretative insights that contributed to a deeper understanding of circular EV battery flows.

3.3 Methods and studies

This thesis is based on three studies: (1) a SLR synthesising supply chain activities of circular EV batteries, (2) an interview study identifying current supply chain structures, actors, activities and flows, and (3) a Delphi study exploring likely future scenarios for circular EV battery supply chains. The following subsections 3.3.1 Study 1: Systematic Literature Review (SLR), 3.3.2 Study 2: Interview Study and 3.3.3 Study 3: Delphi Study describe the data collection and analysis procedures for each study.

3.3.1 Study 1: Systematic Literature Review (SLR)

Study 1 addressed the first research question of this thesis by synthesising the current state of knowledge on supply chain activities for circular EV batteries. Although circularity in EV batteries is becoming increasingly important, there is still limited understanding of the supply chain activities that support the circularity of EV batteries once they are retired from vehicles. Prior research has extensively addressed the technical aspects of battery reuse and recycling, as well as the development of circular business models. However, studies that examine EV battery circularity from a supply chain perspective, covering collection, testing, sorting, remanufacturing, repurposing, and recycling, remain scarce. Existing knowledge is fragmented and dispersed across multiple disciplines, which constrains an integrated understanding of how circular EV battery supply chains can be structured, coordinated and managed. Much of the existing work addresses individual stages or activities in isolation, rather than taking a holistic view of how supply chain activities and processes interact to enable circular flows. As a result, key challenges such as insufficient collection volumes, insecure access to used batteries and inefficient repurposing and recycling pathways remain unsolved. This fragmentation underscores the need for a systematic integration and synthesis of supply chain-focused research on EV batteries for reuse, repurposing and recycling. Therefore, the purpose of this paper constituted as 1) to systematically review and analyse how supply chain aspects related to the circular performance of EV batteries, considering reuse, repurposing and recycling, are discussed in the literature; and 2) to identify key knowledge gaps and priority areas for future research on circular EV battery supply chains.

Data collection and analysis

A systematic literature review (SLR) was adopted to achieve the purpose of this paper. An SLR is a structured and transparent method that involves systematically searching relevant studies in reliable databases, critically assessing their contributions, synthesising insights and deriving reasonable conclusions (Denyer and Tranfield, 2009). Beyond summarising prior research, this method enables the identification of prevailing themes, trends and gaps in the literature (Grant and Booth, 2009). To ensure methodological rigour and transparency, the review followed the established procedures defined by Tranfield et al. (2003) and Durach et al. (2017). The process followed a systematic six-step structure comprising the development of a theoretical framework, definition of inclusion and exclusion criteria, retrieval and reduction of the literature sample, synthesis of findings and reporting of results.

The theoretical framework for this study was developed to guide the systematic search, retrieval, selection and categorisation of relevant papers. The framework was designed as a two-dimensional matrix, with one dimension addressing supply chain aspects and the other battery performance aspects, enabling a structured approach for comprehensive classification of the literature. The supply chain dimension was grounded in established research on SCM, encompassing processes and activities, flows, technologies and systems, and actors, following the categorisation of Fabbe-Costes and Jahre (2008). The battery performance dimension was developed to reflect the key outcomes of circularity relevant to this study. It was built on the three-dimensional performance measurement proposed by Boyer et al. (2021), comprising material recirculation, utilisation and endurance. Economic and environmental impacts were additionally considered as critical performance outcomes.

The *data collection* was conducted through a systematic search of the Scopus and Web of Science databases, focusing on peer-reviewed journal articles published in English. A comprehensive search string combining the terms "EV battery" and "circular economy" was applied, without including "supply chain" in the search string to avoid excluding relevant studies that implicitly discuss supply chain aspects. Given the emerging nature of the topic, no publication year restrictions were applied. The initial search provided a list of 564 papers that were assessed for relevance based on predefined inclusion and exclusion criteria. After the first screening process, 294 papers were reviewed in full text, of which 119 were retained for final analysis. These papers were classified according to the theoretical framework, linking supply chain and battery performance aspects. Disagreements in classification were resolved through collective review and consensus among the research team. Papers not meeting predefined eligibility and quality standards (Tranfield et al., 2003; Seuring and Gold, 2012) were subsequently excluded.

The *data analysis* was carried out through a content analysis that was performed in parallel with the full-text screening stage. For each paper, detailed notes were made and recorded in a structured database to support consistent classification and synthesis of findings. All 294 papers were read in full and examined to identify findings relevant to the aim of the study. The analysis focused on assessing how they addressed the supply chain and battery performance aspects defined in the theoretical framework, and whether relationships between these aspects were discussed. A framework matrix developed in Microsoft Excel was used to document these connections, enabling a consistent comparison across studies. The main insights from each paper were summarised in dedicated Word documents, which facilitated the refinement of the analysis and supported the development of a coherent narrative for presenting the results, discussion and conclusions. Combining qualitative content analysis with structured data extraction enabled an in-depth understanding of how supply chain and battery performance aspects are addressed in the literature and a comprehensive overview of the existing patterns, research gaps and priority areas for future research. Figure 4 summarises the systematic selection process of the study.

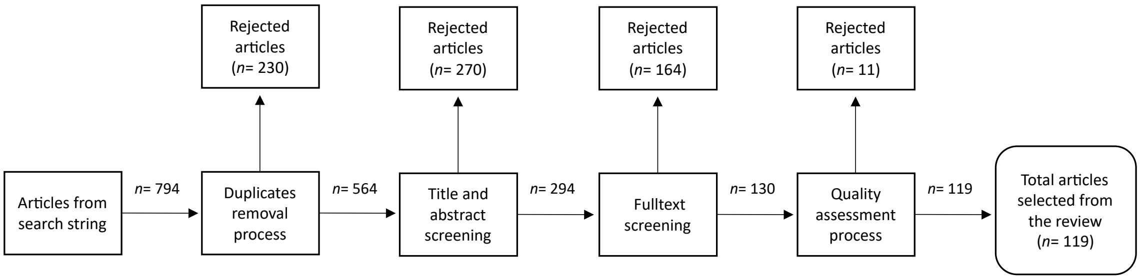

Figure 4. Summary diagram of the selection process

3.3.2 Study 2: Interview Study

Study 2 addressed the second research question of this thesis by identifying current supply chain structures and logistics services for circular EV batteries, considering involved actors, activities and flows. Although understanding individual supply chain activities is an important foundation, achieving circularity requires a more holistic perspective on how actors, activities and flows are integrated into coherent supply chain structures. Existing literature reveals a critical knowledge gap regarding which actors are currently involved in circular EV battery supply chains, the distribution of roles and responsibilities among them, and the coordination of activities across reuse, repurposing and recycling pathways. Moreover, the inherent complexity of circular EV battery supply chains highlights the need for coordinated structures that can support multiple circular flows, for which empirical insights into how these structures are configured and operated in practice remain limited. This lack of empirically grounded understanding hinders the identification of inefficiencies, bottlenecks and coordination challenges, and constrains assessments of how supply chains can be structured to manage the increasing volume of used batteries and comply with emerging regulatory requirements. Therefore, the purpose of this paper constituted as 1) to identify current actors, activities, and flows within circular EV battery supply chains; and 2) to provide empirical evidence on how supply chain structures and logistics services facilitate EV battery reuse, repurposing and recycling.

Data collection and analysis

Semi-structured interviews were adopted as the primary data collection method of this paper, as they offer a structured yet flexible approach that is well-suited to investigating complex and evolving phenomena, allowing rich and contextual insights to emerge (Bell et al., 2019). By enabling participants to articulate their own perspectives and interpretations, semi-structured interviews facilitate gathering insights into practices, behaviours and issues they consider most relevant, therefore supporting an in-depth understanding of underlying patterns and phenomena (Bell et al., 2019). These industry-focused insights are particularly valuable for examining how circular supply chains operate in real-world settings (Chirumalla et al., 2024).

The *data collection* was conducted through purposive sampling (Flick, 2014), applied iteratively to select interviewees representing the actors currently engaged in the circular EV battery supply chain. The sample included OEMs, energy solution providers, recyclers and various BSPs responsible for activities such as collection, sorting, dismantling, module assembly, repair and resale. Semi-structured interviews were carried out between April 2023 and November 2024, resulting in a total of 14 interviews with representatives from the EV battery supply chain (see Table 1). An interview guide was developed to ensure consistency while retaining flexibility, covering questions about the actors' involvement in after-first-life use EV battery processes, their expected roles, activities, coordination of information and material flows in their respective organisations, and expectations regarding the future developments of circular EV battery supply chains. Most interviews were conducted and recorded online via Microsoft Teams or Zoom, with one on-site interview at the company, documented through detailed field notes. All recorded interviews were transcribed with the informed consent of participants.

Table 1. Details of the interviews in Study 2

#	Interviewee Code	Actor type	Industry	Country	Focus on the SC
1	BSP1	BSP	Recycler	Sweden	Recycling
2	OEM1	OEM	Automotive industry	Sweden	Production
3	C1	Customer	Energy Solution Provider	Finland	Repurposing
4	C2	Customer	Energy Solution Provider	Sweden	Repurposing
5	S1	Supplier	Supplier of retired batteries	Sweden	Reselling
6	BSP2	BSP	Refurbished battery	Sweden	Repurposing
7	C3	Customer	Charging Solution	Sweden	Repurposing
8	OEM2	OEM	Automotive industry	Sweden	Repurposing
9	OEM3	OEM	Automotive industry	Sweden	Repairing and reuse in the same application
10	C4	Customer	Energy solution provider	Sweden	Repurposing
11	OEM4	OEM	Automotive industry	Sweden	Sorting and refurbishing
12	BSP3	BSP	Battery dismantling	Norway	Collection, sorting, dismantling, reuse, recycling
13	BSP4	BSP	Logistics provider for used battery	Belgium	Work with production scrap and almost all the activities from the SC
14	BSP5	BSP	Battery recycling technology provider	Luxembourg	Dismantling, sorting, cleaning, refurbishing

The *data analysis* was performed through a structured qualitative coding process using NVivo 15 (Jackson and Bazeley, 2019), with Microsoft Excel used to support further synthesis and comparison. A provisional coding approach was adopted, initiated with a set of predefined codes aligned with the study´s focus, including actors, activities and structures, while allowing additional categories and subcategories to emerge inductively from the empirical data (Miles et al., 2014). The coding scheme was continuously refined as new themes were identified, revised or merged (Idem). To enhance reliability and reduce bias, two PhD students independently coded the interview transcripts and engaged in regular meetings to discuss divergences and align interpretations of the data. In addition, one PhD student (licentiate thesis author) focused primarily on supply chain aspects and another on logistics perspectives, after which the coded results were then integrated to provide a comprehensive analytical perspective.

3.3.3 Study 3: Delphi Study

Study 3 also addressed the second research question of this thesis by investigating likely future supply chain scenarios and developments for circular EV batteries. Understanding current supply chain structures for circular EV batteries is a necessary foundation, but it is insufficient for guiding long-term strategic decision-making in a dynamic and uncertain context. While existing research has largely focused on technical aspects, little is known about how circular EV battery supply chains may evolve in practice or which pathways are likely to dominate under diverse conditions such as regulatory change, resource scarcity and changes in ownership and control. Furthermore, there is a limited insight into how industry actors anticipate future supply chain configurations or how competing interests may define alternative circular pathways. As a result, responsibilities among actors remain unclear, and multiple, potentially conflicting, after-first-use scenarios for EV batteries are possible. This lack of future-oriented, system-level understanding constrains the development of shared visions and coordinated strategies for circular EV battery ecosystems. To address this gap, the purpose of this paper constituted as 1) to outline likely future supply chain scenarios for after-first-use EV batteries; and 2) to identify concurrences and divergences in actors' perspectives regarding collection, reuse, repurposing and recycling pathways.

Data collection and analysis

A Delphi-based study was adopted in this paper as a structured research method designed to facilitate systematic expert discussions and explore consensus and divergence on complex topics and uncertain issues (Gnatzy et al., 2011; Beiderbeck et al., 2021). Although achieving consensus or a single answer is not the primary objective (Gupta and Clarke, 1996), the method is particularly valuable for generating in-depth insights from diverse expert perspectives, identifying alternative viewpoints and directions for future investigation (Shanteau, 2015; Huscroft et al., 2013). Recent research increasingly adopted Delphi-based studies in logistics and supply chain contexts to investigate long-term developments, risks, sustainability challenges, and reverse logistics (Von der Gracht and Darkow, 2010; Huscroft et al., 2013; Kwak et al., 2018; Altuntas Vural et al., 2020; Münch et al., 2021; Meyer et al., 2022), underscoring the method's relevance and robustness in this domain. Therefore, this method was well-suited to investigate an emerging phenomenon characterised by uncertainty and limited empirical knowledge, such as circular EV battery supply chains.

The *data collection* for this study was conducted following the structured three-phase Delphi framework comprising preparation, conducting and analysis, as outlined by Münch et al. (2021). The preparation stage began with a series of collaborative brainstorming sessions among the research team to define the study´s objectives and establish its overall scope. After that, it was conducted desk-based research on industry initiatives and plans related to circular EV batteries, supplemented by insights from the SLR on circular EV battery supply chains. This groundwork was complemented by seven exploratory interviews with industry experts engaged in after-first-life EV battery activities, consistent with recommended preparation steps for Delphi studies (Beiderbeck et al., 2021). Insights from the desk research and interviews were discussed in several research team workshops and used to formulate an initial set of possible future-oriented projections. A pre-test both internally and with four industry experts was conducted, resulting in a final set of 12 Delphi statements representing likely future scenarios for circular EV battery supply chains.

The execution phase involved an online, real-time Delphi survey conducted via SurveyLet, which enabled anonymous interaction and exchange of opinions among participating experts regarding the 12 Delphi statements. Respondents represented key stakeholder groups within the EV battery supply chain, including vehicle OEMs, collectors, vehicle insurance, BSPs, second-life application providers, dismantlers and recyclers. Experts were selected based on predefined criteria, including their organisational role, direct involvement in battery-related decision-making, and relevant professional experience, to ensure field expertise (Mauksch et al., 2020). In total, 87 experts were invited to participate, of whom 32 completed the survey, corresponding to a response rate of 36.8%. The expert panel comprised respondents from across Europe, including EU member states and Nordic countries. Each scenario was evaluated in terms of the expected timeframe for becoming a commonly adopted solution, if at all (Förster, 2015; Meyer et al., 2022) and its potential impact on the expert's organisation. Experts indicated the expected timeframe using a scale ranging from 0 to 100 years, where 100 represented "never", and assessed organisational impact using a five-point Likert scale. Participants also self-rated their confidence in each response on a five-point Likert scale; responses with low self-rated confidence were excluded from subsequent analyses to enhance data reliability (Förster, 2015; Meyer et al., 2022). In addition to these quantitative assessments, experts were encouraged to provide qualitative comments on both timeframe and impact evaluations to explain their reasoning. The survey also gathered expert perspectives on driving and restraining forces influencing the uptake of reuse, second-life and recycling of EV batteries within their organisations by 2030 and 2050.

The *data analysis* was conducted using a combination of quantitative and qualitative techniques to identify measurable response patterns and underlying expert reasoning. The analysis began with descriptive statistics to examine response distributions for each scenario. Expected timeframes for scenarios becoming common solutions were analysed as a numeric variable and grouped into intervals (0 years = now; 1-5 years = near-term; 6-10 years = medium-term; 11-25 years = long-term; >25 years = very long-term; 100 years = never) to facilitate interpretation. Perceived organisational impact was assessed using relative frequency distributions on a five-point Likert scale ranging from strongly negative to strongly positive. Self-rated confidence was summarised using means and standard deviations.

Subsequently, qualitative data consisting of 376 expert comments were examined using content analysis methods (Beiderbeck et al., 2021; Förster and Gracht, 2014). The qualitative analysis focused on identifying drivers, barriers and challenges influencing the likelihood and perceived impact of each scenario. Furthermore, expert insights on driving and restraining forces by 2030 and 2050 were synthesised across political and regulatory, economic, social-cultural, and technological dimensions. By integrating quantitative indicators with qualitative insights, the analysis offered a comprehensive and holistic view of likely future developments in circular EV battery supply chains, while accounting for diverse expert perspectives rather than focusing on individual stakeholder groups.

3.4 Research Quality

The quality of this qualitative research was assessed using the concept of trustworthiness as proposed by Lincoln and Guba (1985), which comprises credibility, transferability, dependability and confirmability. Given the focus of this thesis, these dimensions were applied in line with the adaptation suggested by Halldórsson and Aastrup (2003), who argue they are particularly suitable for qualitative research on logistics and supply chains. Therefore, these four dimensions provide a structure for assessing the rigour, transparency and reliability of this research.

3.4.1 Credibility

Credibility refers to the extent to which a study's findings are recognised as accurate and trustworthy within the research context and by the participants involved (Bell et al., 2019). It reflects confidence in the truth value of the findings and is commonly understood as a criterion assessing the "value of the truth" (Halldórsson and Aastrup, 2003). Credibility is achieved through rigorous methodological design and execution, which enhances the reliability and trustworthiness of the research outcomes.

Credibility in this thesis was established through the use of multiple data sources and carefully designed procedures for data collection and analysis. Clear and transparent reporting of methodological decisions and analytical processes ensured that the findings reflect participants' perspectives rather than researcher bias, thereby strengthening confidence in the results (Bell et al., 2019). Accordingly, credibility was primarily achieved through methodological rigour, transparency, and triangulation, rather than through participant validation alone.

In Study 1, credibility was supported by the application of established SLR methodology (Durach et al., 2017; Tranfield et al., 2003). Clearly defined inclusion and exclusion criteria reduced the risk of selection bias, while a structured analytical framework linking supply chain aspects with battery performance dimensions ensured consistency in data extraction and interpretation. Credibility was further strengthened through collective review within the research team, where differing interpretations were discussed and resolved through consensus, therefore reducing individual researcher bias. In Study 2, credibility was enhanced through in-depth engagement with experienced industry actors directly involved in circular EV battery supply chains. Semi-structured interviews enabled participants to express their perspectives in detail while ensuring systematic coverage of key themes relevant to the research objectives. The use of audio recordings, transcription, and field notes supported accurate data capture and faithful representation of participants' perspectives. In addition, structured coding using NVivo, combined with investigator triangulation, where two PhD students independently coded the data and aligned interpretations through discussion, helped to limit subjective bias.

In Study 3, credibility was established through the careful selection of EV battery supply chain experts and the application of a structured three-phase Delphi framework (Münch et al., 2021). Anonymity supported independent expert reasoning, while internal and external pre-testing of Delphi statements reduced ambiguity and improved clarity. The combination of qualitative reasoning with quantitative measures further strengthened the credibility of the findings. Throughout the thesis, credibility was reinforced through triangulation across methods (SLR, interviews and Delphi study), a coherent analytical focus on actors, activities and flows, and progressive validation across literature, empirical data, and expert perspectives. Consequently, the findings of this thesis are not dependent on a single data source or method, substantially enhancing confidence in their truth value.

3.4.2 Transferability

Transferability refers to the extent to which the findings of a study can be applied beyond the specific context in which the research was conducted (Bell et al., 2019; Miles et al., 2020). It concerns whether insights derived from one setting can contribute to understanding similar phenomena in other contexts. Important aspects influencing transferability include the richness of contextual description, the diversity and relevance of sampling, the researcher's reflexivity regarding their influence on the research process, and systematic comparison of findings with existing literature (Bell et al., 2019).

This thesis focused on a specific phenomenon, circular supply chains for EV batteries, and therefore did not aim for universal generalisation across all CSCs. Instead, its findings can be transferred to contexts that exhibit comparable structural, regulatory, and technological characteristics. For instance, it can be applied to other EV battery contexts, such as regions beyond the EU or under alternative ownership models, as well as to related supply chains involving industrial batteries, electronics and critical materials.

Transferability was further strengthened through the research design of the thesis. Across the individual studies, this is achieved through systematic synthesis of the literature (Study 1), in-depth empirical description and comparative analysis across diverse actor groups (Study 2) and scenario-based expert assessments encompassing multiple actors' perspectives and national contexts (Study 3). Most importantly, transferability emerges from the integration of these studies, in which insights from the literature, empirical evidence and future-oriented scenarios are linked. This approach enabled the identification of mechanisms and structural patterns that are likely to be relevant beyond the EV battery supply chain setting, particularly for CSCs characterised by high asset value, regulatory complexity and multi-actor coordination.

3.4.3 Dependability

Dependability concerns the consistency, stability, and transparency of the research process over time. In qualitative research, where exact replication is often not possible, dependability focuses on whether the research process is logical, traceable and systematically documented (Halldórsson and Aastrup, 2003). It requires transparent reporting of the research design, data collection procedures, analytical techniques, and underlying assumptions, enabling others to understand how the study was conducted and how conclusions were derived (Bell et al., 2019).

In this thesis, dependability was ensured through systematic documentation of the research design, data collection and analytical procedures in all three studies. In Study 1, dependability was supported by the structured and traceable SLR process, following established procedures (Tranfield et al., 2003; Durach et al., 2017). The six-step review structure (framework development, inclusion and exclusion criteria, retrieval, reduction, synthesis, and reporting) provided a coherent and replicable analytical logic. The stepwise reduction of articles from 564 to 119 was documented and visualised (Figure 4), ensuring transparency in selection decisions. A two-dimensional framework (supply chain and battery performance aspects) maintained consistency in the classification of the reviewed literature, while their structured matrices available in Excel and documented summaries on Words provided an audit trail of this study.

In Study 2, dependability was established through consistent data collection using a semi-structured interview guide that ensured coverage of key topics while allowing for contextual flexibility. The coding structures and analytical procedures were fully documented, enabling the research process to be traced and assessed. In Study 3, dependability was supported through a formalised Delphi research design with defined decision rules and structured analytical procedures. Transparent expert selection criteria, predefined rating scales, and clearly reported quantitative and qualitative results from the online survey enhanced traceability. Therefore, the three studies presented the stability, coherence and traceability of the research process, fulfilling the requirements of dependability in qualitative research.

3.4.4 Confirmability

Confirmability in research quality refers to the extent to which study findings can be independently verified, ensuring that results are free from the researcher's personal biases, values, or theoretical influences (Bell et al., 2019). It reflects the researcher's objectivity while recognising potential limitations that may affect the research process (Halldórsson and Aastrup, 2003). Confirmability emphasises that the researcher acted in good faith, maintaining transparency and accountability throughout the study (Bell et al., 2019).

To ensure confirmability in this thesis, multiple strategies were applied across the three studies to maintain objectivity and minimise research bias. In Study 1, confirmability was supported through a rigorous and transparent SLR process (Durach et al., 2017; Tranfield et al., 2003), ensuring that literature identification, selection and analysis of the papers were guided by clearly defined and reproducible criteria rather than subjective judgment. To further reduce individual bias, papers were classified using a theoretically grounded framework, with disagreements resolved through team consensus.

In Study 2, confirmability was addressed through methodological design choices that limited researcher bias in data collection and analysis. Interviews were conducted by at least three researchers, reducing individual influence during data collection. Data analysis followed a transparent and structured coding process, with two PhD students independently coding the interview transcripts and resolving divergences through regular alignment meetings. In Study 3, confirmability was ensured through a structured and anonymised Delphi design, reducing researcher influence and social desirability bias among participants. The Delphi statements were derived from multiple sources (desk research, exploratory interviews and SLR) rather than solely from the researcher's assumptions. Anonymity helped reduce dominance effects among experts, whereas opportunities for participants to review and revise their inputs before survey closure enhanced traceability to the original empirical material (Bell et al., 2019). Confirmability was further strengthened by integrating qualitative expert comments to contextualise and support interpretations of the quantitative findings.

Overall, confirmability was enhanced through transparent documentation, adherence to established methodological guidelines, and triangulation of researchers and data sources, ensuring that findings were grounded in data and analytical procedures rather than researchers' personal values or theoretical predispositions.

3.4.5 Ethical considerations

Ethical considerations ensured participant confidentiality and research integrity. Participation in the interview and survey of Studies 2 and 3 was voluntary, and informed consent was obtained prior to data collection. Participants were provided clear information about the purpose, scope, and procedures of the research, enabling informed decisions about their participation.

Participant confidentiality was ensured by withholding any identifying information related to individuals and their affiliated organisations. All empirical material, including interview recordings, transcripts, and survey data, was securely stored on protected servers and accessed only by authorised members of the research team. The data were used exclusively for academic purposes and were not disclosed to external parties. Data collection, analysis, and reporting were conducted with attention to accuracy, impartiality and responsible data handling. The findings were reported transparently to faithfully reflect participants' perspectives, thus supporting methodological rigour and the overall trustworthiness of the research (Bell et al., 2019).

4 Summary of the papers

This chapter briefly summarises the three appended papers.

4.1 Paper I

Paper 1 aims to understand the current knowledge and knowledge gaps concerning how supply chains can enable and improve circularity of EV batteries. Given the fragmented literature on EV battery supply chains in a circular context, and the limited understanding of how supply chain aspects influence battery circularity, the following research question was formulated: *How are supply chain perspectives in relation to the circular performance of EV batteries across reuse, second-life, and recycling strategies discussed in the literature?* To address this question, a SLR was conducted to retrieve, select and synthesise the relevant academic studies. A two-dimensional framework was developed to classify the reviewed papers, integrating supply chain and battery performance dimensions. Supply chain aspects were categorised into processes and activities, flows (physical, information and financial), technologies and systems, and actors, while battery performance was assessed across material recirculation, utilisation, and endurance, together with economic and environmental impacts. These dimensions formed a matrix to structure the content analysis of the paper.

The initial search comprised of 794 papers, of which 119 articles were retained after screening criteria. Results were organised according to the five battery performance aspects, each comprising four subsections corresponding to the supply chain aspects. In total, 50 supply chain topics were identified, distributed across recirculation (16), utilisation (11), endurance (7), economic impact (13), and environmental impact (3). The results show that only a few articles were published in journals associated with the supply chain research community, indicating a fragmented knowledge base. Existing studies primarily examine operational, logistical, and strategic challenges associated with battery reuse, repurposing, and recycling, but many relevant topics remain underexplored in the literature.

Seven key research gaps were identified, reflecting both practical relevance and limited scholarly attention. These gaps demonstrate the demand for interdisciplinary research integrating technical, economic, organisational, and policy perspectives. Overall, the findings confirm that the relationship between supply chain aspects and improved EV battery circularity remains insufficiently understood.

4.2 Paper II

Paper 2 identifies the structures of CSCs for EV batteries, together with the logistics services required to facilitate reuse, repurposing, and recycling. Addressing existing gaps in understanding the actors involved in circular battery flows and their specific roles, as well as the importance of creating multiple resource flows by having the logistics as critical connector between CSCs, the following research question was formulated: *How are circular supply chain structures and supporting logistics service systems designed to enable reuse, repurposing, and recycling of EV batteries?* To address this question, empirical data were gathered through semi-structured interviews with current CSC actors, including OEMs, energy solution providers, recyclers, and BSPs, who are responsible for activities such as used battery collection, sorting, dismantling, making modules, repair, and resale. In total, 14 interviews were conducted.

The findings were structured into three main phases describing the circular EV battery supply chains: the collection phase, the treatment phase, and the emergence of new SC and logistics structures resulting from the former two phases. The collection phase includes activities such as battery acquisition, preliminary testing, specialised packaging, and transportation, whereas the treatment phase comprises discharging, diagnosing, testing, sorting, dismantling or disassembling, storage, repair, refurbishment or remanufacturing, and recycling. The results indicate that some actors in the EV battery sector are increasingly assuming new responsibilities within the SC. Moreover, many actors are developing specialised skills and capabilities to meet the demands of battery SCs, while new actors are emerging to consolidate second-life EV batteries through new CSC configurations.

Drawing on the findings, two intertwined CSC structures for EV batteries were identified: an OEM-led and BSP-led SCs. These structures differ in control and ownership of EV batteries or dismantled components, with one led by OEMs and the other coordinated by BSPs. Accordingly, the paper proposes an interconnected CSC structure comprising physical and support supply chains, focusing on enabling circular battery flows. By adopting a multi-actor perspective and incorporating insights from a wide range of members of EV battery supply chains, the study contributes to the literature by advancing understanding of CSC structures and associated logistics services that support reuse, repurposing, and recycling of EV batteries.

4.3 Paper III

Paper 3 aims to outline likely future SC scenarios for EV batteries after their first life in a vehicle. Business uncertainty and the demand for collaboration among multiple supply chain actors create challenges for stakeholders in identifying effective circular pathways and clarifying their roles. Consequently, responsibilities across recycling, second-life applications, and reuse remain unclear, making it challenging to anticipate how circular EV battery supply chains may evolve, and allowing multiple future scenarios to be envisioned.

A Delphi expert survey was conducted to investigate aspects related to collection, reuse, repurposing, and recycling. The survey also examined convergences and divergences in stakeholder perspectives and the impacts of the proposed scenarios. The study followed the systematic Delphi procedure outlined by Münch et al. (2021). Based on desk research, interviews, research team workshops, and pre-testing of projections with experts, 12 scenarios were formulated. Each scenario was grounded in prior literature and expressed as a statement representing a potential future development within a circular EV battery supply chain.

The Delphi study was conducted in an online platform, enabling experts to anonymously share and exchange opinions regarding the 12 statements. Participants included vehicle producers, second-life application providers, dismantlers, and recyclers, with a total of 17 experts. Experts evaluated each scenario in terms of the expected timeframe for widespread adoption, if any, and its potential organisational impact. They also self-rated their confidence and provided comments. Additionally, experts identified driving and restraining forces influencing the adoption of reuse, second-life applications, and recycling by 2030 and 2050. Quantitative data were analysed using statistical measures and presented graphically, while qualitative insights were examined through analysis of expert arguments.

The findings indicate divergent expert views on the future of EV battery supply chains: emerging actors tend to favour second-life applications, whereas other stakeholders prioritise recycling due to concerns over future raw material shortages. Ownership structures are expected to influence pathway selection. Overall, the results highlight the possibilities of circular EV battery transition, and it can support managerial decision-making regarding long-term strategies. The study also underscores the need to reconcile conflicting stakeholder priorities to establish a shared ecosystem vision. The study contributes to a deeper understanding of the short- and long-term perspectives on circular EV battery supply chains shaped by actors' distinct objectives and motivations.

5 Results

This chapter presents the thesis findings in relation to the two research questions formulated in Chapter 1. The results are structured into two main sections 5.1 and 5.2. The first focuses on supply chain activities for circular EV batteries, synthesising the literature from collection to recycling. The second identify current supply chain structures and explore their likely future developments, including circular strategies, battery control and ownership perspectives, market dynamics and the emergence of new actors, and centralised and decentralised models.

5.1 RQ1: Knowledge on supply chain activities for circular EV batteries

This section presents the findings related to the first research question: *What do we know about supply chain activities for circular EV batteries?* Based on Study 1, a comprehensive SLR, it identifies and synthesising the activities that constitute circular EV battery supply chains. The section synthesises the literature on activities, namely collection, testing and diagnosing, sorting, disassembly, remanufacturing for reuse in the vehicle, repurposing and recycling (see Figure 5), highlighting each activity's functional role, associated challenges and its contribution to circular battery flows.

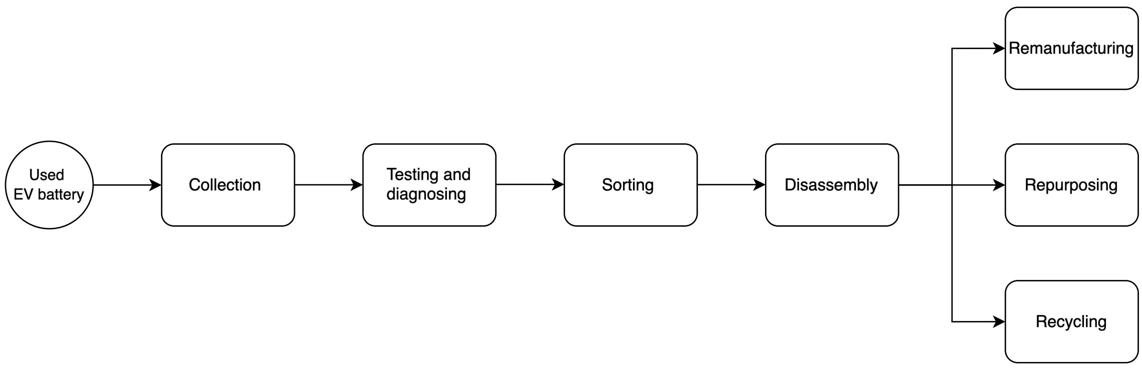

Figure 5. Supply chain activities in a circular EV battery

5.1.1 Collection

Collection constitutes a critical first step in the circular EV battery supply chain, as it enables the recirculation of valuable materials (Kamran et al., 2021). However, several challenges hinder the development of efficient collection systems. These include limitations in current collection infrastructure that reduce profitability and operational efficiency (Rajaeifar et al., 2022), as well as restricted availability of used batteries. Used EV batteries are often not directly accessible from OEMs and must instead be obtained from dispersed actors and locations, complicating the design of effective collection systems (Lee et al., 2021). Establishing optimal reverse logistics network and collection centres remains a significant obstacle (Rajaeifar et al., 2022).

The literature presents different perspectives on the role of battery volume in collection network design. Yan et al. (2024), using a stochastic programming model, demonstrate that while battery volume has a minimal impact on network design, it significantly influences the scale and number of collection locations. In contrast, Wang et al. (2020) argue that battery quantity directly affects network design, along with transportation costs and carbon taxes. These factors are identified as key determinants in optimising logistics networks, influencing both cost and design.

Research highlights the importance of financial mechanisms in enhancing battery collection and recycling efficiencies (Beaudet et al., 2020; Hao et al., 2022; Li et al., 2020, 2019; Zhang et al., 2021). Achieving high collection rates is crucial, as larger volumes can reduce operational costs through economies of scale (Yan et al., 2024; Koroma et al., 2022; Wang and Yu, 2021). Reward-penalty and deposit-refund systems are relevant tools to incentivise battery returns for recycling (Hao et al., 2022). Reward-penalty systems align economic incentives with environmental goals by offering rewards for compliance and penalties for non-compliance (Tang et al., 2019). Their effectiveness depends on policy design and industry maturity (Beaudet et al., 2020; Zhang et al., 2021). Deposit-refund schemes, in which the users pay refundable deposits at purchase, can further enhance collection, especially when trade-in incentives or refund rates are substantial (Hao et al., 2022; Li et al., 2020).

There is an ongoing discussion in the literature regarding centralised versus decentralised collection strategies. Centralised facilities can benefit from economies of scale, while decentralised models seem to offer greater logistical flexibility. Rosenberg et al. (2023) suggest integrating disassembly and recycling operations into shared locations to reduce coordination needs and transport costs. Yazdekhasti et al. (2022) emphasise the importance of geographic proximity between repair and depot centres, noting that closer distances reduce lead times, transport costs and enhance service efficiency for EV battery warranty repairs. Supporting a decentralised approach, Iloeje et al. (2022) claim that small-scale local facilities can increase storage capacity, reduce uncertainty in battery supply and improve facility utilisation.

The strategic placement of facilities near OEMs is also considered advantageous. Sanclemente Crespo et al. (2022) stress that locating battery handling centres close to vehicle manufacturers reduces transport distances, which is especially important given the high cost of moving EOL batteries. Kampker et al. (2023) further support this view, by suggesting that recycling facilities located near OEMs and battery producers can significantly lower overall costs. While proximity to OEMs and battery producers can reduce transport costs, locating collection and sorting centres close to the market can further optimise logistics by enabling the aggregation of higher battery volumes prior to transport (Slattery et al., 2024).

Transportation from collection to dismantling facilities significantly impacts overall costs. Gonzales-Calienes et al. (2022) recommend optimally locating dismantling facilities to minimise transport distances, thereby improving cost efficiency and safety compliance. Transportation expenses are further affected by the logistics challenges of handling large, heavy and hazardous battery materials (Gonzales-Calienes et al., 2022; Rosenberg et al., 2022; Beaudet et al., 2020). In Europe, these challenges are intensified by the limited volume of batteries transported in bulk and by inconsistencies in hazardous material classifications across EU members states, leading to delays and increased costs (Skeete et al., 2020). To address these barriers, the literature suggests international standardisation of shipping regulations and enhanced regional cooperation to streamline cross-border transport while maintaining safety standards (Rajaeifar et al., 2022; Beaudet et al., 2020).

5.1.2 Testing and diagnosing

Accurate diagnosis of EV batteries upon arrival at treatment centres is critical for determining their most appropriate circular pathway, whether reuse, repurposing, or recycling. Kampker et al. (2023) emphasise the benefits of accessing SOH data while the battery is still installed in the vehicle. In practice, however, batteries often arrive without any diagnostic information, creating a major challenge for downstream processes (Kampker et al., 2023).

The absence of pre-removal diagnostics necessitates extensive testing at the treatment facilities, which often represents the most costly phase of the reuse process (Kampker et al., 2023). These testing requirements compromise economic viability and highlight the need for more effective diagnostic protocols. Battery degradation is inevitable and influenced by multiple factors, particularly user behaviour, resulting in high variability in battery condition at EOL (Bräuer et al., 2020; Neubauer and Pesaran, 2011; Neubauer et al., 2015; Wu et al., 2020). Consequently, the unpredictability of battery returns, in both time and condition, creates significant challenges for reuse and repurposing strategies (Geng et al., 2022; Glöser-Chahoud et al., 2021).

Among the drivers of degradation, calendar ageing, particularly under sustained high temperatures, has been identified as a critical factor limiting second-life value (Neubauer et al., 2015). To better address such effects, researchers have increasingly employed advanced diagnostics, statistical models and cell-spread simulations to predict degradation patterns and optimise charging strategies (Galatro et al., 2023).

Building on these efforts, a central focus in the literature is the development of reliable diagnostic methods for SOH evaluation and remaining useful life estimation of retired batteries (Börner et al., 2022; Moore et al., 2020; Ramirez-Meyers et al., 2023). Accurate SOH assessments are essential to ensure that repurposed EV batteries deliver adequate performance and retain functional capacity in their next application (Hu et al., 2022; Iqbal et al., 2023).

A growing debate in the literature concerns the role of SOH in determining the retirement point of EV batteries (Costa et al., 2022; E. Martinez-Laserna et al., 2018). While the conventional use of a fixed SOH threshold of 70-80% to indicate EOL has been widely adopted, several studies argue that this approach is overly rigid and should not be regarded as a universal standard (Börner et al., 2022; Bülow and Meisen, 2023; Etxandi-Santolaya et al., 2023; Egoitz Martinez-Laserna et al., 2018a). Instead, SOH should be evaluated in relation to the requirements of future second-life applications, as varying operational conditions may allow batteries to remain viable at lower SOH levels (Bülow and Meisen, 2023). This perspective highlights the significance of SOH not only as a retirement indicator but also as a determinant of the necessary refurbishment processes, including repairs, upgrades, or conditioning (Idem). However, inconsistencies in the definition and measurement of SOH due to the lack of battery standardisation have led to considerable variability among studies examining battery retirement in both first- and second-life contexts (Al-Alawi et al., 2022). Drawing on 21 studies, Al-Alawi et al. (2022) attribute this variability to the lack of unified evaluation criteria, which maintains uncertainty about whether retired EV batteries can operate efficiently at lower residual SOH levels.

Two primary approaches to SOH diagnostics have been discussed in the literature. The first involves using BMS to collect real-time performance data during battery´s first life (Bordes et al., 2022). This information supports the development of prognostic models that can predict SOH trends based on metrics such as internal resistance, capacity fade, cycle life, temperature and charging behaviour (Alamerew and Brissaud, 2020; Lih et al., 2012; Neubauer et al., 2015; Ramirez-Meyers et al., 2023). When shared effectively, this data can enhance battery second-life planning and reduces reliance on costly in-house testing (Slattery et al., 2024; Neubauer et al., 2015).

The second approach to SOH diagnostics relies on using historical data from battery service life databases to estimate repurposing potential (Zhu et al., 2021). However, the limited availability of high-quality datasets introduces significant uncertainty in SOH estimation, which in turn constrains the industry´s ability to define robust warranties and develop viable battery ownership models (Martinez-Laserna et al., 2018). To mitigate this uncertainty and improve data availability, OEMs could leverage their dealer networks to provide cost-effective battery performance assessments aiming to generate reliable operational data (Ahmadi et al., 2017). Alternatively, recyclers could develop in-house SOH testing at the pack or cell level, enabling accurate diagnostics and supporting improved decision-making for second-life planning (Ahmadi et al., 2017).

5.1.3 Sorting

Sorting EOL EV batteries involves identifying, categorising and separating batteries based on key characteristics such as cathode chemistry, configuration and size (Beghi et al., 2023). This process is critical for forming homogeneous batches, which are essential for both recycling and repurposing operations. Sorting by cathode chemistry, for instance, enhances recycling efficiency by ensuring consistent material composition (Slattery et al., 2024). Without effective sorting, mixed and uncertain waste streams may arise, reducing the purity of recovered materials and increasing operational complexity and costs (Beghi et al., 2023).

The need for sorting derives from the wide variation among EV battery models. Differences in cell chemistry, functional characteristics, cell type, module dimensions, power and capacity, cooling systems, battery management algorithms, communication protocols and packaging (Canals Casals and Amante García, 2016) significantly increase the complexity and duration of sorting and following disassembly.

Standardisation and labelling can further improve sorting efficiency. According to Alamerew and Brissaud (2020), consistent labelling and detailed battery records can streamline sorting, testing and dismantling processes, while facilitating the identification of battery chemistry. Comprehensive labelling methods, such as physical labels, QR codes or RFID tags, potentially integrated with diagnostic systems indicating SOH, can enable the efficient separation of batteries suitable for reuse or repurpose in second-life applications from those intended for recycling (Beghi et al., 2023).

5.1.4 Disassembly

Disassembly is a fundamental activity to facilitate reuse, repurposing and recycling of EV batteries (Canals Casals et al., 2017; Etxandi-Santolaya et al., 2023; Patel et al., 2024). It involves multiple stages, including preprocessing, planning and decision-making and operational execution (Meng et al., 2022). Disassembly is highly sensitive to factors such as cost, safety and processing time (Rajaeifar et al., 2022). Despite its importance, disassembly costs are often neglected in economic assessments (Rosenberg et al., 2022). These costs are affected by battery pack weight and processing volumes (Narang et al., 2023). In some cases, the cost of disassembly alone can surpass half the price of a new battery pack. Moreover, additional costs tied to components like BMS further underline the need for technological improvements to make second-life applications economically competitive (Zhu et al., 2021).

Recent studies highlight the importance of optimising disassembly strategies for battery repurposing by determining appropriate disassembly levels and sequences (Beghi et al., 2023). Commonly, battery packs are dismantled to the module level, tested and reassembled into stationary storage systems (Kampker et al., 2023, 2021). Nonetheless, final testing remains a significant cost driver due to expensive diagnostic equipment and long processing times (Kampker et al., 2023). The development of efficient testing and sorting algorithms is therefore essential for guiding disassembly and refurbishment decisions (Ramirez-Meyers et al., 2023). Studies also indicate that partial disassembly is generally more cost-effective than full disassembly in most use cases (Alfaro-Algaba and Ramirez, 2020), with partial disassembly typically employed for repurposing, whereas full disassembly is more common in recycling contexts (Rosenberg et al., 2022; Alfaro-Algaba & Ramirez, 2020).

Approaches to battery reuse vary in intervention level. Some researchers advocate for direct reuse of entire battery packs without refurbishment or SOH assessment (Laserna et al., 2018; Ambrose et al., 2014, Alfaro-Algaba and Ramirez, 2020). In contrast, others suggest disassembling the packs to recover viable cells, which can then be reconfigured into new battery packs (Ramirez-Meyers et al., 2023). These contrasting approaches reflect the inherent trade-offs between cost-effectiveness, safety assurance and overall system performance. One factor underlying the preference for full-pack reuse is the technical challenge and risk associated with disassembly, since battery packs are by design glued or welded together, making the process costly, labour-intensive and subject to damaging cells. These limitations highlight the importance of Design for Disassembly (DfD), which directly addresses such barriers by enabling safer and easier dismantling (Meng et al., 2022).

DfD is considered as a strategic enabler of circularity (Sanclemente Crespo et al., 2022). Its core principles advocate for modular construction and the prioritisation of easy component separation to streamline disassembly (Meng et al., 2022). Recommended design practices in the literature include replacing permanent bonding methods such as adhesives and welding, with reversible mechanical fasteners like screws and plug connectors (Bordes et al., 2022). Further suggestions involve standardising screw heads, eliminating the use of adhesives and integrating QR codes that provide disassembly instructions (Rosenberg et al., 2022). Additionally, AI-powered eco-design tools are being employed to predict disassembly performance and support modular design decisions in battery systems (Meng et al., 2022).

Beyond technical challenges, additional barriers constrain the efficiency of battery disassembly, including the absence of standardised diagnostic protocols and the high variability of returned battery, which hinder scalability (Zhu et al., 2021; Glöser-Chahoud et al., 2021). Moreover, the continued reliance on manual disassembly remains costly and labour-intensive, highlighting the limited adoption of automation. Accordingly, automation is increasingly recognised as a prerequisite for commercial viability (Canals Casals and Amante García, 2016), with current research emphasising human-robot collaboration, AI integration and process optimisation as important enablers (Kay et al., 2022; Rosenberg et al., 2022; Villagrossi and Dinon, 2023; Beghi et al., 2023; Meng et al., 2022).

Emerging research highlights the potential of human-robot collaboration, AI and virtual reality (VR) to improve safety, flexibility and efficiency of disassembly operations (Kay et al., 2022; Rosenberg et al., 2022; Villagrossi and Dinon, 2023; Beghi et al., 2023; Meng et al., 2022). Human-robot collaboration facilitates shared perception, learning and decision-making, thereby supporting adaptative and productive workflows (Meng et al., 2022; Kay et al., 2022; Villagrossi and Dinon, 2023; Beghi et al., 2023). In parallel, AI and machine learning (ML) technologies can be applied throughout the disassembly process, from component identification using RFID tags, QR codes and computer vision to planning through grapy theory, metaheuristics and deep learning, as well as real-time operational adjustments (Meng et al., 2022; Bordes et al., 2022; Beghi et al., 2023; Choux et al., 2021). Additionally, AI-enabled teleoperation and intelligent tool switching offer improvements in both safety and adaptability (Meng et al., 2022).

Nevertheless, the widespread implementation of automated disassembly continues to be restricted by persistent challenges, including high design variability of batteries, limited access to historical battery data and the inherent technical complexity of robotic manipulation (Faessler, 2021; Meng et al., 2022; Hu et al., 2022). Addressing these limitations necessitates the active involvement of OEMs, whose expertise in battery architecture and access to lifecycle data can support the development of standardised and efficient disassembly systems (Rosenberg et al., 2022; Glöser-Chahoud et al., 2021).

5.1.5 Remanufacturing

Following battery collection up to disassembly, the subsequent activity depends on the battery´s condition and its potential for further use. In the context of a circular supply chain, the reuse of battery components, based on their SOH, is suggested as the most cost-effective and environmentally recovery option (Baazouzi et al., 2023). However, direct reuse of entire EV batteries is frequently impractical due to technological incompatibilities with new vehicle systems and associated safety concerns (Huster et al., 2022). Instead, battery components undergo maintenance, repair, upgrading, and refurbishment (Chirumalla et al., 2024).

Given these limitations, remanufacturing is proposed as an alternative to extend battery utilisation (Koh et al., 2021). The literature highlights several critical factors influencing the feasibility of remanufacturing EV batteries, including economic viability, production capacity, supply and demand dynamics, battery return rates and quality, operational strategies and policy incentives (Li et al., 2018; Gu et al., 2018). Among these, the quality and volume of returned batteries are particularly critical. Gu et al. (2018) emphasise that higher return rates and better battery quality significantly enhance remanufacturing profitability, especially when supported by government incentives. Similarly, Zhu et al. (2021) suggest that re-evaluating SOH thresholds for battery retirement could improve the alignment between the supply of used batteries and remanufacturing demand.

Several studies also stress that remanufacturing can reduce reliance on new battery production while offering profitability gains (Li et al., 2018; Huster et al., 2022; Zhang and Zhang, 2022). Nevertheless, profitability remains sensitive to factors such as transportation and processing costs, as well as the volume and quality of returned batteries (Li et al., 2018; Li et al., 2021). For instance, Li et al. (2021) demonstrate that high-quality returned batteries improve remanufacturing outcomes, with a single selling model outperforming a leasing model in both quality and profitability. Their findings suggest that when returned battery quality is significantly higher, the selling model enables firms to maximise profits by selling new batteries in the first period and remanufactured ones in a subsequent period. While higher return quality may slightly reduce demand for new batteries, it concurrently increases consumer acceptance of remanufactured batteries (Li et al., 2021). Enhancing customer confidence through robust warranties and pricing incentives can further strengthen the competitiveness of remanufactured batteries (Huster et al., 2022).

In this context, refurbishment is often treated as a specific pathway within or closely related to remanufacturing. Refurbishment generally involves inspection, repair, replacement of faulty cells and reassembly of packs to restore used batteries to a functional condition for either continued in their first-life application use or as second-life stationary applications (Ramirez-Meyers et al., 2023; Chirumalla et al., 2024). Nonetheless, the scope of refurbishment remains contested in the literature.

5.1.6 Repurposing

Used batteries that are no longer suitable for their original purpose can be repurposed for less demanding applications such as stationary energy storage for renewable energy, fast-charging stations and grid stabilisation (Kamath et al., 2020; Huo et al., 2021; Shahjalal et al., 2022). According to Heymans et al. (2014), second-life applications have the potential to enhance battery utilisation, reduce resource consumption and environmental impact, and lower costs.

The absence of standardised global and regional policies represents a critical barrier to the development of second-life battery markets (Börner et al., 2022; Lee et al., 2021). Furthermore, Moore et al. (2020) argue that the prevailing regulatory emphasis on recycling may unintentionally restrict circular economy strategies by limiting opportunities for the secondary use of EV batteries that retain significant capacity and value after their initial use. Hence, regulatory advancements are urgently required at both national and international levels, with a specific focus on the standardisation, transferability and effective management of EV batteries to support the growth of second-life markets (Faessler, 2021).

An important topic addressed in the literature is the challenge of effective information sharing to support battery repurposing. Nasari et al. (2023) argue that legislation is required to standardise what data should be shared, how it should be accessed and who is authorised to use it, particularly given concerns over proprietary battery data and trade secrets, which discourage stakeholders from disclosing critical information.

Effective information sharing is essential for the successful repurposing of EV batteries, directly influencing both supply chain efficiency and economic viability (Bräuer et al., 2020; Zhao et al., 2022). Accordingly, Bräuer et al. (2020) propose five key design principles for information systems in this context: (1) comprehensive data management, including import, storage, processing and distribution; (2) facilitate decision-making for repurposing; (3) access to second-life battery data and related services; (4) analysis and dissemination of data from second-life applications; and (5) transparent reporting throughout the repurposing process.

Various information systems and tools have been explored in the literature to address these requirements. Business intelligence (BI) systems, for example, can consolidate data across the battery lifecycle, integrating first- and second-life usage with application-specific requirements (Bräuer et al., 2020). BI-generated reports can be tailored to the needs of stakeholders, such as OEMs, to enhance regulatory compliance and optimise battery design for second-life applications (Idem).

Digital twin technology has also been proposed as a means to continuously assess and predict battery SOH, enabling stakeholders to forecast battery availability and economic feasibility of various second-life applications based on individual battery performance (Naseri et al., 2023). Similarly, IoT technologies such as RFID, BLE and LoRaWAN offer potential for facilitating information sharing, although their effective deployment requires careful alignment with system requirements and technological capabilities (Garrido-Hidalgo et al., 2020).

Blockchain technology is frequently referred to as a promising solution for ensuring data integrity and building trust among EV battery supply chain actors (Bräuer et al., 2020). By providing an immutable record of battery history, blockchain can support informed decision-making in second-life applications (Bräuer et al., 2020). However, Bräuer et al. (2020) emphasise that inaccurate, incomplete or manipulated data entered into the blockchain could undermine trust and propagate misinformation.

Despite the recognised importance of effective information systems for facilitating battery repurposing, empirical studies examining the practical implementation of these tools remain scarce, highlighting the need for further research and validation.

5.1.7 Recycling

Recycling EV batteries can significantly contribute to the long-term supply of critical materials including lithium, cobalt, manganese, nickel, copper and aluminium (Raj et al., 2022), particularly for countries with limited or no domestic reserves (Narang et al., 2023). Recovering these critical metals supports the growth of the EV market in such regions (Narang et al., 2023). Xu et al. (2020) estimate that by 2050, demand for lithium, cobalt and nickel could increase by 18 to 31 times due to the growth of EV battery consumption. European market studies suggest that recycling could meet 20% to 80% of the material demand by 2040-2050, depending on the specific metal (Abdelbaky et al., 2021; Raj et al., 2022; Sanclemente Crespo et al., 2022; Xu et al., 2020) In an even longer-term, a larger proportion of demand is expected to be met through recycling due to increased availability of recovered materials and their decreasing share in EV components (Abdelbaky et al., 2021). However, short-term projections indicate that by 2030, recycling will cover only 5% to 11% of key EV battery material demand, necessitating a substantial expansion of production capacity to meet the future requirements (Kastanaki and Giannis, 2023; Xu et al., 2020).

Lithium scarcity has generated particular concern, emphasising the urgent need for efficient recycling strategies (Kamran et al., 2021). Lähdesmäki et al. (2023) project that recycling alone could reduce global lithium waste by only 30% by 2050, highlighting the need for multiple circular strategies to ensure a sustainable lithium supply. Cobalt presents a similar challenge, which is highly attractive in the recycling market due to its economic value (Baars et al., 2021; Glöser-Chahoud et al., 2021b). To address the material scarcity challenge, EV battery manufacturers are reducing cobalt content in batteries to lowers production costs, which in turn affects recycling economics (Glöser-Chahoud et al., 2021b; Skeete et al., 2020; Wang and Yu, 2021; Zhu et al., 2021). Nickel has been increasingly used as alternative to cobalt in EV batteries, particularly in the European Union, but this substitution may drive substantial nickel demand growth and price volatility (Baars et al., 2021).

A significant challenge in battery recycling is the time lag between emerging EV battery chemistries and the corresponding recycling technologies, with an average delay of four years (Beghi et al., 2023). Current recovery processes primarily focus on high-value metals such as cobalt, while other elements are often lost (Beghi et al., 2023). Closed-loop recycling, where recovered materials are reintegrated into the production of new batteries, facilitates material recirculation within the battery supply chain. This approach can directly reduce the demand for primary raw materials and improve overall battery supply chain efficiency (Beaudet et al., 2020; Xu et al., 2020; Ziemann et al., 2018). Conversely, when recycled cobalt is directed to other industries, it does not contribute to reducing the demand for raw materials in battery manufacturing. To enhance closed-loop recycling, strategies such as battery standardisation, the development of the advanced recycling technologies, financial subsidies to offset high processing costs and the implementation of regulations that specify material-specific recycling targets rather than general recycling rates has been proposed (Xu et al., 2020; Ziemann et al., 2018). Nevertheless, relying entirely on recycled materials in battery manufacturing is impractical due to limitations in quality, materials properties, safety regulations and industry standards, meaning some virgin materials will remain necessary (Rosenberg et al., 2023).

Recycling operations require flexibility to process various battery types and sizes efficiently (Nurdiawati and Agrawal, 2022; Rajaeifar et al., 2022). Conversely, some researchers argue that standardising battery design could improve efficiency by enabling automated recycling systems, though intellectual property concerns make widespread adoption by OEMs unlikely (Dunn et al., 2012; Nurdiawati and Agrawal, 2022; Xu et al., 2020). Despite these differing perspectives, there is consensus that improving EV battery recycling and material recovery depends on product designs that facilitate easy disassembly and separation of materials (Thompson et al., 2020).

In summary, this section clarifies the first research question by synthesising the activities for circular EV battery supply chains. From collection, testing and diagnosing, to sorting, disassembly, remanufacturing, repurposing, and recycling, each activity assumes a distinct role, presents specific challenges, and together drives the circular flow of batteries. This synthesis provides an understanding of how these interconnected processes enable circular EV battery supply chains.

5.2 RQ2: Current supply chain structures and their likely future developments for circular EV batteries

This section presents the findings related to the second research question: *What are the supply chain structures for circular EV batteries today and their likely future developments?* Based on empirical evidence from Studies 2 and 3, it identifies current supply chain structures and explore their likely future developments for circular EV batteries, highlighting areas of convergence and divergence across industry actors.

5.2.1 Current supply chain structures

Based on interviews conducted in Study 2 with actors currently participating in the EV battery supply chain, two intertwined supply chains for circular EV batteries were identified: an OEM-led supply chain and a BSP-led supply chain. Figure 6 illustrates the current SC structures and their sequences. These supply chains are further explained in Sections 5.2.1.1 and 5.2.1.2, which describe the OEM-led and BSP-led supply chains, respectively, to clarify the material flows and actors involved within circular EV battery supply chains.

5.2.1.1 OEM-led supply chain

(1) In the OEM-led supply chain, in the first use of the battery, the supplier is the battery manufacturer, who are usually Chinese battery manufacturers, as indicated in the interviews. **(2)** The end customers are vehicle users. Ownership of the batteries during this phase may be kept with the OEM, through e.g. leasing, or with the customer. In a closed-loop system, batteries are generally returned to the OEM, either directly by **(2a)** customers, or via authorised dealer workshops. However, if the vehicle user owns the battery, they may choose to sell or dispose of it independently. **(3)** In such cases, intermediary actors such as dismantlers, recyclers, insurance companies or independent traders may acquire these retired batteries. **(3a)** These intermediary actors can still facilitate the return of batteries to OEMs.

During the collection phase, considering a supply chain led by the OEM, they acquire used batteries through **(2a)** customers or **(3a)** intermediary actors and **(4)** direct them to their central warehouse or workshop, or **(5)** to a recycling facility. This stage involves supporting activities such as specialised packaging and transportation.

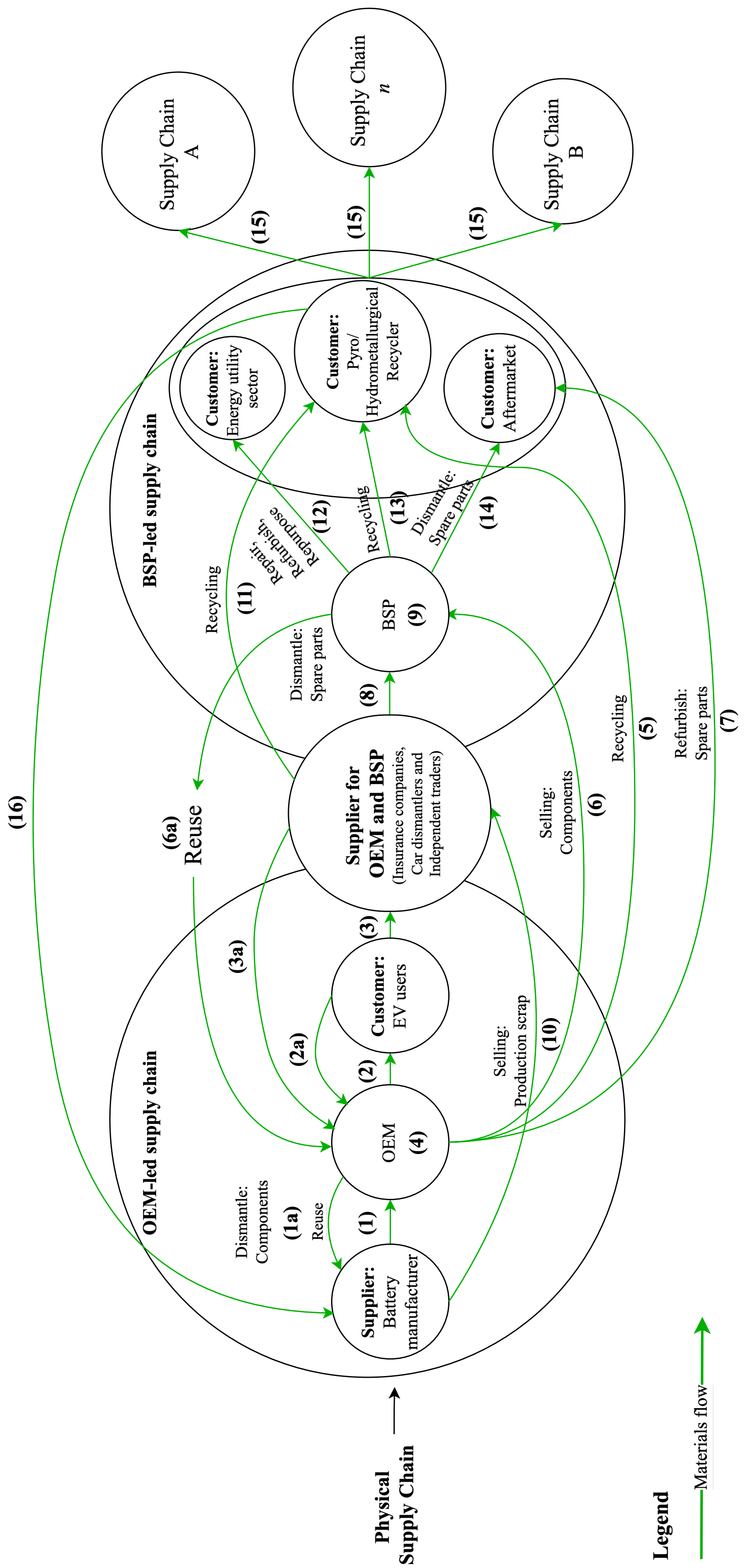

Figure 6. Current SC structures for circular EV batteries

(4) In the treatment phase, processing may be conducted in-house, in an OEM central warehouse or workshop or **(6)** outsourced to BSPs facilities. **(4)** At the OEM's treatment infrastructure, it typically initiates with diagnostics, testing and sorting. Diagnostics include assessing performance parameters such as cell and operational parameters, hardware design, usage history, fault records and SOH. The interviewees state that these data are readily available for batteries from the OEM´s fleet. Testing may be conducted at the pack, module or sub-component level. Based on these assessments, batteries are sorted for various circular strategies. Those in good condition may be **(4)** reused in vehicles or **(1a)** dismantled for component reuse at the battery manufacturer. **(7)** Refurbished batteries can serve as spare parts for older models, **(6)** while specific components may be sold to integrators or repurposers (BSPs), **(11)** serving customers such as energy or charging solution providers. **(5)** Batteries that do not meet performance thresholds for reuse, refurbishment or repurposing are ultimately designated for recycling.

5.2.1.2 BSP-led supply chain

In the BSP-led supply chain, **(6)** BSPs acquire used batteries either from OEMs or **(8)** through intermediary suppliers such as recyclers, insurance companies and independent traders. **(9)** BSPs perform various activities to deliver battery components and materials to their customers, who in this study include **(6a)** OEMs, **(11)** energy utility companies, **(12)** recyclers and **(13)** aftermarket service providers.

(9) The collection of used batteries is managed either through the BSPs or through third-party LSPs contracted by the used battery suppliers. Some BSPs identify as LSPs, given their specialised capabilities in packaging used and damaged batteries, transportation and temporary storage of hazardous products. BSPs may also be responsible for the collection of used batteries from geographically dispersed authorised dealer workshops, in cases such as vehicle recalls. **(8)** Additionally, they may acquire used batteries via independent traders, whose first-tier suppliers include vehicle dismantlers, insurance companies, vehicle owners and **(10)** battery manufacturers handling production scrap. **(11)** These independent traders can also decide to sell used batteries directly to recycling.

(9) Once used batteries arrive at BSP facilities, the treatment phase initiates with discharging, diagnostics, testing and sorting. Diagnostics are usually conducted using their own developed software to assess performance parameters such as battery SOH, as BSPs often receive limited or no data from their suppliers. In certain cases, depending on contractual terms and trust levels with OEMs, BSPs may have access to battery specifications and performance metrics. However, according to the companies interviewed, data such as driving and charging patterns and communication protocols are often treated as confidential and restricted from BSPs.

(9) Testing and sorting are conducted based on the intended circular strategy and customer requirements. Dismantling is executed from the module level or up to the cell level, with one BSP interviewed employing a fully automated system. However, as discussed in Study 1, not all organisations have automated dismantling operations. **(6a)** Following dismantling, batteries may be repaired for reuse in vehicles and, therefore, returned to OEMs. **(9)** Remanufacturing and refurbishment for repurposing (e.g. in energy storage systems) can be carried out in-house or outsourced to BSP´s partners. **(14)** Spare parts are stored for resale and may be reused, **(12)** repurposed for energy storage applications or **(15)** sold for first-application products in an open-loop system. **(14)** These spare parts may also support aftermarket services.

(13) Components and materials unsuitable for reuse or repurposing, after dismantling, may be sold directly for material recycling or before, subjected to pre-treatment recycling processes, such as transformation into black mass, which is usually exported to recyclers in Asia. **(16)** The recycled materials may return to the battery manufacturer for the production of new batteries or **(15)** be used in other supply chains in an open-loop system. **(9)** BSPs often share diagnostic and test results with customers and may disclose battery chemistries to recyclers. However, non-disclosure agreements with OEMs can limit the extent of information sharing. In summary, the structure of BSP-led supply chains is highly dependent on the circular strategies adopted, with flexibility in operations based on contractual relationships, customer needs and available capabilities.

In conclusion, the OEM-led and BSP-led supply chains are deeply interconnected, centred on the circular flow of EV batteries. Within the CSC context, the roles of suppliers, BSPs and customers are dynamic, as batteries may circulate through either closed-loop or open-loop systems depending on ownership models, contractual agreements and circular strategies. This shift in roles reinforces the complexity and interdependence of supply chain actors and uncovers the need for strategic coordination among them.

5.2.2 Likely future developments

This section presents the findings on the likely future developments of circular EV battery supply chains, based primarily on empirical insights from the Delphi study (Study 3) and complemented by interview findings from Study 2. It describes likely developments across circular strategies, including reuse, repurposing and recycling, as well as the influence of battery control and ownership, evolving market dynamics that include the entry of new actors, and the implications of centralised and decentralised collection models.

5.2.2.1 Circular strategies: Reuse, Repurposing and Recycling

Findings from Study 3 indicate that the reuse of batteries in their original applications is expected to become increasingly common over the next five years. This view is supported by 54% of experts, while approximately 20% consider reuse unlikely to be a mainstream solution, and expect it to remain a niche market. Experts further emphasise that greater standardisation in battery design and configuration would substantially facilitate the advancement of reuse. Some experts argue that reusing batteries in vehicles is generally more technically viable than applying them in second-life applications, as it preserves the endurance of the battery serving its originally intended purpose. Conversely, other experts in Study 3 highlight that achieving the necessary quality standards for reuse often involves long lead times, since repair processes remain inefficient and associated risks contribute to higher overall costs. These observations are supported by findings from Study 2, where some BSPs reported significant operational challenges related to battery repair and preparation for reuse. Specifically, BSPs described difficulties in obtaining suitable spare parts required to restore batteries for vehicle reuse. As a result, they frequently source used batteries from which components can be conserved and reused as replacement parts. One BSP explained that some vehicles received from customers remain in storage for extended periods while awaiting these missing components, emphasising the supply and repair constraints that currently limit the full implementation of reuse in the automotive sector. Despite these challenges, some experts in Study 3 view reuse as a potential opportunity for OEMs to generate additional revenue through aftermarket sales. Where reuse is not technically or economically feasible, experts anticipate that repurposing will serve as an alternative strategy to extend battery value and promote circularity within the battery lifecycle.

Considering repurposing, findings from Study 3 indicate that the use of retired batteries in second-life applications is already occurring, as reported by 28% of experts, and is expected to become a common practice within the next five years according to 45% of experts. This scenario is particularly evident in the energy utility sector, where second-life batteries are increasingly being deployed in stationary storage systems and energy trading activities. At this stage, according to the experts in Study 3, production scrap is expected to serve as the primary source of batteries for repurposing, although several actors are already preparing and owning second-life batteries. Complementary insights from Study 2 indicate that used batteries could be repurposed across a diverse range of markets and applications, such as electric bicycles, ferries and other mobility solutions, depending on their format (e.g. cylindrical or rectangular) and performance condition. Additionally, dismantling down to the cell level may enable the reuse of these components in alternative applications, therefore expanding the potential for second-life deployment.

Despite these early developments, experts from both studies note that the limited availability of used batteries currently constrains the economic viability of repurposing. However, experts in Study 3 anticipate that as larger volumes of used batteries become available, various actors are expected to emerge seeking to integrate these batteries into their own products and operations. At the same time, one expert in Study 2 emphasise that the anticipated volume of used batteries will likely exceed demand for second-life ESS, underscoring the need to develop new applications to maintain the economic viability of repurposing in the coming years. The expansion of second-life markets could also create new opportunities for EOL treatment companies to diversify their business activities, secure material streams from multiple sources and foster innovation in product development. Concurrently, these developments are expected to strengthen incentives for maximising and extending battery lifetimes.

Considerable discussion remains regarding the motivations for repurposing batteries and the challenges associated with scaling such practices. Economic factors play a central role, especially the relationship between the market price of used batteries and the value and demand for recycled materials. Some experts in Study 2 indicate that lithium iron phosphate (LFP) batteries are likely to be repurposed first, as recycling technologies for this chemistry remain costly and underdeveloped. Consequently, companies are exploring strategies to extend the operational life of LFP batteries through repurposing, thereby postponing recycling and enhancing resource efficiency. In parallel, Study 3 highlights several regulatory challenges that may constrain the broader implementation of repurposing. Some experts emphasised the lack of clear legislation governing repurposing activities and potential conflicts with existing recycling mandates. While the EU battery regulation is generally supportive of repurposing, experts underline that more explicit and consistent rules for second-life batteries are essential to build customer trust and ensure long-term market stability.

Battery quality has also emerged as a decisive factor for the successful development of the second-life market. Some experts from Study 3 emphasised that batteries with limited remaining cycles or lower energy densities compared to new batteries are generally less attractive for repurposing due to their reduced performance and uncertain liability. Furthermore, factors such as durability, cost efficiency, safety and consumer liability are expected to considerably influence the expansion of the second-life market, particularly if industry expectations regarding performance standards are not adequately met. Some experts also highlight the need for greater industry maturity to establish consistent methods for classifying and characterising used batteries for second-life applications. However, not all batteries are considered appropriate for repurposing, as their condition mostly depends on prior usage and degradation patterns. In such cases, experts suggest that recycling represents a more viable alternative, enabling the recovery of materials for the production of new cells with significantly improved technology.

Recycling was identified by the majority of experts in Study 3 as a key circular strategy expected to expand substantially in the coming years. In Study 3, 48% of experts indicated that recycling will become a common practice within the next five years, while 21% anticipate this occurring within six to ten years. This timeline reflects both the projected increase in returned battery volumes and the limited suitability of many used batteries for second-life applications. Experts further highlighted that the scarcity and rising cost of raw materials will accelerate recycling initiatives, particularly as OEMs are required to meet recycled content targets from 2027 under the new EU battery regulation. Maximising recycling efficiency to recover critical raw materials for new battery production in Europe was regarded by experts in both studies as essential for strengthening the European battery value chain.

Complementary insights from BSPs in Study 2 highlight the need to establish large-scale hydrometallurgical recycling infrastructure in Europe. Currently, limited processing capacity forces most black mass to be exported to Asia, primarily China, and, to a lesser extent, the United States, therefore, losing the economic value of critical material recovery and the strategic benefit of retaining these resources in its supply chain. These BSPs also expressed concern regarding the recycling of LFP batteries, noting that their limited content of high-value materials, such as the absence of cobalt and nickel, makes recycling economically unattractive and costly for producers. Consequently, the future of LFP recycling remains uncertain. Some experts in Study 3 suggested that recyclers are likely to prioritise investment in products that are easier to process, to strengthen integration with cell manufacturers in Europe. Nevertheless, concerns were raised regarding potential increases in recycling costs and the environmental impacts associated with energy and resource consumption. To ensure economic and environmental viability, some experts proposed that the recycling industry should strategically determine which metals to prioritise for recovery.

5.2.2.2 Battery control and ownership perspectives

Before presenting the findings, it is important to clarify how *control and ownership* of used batteries are understood within OEM- and BSP-led supply chains, as perceived by actors participating in Studies 2 and 3. In this thesis, *control* refers to scenarios in which batteries are sold to vehicle users, who become legal owners, while OEMs retain influence over post-use handling through mechanisms such as warranties, deposit systems, or core charges that facilitate battery return. *Ownership,* by contrast, involves models in which OEMs retain legal ownership of batteries, typically through leasing, subscription or battery-as-a-service models. These distinctions are critical, as control and ownership structures also influence decisions regarding battery collection and subsequent treatment processes.

Findings from Study 3 suggest that OEMs are likely to seek greater control over batteries within the next five to ten years, according to 60% of experts, primarily driven by the need to reuse them as spare parts or recycle them for new battery production. A similar perspective emerged in some interviews conducted during Study 2. However, achieving full control remains unlikely for 23% of experts, due to challenges associated with tracking and tracing batteries throughout their lifecycle. Enhanced control would provide OEMs with improved visibility into the availability of used batteries for collection, thereby supporting more effective operational decision-making. Lastly, it is indicated that the potential for OEMs to expand their control over batteries is contingent upon future regulatory frameworks that may incentivise such a position.

Regarding the OEM ownership of the batteries, expert opinions reveal a clear divide. In Study 3, 43% of experts expect this ownership perspective to become common within the next five years, while 37% believe it will never happen. Experts from Study 3 argue that ownership would allow OEMs to determine the optimal time for transitioning batteries into second-life applications, potentially enhancing their business models. Furthermore, interviews from Study 2 indicate that OEMs view ownership as a means to improve customer convenience, operational control and technological optimisation. Experts further noted that OEM battery ownership could support more profitable repair and maintenance terms by providing access to real-time battery performance data, which supports optimised lifecycle management and enhances the efficiency of repair activities.

These developments align with regulatory initiatives such as the Battery Passport and EPR framework. The recent EU battery regulation, which mandates minimum shares of recycled materials in new batteries, will further hold OEMs and battery manufacturers accountable for compliance. Consequently, ensuring access to recycled materials is expected to become a strategic priority. In this context, battery ownership and leasing agreements may also serve as practical future mechanisms for securing the return of batteries and maintaining a stable supply of recycled raw materials for future EU production. Nevertheless, despite these potential advantages, one interviewee pointed to significant legal and financial challenges in implementing this ownership model, particularly at scale.

In parallel, experts from Study 3 indicated that batteries outside by OEM-controlled systems may present acquisition opportunities for independent actors in the market. According to 73% of experts, this practice is already occurring or is expected to become common in a maximum of three years. These independent actors, referred to in this study as BSPs, include dismantlers, recyclers, and companies operating in scrap and secondary materials markets. Their growing interest in used batteries for such as recycling or resale suggests the likely continuation of a parallel supply chain operating outside OEM control, which may contribute to a broader material recovery and redistribution efforts.

However, experts state that BSPs face significant barriers in accessing essential battery performance data, often restricted by OEMs due to intellectual property concerns. This lack of transparent diagnostics, particularly for the BSPs, limits the ability to accurately assess battery condition. Furthermore, some experts also noted that greater industry maturity is needed to establish consistent, reliable methods for battery classification and characterisation, which are essential for enabling reuse, repurposing, and recycling.

5.2.2.3 Market dynamics and the emergence of new actors

Findings from Study 3 indicate the emergence of new and evolving actors within the EV battery supply chain, particularly those expected to play a significant role in the collection, trading and reintegration of used batteries. In parallel, some traditional actors are also likely to assume new responsibilities within these processes, further diversifying the market landscape.

Given the anticipated increase in used EV battery volumes, experts expect a market shift driven by growing incentives for reuse and repurposing. This development is likely to attract a new type of actor, referred to here as independent traders, who facilitate the exchange of used batteries through open trading platforms. According to Study 3, 61% of experts believe that such platforms will become a common market solution within the next five years. These platforms are expected to extend beyond basic battery exchanges by offering additional services such as the supply of battery spare parts and components, logistics coordination, storage and component consolidation, therefore supporting greater integration across the EV battery supply chain.

These open trading platforms are expected to be used by dismantlers, repair shops, independent dealers and recyclers, operating largely outside OEM control. In Study 3, 72% of experts predicted that these actors will intensify their trading activities over the next five years. While OEMs may also use these platforms to access used batteries, one OEM expert in Study 2 advised that such independent markets could compromise traceability. When batteries are sourced through these channels, information on their origin, handling and service history is often incomplete or unavailable, raising concerns about safety and accountability.

An additional actor highlighted in Study 2 is the insurance companies, which, although not mentioned by experts in Study 3, are expected to assume a more prominent role in the used battery market. According to an open trading platform provider, insurance companies already own batteries from accident-damaged vehicles and have extensive experience trading second-hand vehicle parts. These existing capabilities could enable them to expand their participation in the used battery trade in the near future.

Despite their potential benefits, open trading platforms also present significant risks. Some experts in Study 3 expressed concern over the absence of standardised norms, quality assurance protocols and regulatory control, which create uncertainty regarding safety, performance and liability throughout the supply chain. Additional challenges include compliance with diverse national and EU-level regulations, risks associated with transporting hazardous or damaged batteries and the entry of inadequately trained or inexperienced actors into the market. To mitigate these risks, experts recommend implementing robust auditing and control mechanisms. Strategic partnerships between OEMs and trading platform providers are also viewed as critical, as such collaborations would facilitate access to battery service histories and technical documentation, enabling safer and more reliable trading practices.

Findings from Study 3 further indicate a growing market demand for recyclers to provide integrated service solutions. In response, recyclers are actively developing business models that combine multiple functions such as collection, storage, inspection, sorting and dismantling of used batteries. According to 66% of experts, such integrated service models are expected to become common within the next five years. Some experts also note that specialised companies may manage the collection and transport of used batteries under contract with recyclers. These integrated approaches aim to streamline battery recovery processes and maximise value retention across the battery lifecycle. Some experts suggest that recycler-managed dismantling may simplify OEM contract management by consolidating services under a single provider, while complementary services offered by recycling centres may further improve process efficiency and reduce costs. Nevertheless, experts acknowledge that other actors, including traditional scrap dealers, dismantlers and independent workshops are also likely to engage in these activities, indicating that a diverse and competitive service landscape is expected to emerge in the coming years.

However, several challenges may impede this transition. To sustain processing capacity, recyclers often rely on sourcing used batteries from multiple countries, making them dependent on complex cross-border logistics. This dependence is further complicated by fragmented regulatory frameworks across Europe. As noted by two BSP experts in Study 2, licensing and permitting procedures for recycling centres remains inefficient, characterised by long lead times and regulatory inconsistencies, which further constrain operational efficiency.

5.2.2.4 Centralised and decentralised models

Future developments in the collection of used EV batteries are expected to focus on the strategic location of collection facilities and the integration of activities within them. Findings from Study 3 reveal a divergence of views: 39% of experts believe that centralised models will become a common solution within the next five years, while 29% consider this unlikely to occur. In this context, a centralised model refers to an organised and coordinated structure in which a single main facility, or a network managed under one actor, integrates the collection, testing and sorting of used batteries.

Some experts in Study 3 highlighted that centralised models can enhance economies of scale by enabling higher collection rates and more consistent quality control. One expert in Study 2 further emphasised that the extensive investment in safety measures required to obtain permits for facilities handling batteries, along with the need for highly skilled workers, contribute to a preference for centralisation. As used battery volumes increase and processes mature, centralised collection, testing and sorting are expected to become increasingly cost-competitive. Moreover, some experts in Study 3 noted that the EU battery regulation has encouraged this direction by reinforcing the role of OEMs in EOL battery management, and that some OEMs are already implementing or moving towards a more centralised approach. Correspondingly, some interviewees in Study 2 reported that indeed many OEMs are already moving toward greater centralisation of battery operations, including involvement in decisions related to second-life applications.

Conversely, other experts in Study 3 argued that decentralised models are also likely to emerge, driven by the growing market potential and the entry of multiple actors seeking to participate in used battery collection, testing, sorting and repairing activities. A decentralised system refers to a distributed model of regional or local facilities, or entities, that independently perform battery testing, sorting and repairing activities, rather than relying on a single centralised operation. In Study 3, 50% of experts indicated that these activities are likely to be organised through decentralised models within the next five years, while 22% projected this would occur within six to ten years.

According to several experts in Study 3, a decentralised system would offer notable advantages, including faster response times, more dedicated service and reduced shipping costs, therefore enhancing financial viability. One expert further noted that localising these activities could enhance control of material flows and allow for more specific criteria in battery assessment and sorting. Many experts also highlighted that decentralised testing, sorting and repairing could reduce transport-related safety risks, as used or damaged batteries would be processed closer to their point of origin. Despite these advantages, concerns were raised regarding the consistency of safety standards and handling practices across multiple decentralised hubs. One expert also warned that excessive decentralisation could strain organisational and logistical systems. Several experts in study 3 stressed that, for a decentralised model to become a widely adopted solution, significant efforts will be required to scale operational capacity, enhance technical competencies and develop specialised expertise, areas that currently remain underdeveloped.

As the economic value of second-life batteries becomes more apparent, several experts in Study 3 anticipate the participation of a broader range of actors such as dealerships, recyclers, reusers, and refurbishers, all referred to here as BSPs, in decentralised models. Some experts in Study 3 further noted that OEMs are likely to contract licensed local repair shops to conduct testing and repair services. Complementary insights from Study 2 reveal that OEMs are already required to provide service information, including dismantling and repair guidelines, to authorised dealers and workshops. As one expert in Study 2 explained, this emerging decentralised repair segment represents a growing service market for workshops, expected to evolve in close cooperation with OEMs through joint training programmes and the provision of mandatory battery repair manuals.

6 Discussion

This chapter discusses the key findings of the thesis in relation to the research questions and highlights their implications for circular EV battery supply chains. Section 6.1 focuses on the crucial aspects of circular EV battery supply chains and Section 6.2 analyses the implications for supply chain structures and presents a novel mapping of likely future supply chain structures for circular EV batteries.

6.1 Crucial aspects of circular EV battery supply chains

This section discusses the crucial aspects that influence the functioning and development of circular EV battery supply chains. Building on the goal of understanding supply chain activities, it extends existing knowledge by presenting how these activities are inserted in broader structural, governance and regulatory context, influencing their feasibility, coordination and value retention. The discussion is organised in seven interrelated aspects: (1) collection models and network configuration; (2) ownership, control and data governance; (3) actor diversity and coordination; (4) logistics and regulatory alignment; (5) testing, diagnosing and sorting as strategic functions; (6) remanufacturing and refurbishment for value retention; and (7) economic and regulatory interdependencies across circular pathways. These aspects provide an integrated perspective on the mechanisms that enable or constrain the development of circular EV battery supply chains. This discussion connects the thesis purpose with the empirical findings and paves the way for the subsequent analysis of likely future supply chain structures in Section 6.2.

6.1.1 Collection models and network configuration

The literature highlights that limited collection infrastructure and restricted access to used batteries reduce the profitability and operational efficiency of circular EV battery supply chains (Rajaeifar et al., 2022). Empirical findings from this thesis reinforce this point, showing that insufficient battery volumes constrain reuse and recycling activities, limiting economies of scale and the economic feasibility of recovery operations. Nevertheless, some experts in Studies 2 and 3 anticipate that as the volume of available used batteries increases, the participation of actors such as recyclers, dismantlers and independent traders will expand collection capacity and likely improve logistical efficiency.

A relevant theoretical debate concerns the influence of battery volume on collection network design. While Yan et al. (2024) suggest that volume affects the number and scale of collection points, Wang et al. (2020) argue that it directly influences network configuration and transport economics. In practice, empirical findings support both perspectives, indicating that the efficiency of emerging collection models (centralised and decentralised) depends not only on battery volume but also on market diversification and collaboration among actors.

An interesting theme in both literature and empirical data is the relative benefits and constraints of centralised and decentralised collection models. In literature, it is argued that centralised models enable economies of scale (Rosenberg et al., 2023), whereas decentralised models provide logistical flexibility and reduced transport distances (Yazdekhasti et al., 2022). Empirical findings from Studies 2 and 3 suggest that these models are not mutually exclusive but co-evolve within EV battery supply chains. OEMs tend to pursue centralised model to maintain control and ensure compliance with safety and traceability requirements. BSPs may also benefit from centralised collection, driven not only by the costs and time associated with obtaining permissions but also by safety considerations. Conversely, decentralised models are likely to be adopted by BSPs, recyclers, and occasionally OEMs in collaboration with authorised dealers and workshops to respond to local market needs and logistics constraints. According to many experts in Study 3, decentralisation can improve responsiveness, reduce transport risk and enhance local engagement, but it may also result in inconsistencies in handling and safety practices, reinforcing the need for harmonised regulation. Overall, the findings suggest that future collection systems are likely to operate through parallel centralised and decentralised models.

6.1.2 Ownership, control and data governance

Ownership structures and access to data emerge as critical determinants of how circular supply chain activities are organised and which actors can participate in them. Empirical findings in Studies 2 and 3 demonstrate that OEMs are increasingly seeking to retain ownership and control over batteries to ensure regulatory compliance, liability management, and secure access to recycled materials for future battery production. The consolidation of ownership directly affects collection, testing, sorting and direction into circular strategy pathways. Actors that operate outside OEM-controlled systems often face restricted access to diagnostic and usage data, which constrains their ability to assess battery condition, manage safety risks, and determine appropriate circular pathways. In this way, control over ownership and data functions as structural force mechanisms, defining supply chain boundaries and reinforcing power asymmetries.

6.1.3 Actors' diversity and supply chain coordination

Empirical findings from Study 3 indicate that circular EV battery supply chains are characterised by increasing actor diversity and, consequently, greater structural complexity. Beyond OEMs, recyclers and other traditional actors (e.g. insurance companies, dismantlers, and authorised dealers), findings from Studies 2 and 3 reveal the emergence of independent traders who provide online trading platforms and actively influence battery flows. These actors facilitate the redistribution and trade of used batteries, thus extending supply chains beyond OEM-controlled channels. Despite their growing relevance, this actor category remains underexplored in the literature, with only a limited number of studies addressing it (e.g. Chirumalla, 2024; Wang and He, 2023; Xu et al., 2023).

Concurrently, these actors can enhance trading activity and expand collection networks, but responsibility, control and value distribution become increasingly dispersed across the supply chain. This dispersion introduces new coordination and governance challenges among stakeholders (Chirumalla et al., 2022; Rufino Júnior et al., 2023; Slattery et al., 2024). In parallel, vertical integration is also becoming more prevalent, particularly among recyclers who are progressively incorporating collection, testing, sorting, dismantling, and storage into their service portfolios. While such integration reflects strategic efforts to internalise a greater share of the value chain, improve operational efficiency, and lower coordination costs (Rosenberg et al., 2023; Gonzales-Calienes et al., 2022), it also generates concerns related to traceability, regulatory compliance and safety management. Overall, the findings indicate that circular EV battery supply chains are evolving toward increased actor diversification, where effective coordination, collaboration and governance arrangements become increasingly important.

6.1.4 Logistics and regulatory alignment

Logistics and regulatory complexity persist as significant barriers in the literature and practice of circular EV battery supply chains. Consistent with earlier studies (Skeete et al., 2020; Beaudet et al., 2020), empirical findings from Studies 2 and 3 indicate that fragmented logistics systems and inconsistent regulatory frameworks significantly constrain the efficiency of EV battery collection. Transporting large, hazardous batteries remains costly and operationally complex, especially due to divergent national interpretations of safety and waste regulations across European countries.

These challenges are further confirmed by findings from Study 2, in which recyclers and BSPs reported lengthy permitting processes, regulatory inefficiencies and a strong reliance on cross-border shipments, all of which directly compromise investment planning and operational performance. These constraints influence not only the day-to-day logistics operations, but also the geographical configuration of circular supply chain infrastructure.

Empirical findings underscore the urgent need for harmonised European standards to manage the collection, handling and transport of used batteries. This aligns with previous studies that advocate for international standardisation and enhanced regional coordination within circular EV battery supply chains (Beaudet et al., 2020; Rajaeifar et al., 2022).

6.1.5 Strategic functions of testing, diagnosing and sorting

Testing, diagnosing and sorting play a critical role in linking collection with downstream circular strategy pathways. The literature emphasises that accurate SOH assessment is a prerequisite for determining whether used batteries can be reused, repurposed or must be recycled. However, prior research indicates that limited data access and non-standardised diagnostic methods continue to constrain the effective scaling of circular flows in the EV battery supply chain (Kampker et al., 2023; Neubauer et al., 2015). Empirical findings from Studies 2 and 3 corroborate this view. BSPs report that restricted access to OEM-specific diagnostic data necessitates extensive testing and inspection, significantly increasing processing time and costs. Used batteries frequently arrive at treatment facilities without service histories or standardised documentation, further amplifying uncertainty and inspection requirements (Kampker et al., 2023). Consequently, testing and diagnosing activities function as gatekeeping procedures that determine technical feasibility and economic viability across circular strategy pathways.

Sorting further links technical assessment with strategic decisions regarding reuse, repurposing, and recycling pathways. Heterogeneity in battery chemistry, cell type, functional characteristics, power and capacity, battery management algorithms and communication protocols complicates sorting processes (Canals Casals and Amante García, 2016) and reduces downstream efficiency. Inefficient sorting increases costs and limits scalability, particularly when access to battery data is restricted (Wu et al., 2020), a finding also supported by the empirical results of this study. The literature identifies standardisation and labelling, ideally linked with diagnostic information such as SOH, as ways to improve sorting performance (Alamerew and Brissaud, 2020; Beghi et a., 2023). In this context, initiatives such as the Battery Passport are also highlighted as important enablers of transparent data sharing and standardised classification across the EU (Wu et al., 2020).

6.1.6 Remanufacturing and refurbishment for value retention

Remanufacturing and refurbishment are discussed in the literature as important strategies for retaining the functional and economic value of EV batteries after their first use (Koh et al., 2021). However, their viability is highly contingent on the constant volume and quality of returned batteries (Li et al., 2018; Gu et al., 2018). Battery design constitutes a further major barrier, as permanently bonded cells, non-standardised components, and diverse pack designs increase disassembly time, labour intensity, and safety risks, restricting efficient value recovery. Accordingly, the literature highlights DfD principles that consider, for instance, modularity, reversible fasteners, and component standardisation as enablers of battery value retention (Meng et al., 2022; Bordes et al., 2022; Rosenberg et al., 2022).

Empirical findings further indicate that limited access to compatible components constrains refurbishment activities. BSPs in Study 2 reported difficulties in obtaining necessary components, often resulting in sourcing used batteries from which recoverable parts can be extracted. This practice creates cascading dependencies within the supply chain and reduces overall system efficiency.

These findings suggest that remanufacturing and refurbishment function as critical intermediary pathways between reuse and repurposing, enabling value retention that would otherwise be lost (Ramirez-Meyers et al., 2023; Chirumalla et al., 2024). However, their effectiveness remains strongly influenced by upstream product design decisions and supply chain coordination.

6.1.7 Economics and regulatory considerations of circular pathways

Synthesising the findings of the three studies, reuse, repurposing, and recycling cannot be understood as isolated circular pathways, but rather as a deeply interlinked system influenced also by economic incentives and regulatory priorities. Decisions in one circular pathway directly impact the feasibility, timing and performance of the others, creating trade-offs that affect investment decisions, policy design, and strategic planning across the EV battery supply chain.

Repurposing is greatly recognised in the literature as an important pathway for extending battery lifetimes by redirecting used batteries into second-life applications, including stationary storage, energy trading, fast-charging support and grid balancing (Kamath et al., 2020; Shahjalal et al., 2022). Nevertheless, empirical findings from Studies 2 and 3 indicate that the development of repurposing remains constrained by limited supply volumes, operational complexity, regulatory fragmentation and restricted access to information. The literature identifies unclear legislation and inconsistent regional interpretation as one of the major barriers to repurposing (Börner et al., 2022; Lee et al., 2021). Empirical findings confirm these barriers that consequently restrain investment, complicate decision-making and impact on customer trust. Current regulations often prioritise recycling, unintentionally limiting repurposing opportunities (Moore et al., 2020). For battery chemistries such as LFP, where recycling is currently technologically challenging and economically unattractive, some experts in Study 2 emphasised that repurposing can postpone recycling and enhance overall resource efficiency. Nevertheless, other experts in Study 3 highlighted that conflicts between repurposing and recycling mandates, especially under EPR frameworks, where recycling content targets and OEM responsibilities create uncertainty regarding strategic prioritisation.

Recycling is presented in the literature as essential for securing the long-term supply of critical materials, especially in regions with limited domestic resources (Raj et al., 2022; Narang et al., 2023). Some experts in Study 2 similarly emphasised its strategic importance for strengthening European supply chain independence, particularly in the context of rising raw material costs and the EU battery regulation mandating recycled content in new batteries from 2027. However, recycling remains constrained by technological lags between emerging battery chemistries and corresponding recycling technologies (Beghi et al., 2023). Empirical findings in Study 2 further indicate that fragmented regulation, including inconsistent permitting processes and cross-border logistics rules, creates delays and constrains recycling efficiency. BSPs from Study 2 described lengthy licensing procedures and regulatory inconsistencies across Europe as critical operational barriers, limiting the speed at which recycling capacity can scale to meet future demand.

Overall, the findings reveal persistent tensions between policy objectives, particularly under EPR frameworks and EU battery regulation, where OEM responsibilities and recycling targets may conflict with value-retention strategies such as repurposing. Consequently, circular EV battery supply chains can be understood as a dynamic, multi-pathway structure in which economic feasibility and regulatory priorities have an influence on EV battery strategic outcomes.

6.2 Implications for supply chain structures

As the volume of used batteries in the market will increase significantly in the coming years (Circle Energy Storage, 2022) this development will require coordinated actions among all actors involved in the EV battery value chain (Wesselkämper and von Delft, 2024) to enable managing proper collection, treatment and following circular pathway to address the environmental concerns and government, industry and consumer pressures (Shqairat et al., 2024; Wrålsen et al., 2021; Hill et al., 2019). The introduction of the EU battery regulation defines obligations for EOL management and promote recycling and second-life use (EU, 2023). This regulation seeks to establish stability in the market while ensuring alignment with the environmental and economic goals intended to be achieved. In parallel, the EPR framework continues to reinforce the role of OEMs as the main actors responsible for their products throughout the entire lifecycle, including EOL management (Shqairat et al., 2024). OEMs are therefore positioned at the centre of this transition, as they deliver the vehicles to customers and retain responsibility for the product until its EOL phase (Altuntas Vural et al., 2024).

However, based on the empirical findings and reflections developed in this thesis, it is likely that OEMs themselves will not be able to guarantee the return of all used batteries from EV users for proper treatment and redirection to circular strategies such as reuse, repurposing and recycling. This limitation opens an important opportunity for OEMs to collaborate with other actors in order to expand access to used batteries and to develop new business models that strengthen their relationships with EV users (Chirumalla et al., 2022; Hu et al., 2022; Olsson et al., 2018). Such collaboration may include partnerships that enable broader collection networks, shared logistics or data-based service models that facilitate the tracking and recovery of used batteries (Bräuer et al., 2020; Costa et al., 2022; Li, 2022). These future opportunities could allow OEMs to maintain some level of control over the post-use stage of the batteries while also creating economic and environmental value across the wider ecosystem.

In situations where not all used batteries are acquired directly by OEMs, there is a growing opportunity for new market actors, which is also confirmed in the empirical findings, to access these batteries and build their businesses around offering services for proper treatment and direction to circular strategies (Wang and He, 2023; Xu et al., 2023; Li, 2022). These activities, focused on reuse, repurposing and recycling could maximise the value of used batteries and support the creation of economically viable circular business models (Ahuja et al., 2020). From industrial, environmental and economic perspectives, there is therefore a clear need to transform current linear supply chains into circular supply chains to keep materials and products in circulation and minimise waste (de Lima et al., 2024; Roy et al., 2022; Wang et al., 2025). A CSC also implies a new level of coordination of activities and relationships among stakeholders (Kreye, 2025; Slattery et al., 2024). In this context, the supply chain becomes an important prerequisite to support the flow of used batteries and ensure their subsequent use within circular strategies (Bressanelli et al., 2019; Gebhardt et al., 2022; Zhu et al., 2025). Understanding how this supply chain should be structured to create continuous circular flows and minimise waste for EV batteries was a key aim of this thesis.

The empirical findings also indicate that the EV battery industry is currently in a transition phase, experimenting with different setups and possibilities to enable a continuous and profitable circular flow of batteries. These movements can be seen in the establishment of joint ventures, pilot projects and product-based collaborations discussed by the experts in Studies 2 and 3, that has allowed for initial testing of technical and business feasibility. Such initiatives indicate that actors are still exploring which models can ensure both economic viability and scalability in the future. It is therefore that these early experiences will serve as learning opportunities for future expansion and standardisation of circular practices. Investments are expected to increase as actors gain more confidence in these initiatives, even though associated risks remain inevitable. New organisations are also recognising the potential of second-life batteries and are developing products and business cases to enter this emerging market. All these movements from different actors support the assumption that future supply chain structures will likely evolve in more diversified and collaborative forms.

Drawing on the empirical findings from Studies 2 and 3, Figure 7 presents the likely future structures of the EV battery supply chain. It synthesises the roles and interactions of the main actors, particularly the OEM and the BSP, together with the corresponding material flows they are expected to lead. Figure 7 also illustrates the circular strategies examined in this thesis, including reuse, repurposing, and recycling. It incorporates an open-loop perspective by acknowledging that some recycled materials will not be re-entered into EV battery production but will instead be directed to other industries. The following discussion in subsections 6.2.1 OEM-led supply chain and 6.2.2 BSP-led supply chain elaborates on these flows, outlining how they are likely to evolve and highlighting the dynamics that comprise them, with a particular emphasis on the leadership roles of the OEM and BSP as well as the key factors that will influence the likely future supply chain structures for circular EV batteries.

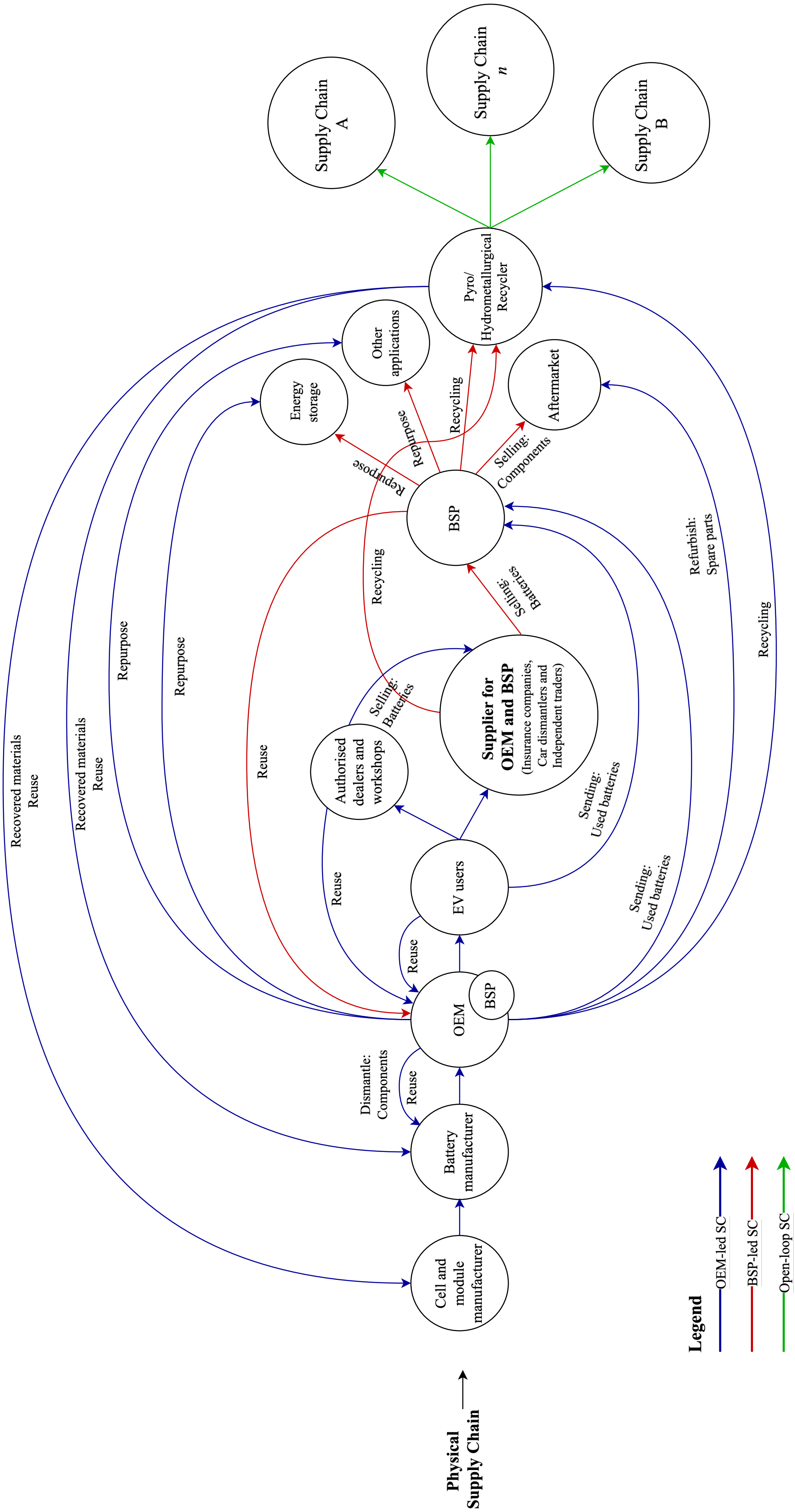

Figure 7. Likely future SC structures for circular EV batteries

6.2.1 OEM-led supply chain

A recurring point identified in this thesis is that OEMs are becoming increasingly eager to retain greater control over the return of used batteries and the subsequent circular strategies that can be applied to them. This tendency is related not only to compliance with regulatory frameworks such as the EPR and the EU battery regulation but also to the market opportunity that circular strategies can generate. The possibility of keeping ownership of used batteries is seen as beneficial by many OEMs and also observed by other actors in this thesis, because it allows for OEMs to participate in multiple value creation pathways. As shown in Figure 7, the flows from and to the OEM present the possibilities for generating revenues from reusing batteries in vehicles, repairing and maintaining batteries currently in use, selling components from used batteries in the aftermarket, and establishing new products such as ESSs that extend the life and value of batteries. Furthermore, ensuring the recycling of used batteries to extract valuable raw materials, that are already scarce and expensive in the market, are also becomes a strategic advantage. This comprehensive control can also help OEMs to meet regulatory requirements related to the management of EOL batteries.

In the future EV battery supply chain, it will likely be essential for OEMs to secure predictability and a constant volume of used batteries. This situation increases their dependence on actors that can supply these batteries. It is expected that OEMs will seek to strengthen their relationships with customers and establish long-term agreements, such as leasing contracts, to secure the return of used batteries at the end of their first life, which is also reinforce previous literature discussion on the role of long-term agreements such as leasing to enable control of the used batteries by the OEMs (Glöser-Chahoud et al., 2021; Li et al., 2021). The empirical findings also suggest that OEMs will therefore likely have a more centralised management role, building stronger connections with authorised repair shops and workshops to support testing, repair and maintenance services locally. Such relationships can improve customer service while also ensuring a continuous supply of used batteries through authorised channels. By maintaining this network, OEMs can control the services performed by authorised repair shops, which, according to some experts in Study 2, they are already influencing through training and repair manuals.

The findings from Studies 2 and 3 also indicate that OEMs will likely develop more centralised and integrated collection, sorting and testing activities. Beyond the traditional channels of customer returns and authorised repair shops, OEMs will likely seek additional access to used batteries from external sources. Independent traders are expected to have a strong influence in this area, particularly through the operation of open trading platforms that facilitate the buying and selling of used batteries. These platforms could become significant channels through which OEMs can secure larger volumes of used batteries while enabling independent traders to offer complementary services including the provision of spare parts, battery components, logistics coordination, storage, and component consolidation. By engaging with these open trading systems, OEMs could establish strategic partnerships with traders to gain access to batteries that would otherwise remain outside their control. For the independent traders, collaboration with OEMs could also generate reciprocal benefits such as access to battery service histories and technical documentation. This type of partnership would contribute to a more reliable and transparent trading environment supported by data-sharing agreements that enhance safety, traceability and mutual trust between the actors involved.

Overall, these findings suggest that open trading of used EV batteries is already occurring, however, it remains underexplored in the literature. Only a few papers have addressed this topic, focusing on emerging e-commerce recycling services (Wang and He, 2023) and auction-based platforms (Xu et al., 2023). While these studies demonstrate how independent online traders can enable recycling and second-life use, they offer limited insight into the availability of such trading systems and their benefits for OEM strategies.

A further question arising from these findings concerns the likely configuration of activities such as testing, sorting, disassembly and repair. It remains uncertain whether OEMs will fully centralise these activities by expanding their internal capabilities or rely more extensively on outsourcing to specialised BSPs. However, the insights derived from Studies 2 and 3 suggest that both approaches will likely coexist. OEMs may expand their in-house facilities to manage part of these activities while simultaneously partnering with BSPs that possess specialised technical expertise to carry out testing, sorting, disassembly and repair for reusing batteries considering in-house or in their own BSP facilities, which is represented in Figure 7 with the BSP circle together with OEM and the flow of sending used batteries from OEM to BSP and the flow returning the batteries to be reused by the OEM. This collaboration would enable OEMs to retain strategic control over the process while ensuring operational efficiency, scalability and compliance with regulatory expectations.

Another crucial factor for OEMs is ensuring the future production of EV batteries. Given the scarcity and rising cost of raw materials today (Raj et al., 2022; Xu et al., 2020) combined with EU battery regulatory mandates on recycled content in new batteries (EU, 2023), recycling is expected to become a key strategic priority for OEMs. The findings from Studies 2 and 3 indicate that OEMs are likely to prioritise sending used batteries to recycling processes to secure the material supply necessary for manufacturing new batteries with improved technologies. For recyclers, this development represents a valuable opportunity to increase recycling volumes and strengthen their role in the circular supply chain. A major concern currently observed in the European EV battery market is that large-scale recycling activities are predominantly dominated by Asia, particularly Chinese companies, which has limited the European autonomy and control over critical materials. Nevertheless, there is a growing understanding that Europe has also the technological know-how, industrial experience and strong EV-manufacturer presence to develop a more robust domestic recycling infrastructure. However, currently constraints such as higher operational costs and the need to achieve greater economies of scale continue to limit the pace and competitiveness of this development (Wesselkämper et al., 2024).

Despite that, the findings in the Studies 2 and 3 suggest that Europe will likely focus on building large-scale (hydrometallurgical) recycling facilities to support a more autonomous and resilient supply chain. Establishing these facilities within Europe would allow used batteries to be recycled locally, therefore supplying recovered materials directly to European cell manufacturers (Neumann et al., 2022). This strategy would reduce dependence on external markets and minimise challenges related to traceability and logistics. Furthermore, a recommendation from experts that participated in the studies is that the recycling industry should strategically determine which metals to prioritise for recovery in order to ensure both the economic and environmental viability of recycling operations. In this way, Europe could enable a more circular supply chain by having the recovery materials back in the loop for the future EV battery production.

Considering the OEMs' interest in having more control and ownership of the batteries, the findings in Studies 2 and 3 indicate that they intend to play a more active role in decision-making related to repurposing batteries for second-life applications. According to EV battery experts, having ownership of the batteries would provide OEMs with clearer insight into the most appropriate timing for removing a battery from its first use in a vehicle and preparing it for second use in another application. This corresponds with prior research demonstrating the benefits of having access to real-time performance data during the first-use phase (Bordes et al., 2022), which supports the development of prognostic models to predict SOH patterns (Alamerew and Brissaud, 2020; Neubauer et al., 2015; Ramirez-Meyers et al., 2023). When shared effectively, such data can enhance second-life planning and reduce reliance on costly in-house testing (Slattery et al., 2024; Neubauer et al., 2015). Therefore, according to Kampker et al. (2023), the OEM involvement is advantageous for repurposing efforts, as direct access to the battery management system can eliminate the need for additional testing and disassembly.

The OEM interest in the repurposing market is also motivated by the potential benefits of extending the life of the batteries, generating new sources of income and taking advantage of current market incentives for repurposing, especially in the energy utility sector, where second-life ESS solutions are expected to grow, along with other possible applications (e.g. micro-mobility applications) that may likely to emerge to maintain the economic viability of repurposing (Altuntas Vural et al., 2024; Dunn et al., 2023; Kamath et al., 2020; Shahjalal et al., 2022; Wilson et al., 2021). The findings from the empirical studies suggest that the demand for ESSs is unlikely to exceed the future volume of retired EV batteries. Consequently, the repurposing market will need to diversify into different applications to accommodate the growing supply of used batteries. This aligns with previous research from Sun et al. (2018) that show that used battery supply is expected to exceed demand for ESSs, which may reduce process and limit profitability. Given that second-life batteries generally have lower performance and shorter lifetimes than new batteries, their economic competitiveness is constrained, which reinforces the need for market diversification such as recycling (Zhao et al., 2021).

Based on the findings from Studies 2 and 3, it is likely that these collaborations will be established either directly between OEMs and actors in the energy utility solutions sector

(Hu et al., 2022) or through BSPs, which would be responsible for preparing batteries for repurposing under service contracts with OEMs. In the literature, joint ventures and collaborations are suggested to expand circular opportunities (Chirumalla et al., 2022). However, it is also emphasised that joint ventures with OEMs can significantly reduce investment and production risks, but it could also limit market opportunities (Canals Casals and Amante García, 2016).

Another important reason for OEMs to engage in battery repurposing concerns to LFP batteries. These batteries are currently less attractive for recycling because they lack high-value metals such as cobalt, nickel and manganese. On the other hand, they present strong potential for repurposing, which could support the development of a profitable second-life market in Europe. Promoting the repurposing of LFP batteries would also contribute to strengthening the recycling industry in the long term, as it would allow time for the European market to develop the necessary recycling infrastructure, technological capabilities and operational capacity for the future EV battery supply chain. This perspective remains underexplored in the existing literature, which has predominantly focused on recycling technologies, process efficiency and economic and environmental impacts (Bordes et al., 2022; Harper et al., 2019; Narang et al., 2023), with limited attention to how different repurposing strategies can impact the development of future recycling infrastructure, particularly in Europe.

6.2.2 BSP-led supply chain

As previously stated, OEMs are unlikely to guarantee full control over the return of all used batteries to be properly treated and directed to reuse, repurposing and recycling under their management. Consequently, the used batteries that will be outside OEM control can be acquired by other actors who will take advantage of market incentives and emerging opportunities to manage and redirect these batteries into their next life cycle (Kurdve et al., 2019; Li, 2022). These actors may contribute to broader battery recovery and redistribution efforts, ultimately benefiting the overall circular EV battery supply chain. Findings from Studies 2 and 3 indicate that several actors operating as suppliers (see Figure 7) are likely to have an active role in this supply chain, including insurance companies, car dismantlers, independent dealers and independent workshops. These actors are expected to have access to used batteries directly from EV users through a range of possibilities such as private resale or vehicle repair processes in which the used battery is not reclaimed by the user and remains disconnected from OEM-controlled channels. Acting as intermediary suppliers, these actors are likely to sell used batteries, components or materials to BSPs, which would then perform the appropriate treatment for following reuse, repurposing, or recycling. Under these conditions, significant coordination challenges among stakeholders are likely to emerge (Chirumalla et al., 2022; Rufino Júnior et al., 2023; Slattery et al., 2024), as responsibility, control and value distribution across the supply chain become increasingly dispersed.

An interesting emerging actor confirmed in the findings is the independent trader. These traders operate open trading platforms that facilitate the buying and selling of used batteries (Wang and He, 2023) while is also expected to expand their services to include spare parts, battery components, logistics coordination, storage and component consolidation to the market. However, a major challenge for these actors lies in obtaining reliable information on battery performance, as they typically do not receive direct data from OEMs. Instead, their batteries often come from intermediary suppliers, which can introduce uncertainty regarding safety, performance and liability. Additional challenges for independent traders relate to battery transportation, compliance with safety and environmental regulations and the need for properly trained personnel to handle and store these batteries. According to the experts interviewed, overcoming these challenges will require the development of robust auditing and control mechanisms to ensure traceability, safety and trust across transactions. These measures would be essential to secure the reliability and long-term viability of these open trading systems.

In the case of the BSPs, they will likely have access to used batteries from several sources, including independent traders, insurance companies, car dismantlers, independent dealers, independent workshops and OEMs themselves (see Figure 7). They can acquire batteries from any of these actors, although all of them are also expected to operate as competitors offering similar solutions such as collection, testing, sorting and dismantling for reuse or repurposing. In particular, recyclers, who are also part of the BSP group of actors, are likely to offer integrated service solutions that include collection, storage, inspection, sorting and dismantling, aiming to streamline processes and reduce costs. A challenge presented in the findings is that they are expected to source used batteries from a wide network of suppliers across multiple countries. This international sourcing will likely increase dependence on cross-border logistics and create additional challenges, especially considering the current fragmentation of regulatory frameworks across the EU that complicates the movement of batteries between member states. Therefore, the market is expected to become increasingly diverse and competitive, with multiple actors providing overlapping services and competing for access to used batteries.

Considering the treatment of the used batteries, the findings suggest that these multiple actors will likely participate actively in collection, testing, sorting, disassembly and repair activities. They are expected to operate in a decentralised model, serving local and regional demand. According to the experts, this decentralisation can present several advantages, including faster response times, more dedicated services, lower transportation costs and reduced safety risks due to shorter transport distances. On the other hand, a highly decentralised model would place pressure on organisational and logistical systems, raising concerns about the consistency of safety standards and handling practices. Nevertheless, integrating activities such as testing, sorting, disassembly and repairing for reuse and repurposing in decentralised facilities is suggested to likely improve control over material flows and allowing for more precise criteria in battery assessment and sorting. According to the findings in Studies 2 and 3, future solutions will need to focus on scaling operational capacity, enhancing technical competencies and developing specialised expertise to support these evolving this decentralisation models within circular EV battery supply chains.

An interesting finding from these studies is the growing interest and business opportunity for BSPs in acquiring used batteries and removing their components, especially modules, for reuse as replacement parts. There is an increasing demand for battery repair services, creating a promising aftermarket opportunity for these actors. Another important activity performed by BSPs involves carrying out repair and refurbishment processes for reuse in the vehicles and repurposing in second-life applications (e.g. ESSs) purposes, as well as managing initial pre-recycling activities, such as the transformation of batteries into black mass to be sent to pyro- or hydrometallurgical recyclers. However, a key challenge to making these activities feasible lies in gaining access to accurate information about battery performance from OEMs. The current lack of transparency and limited data sharing on battery diagnostics restrict BSPs' ability to accurately assess battery conditions, which in turn constrains their efficiency and the reliability of the services they can offer.

7 Conclusion

The purpose of this thesis is to understand the supply chain activities and supply chain structures through which activities, actors and flows are currently organised and may develop in the future in circular EV battery supply chains. To fulfil this purpose, two research questions were formulated: the first research question synthesises existing knowledge on supply chain activities for circular EV batteries and the second research question identify current supply chain structures and explore their likely future developments.

The thesis is based on three appended papers. Paper 1 answers the first research question through a SLR, which identifies and analyses supply chain activities, including collection, testing and diagnosing, sorting, disassembly, refurbishment and remanufacturing, repurposing, and recycling, within the context of circular EV batteries. The review enables to understand how these activities relate to CSCs and how they support the circular strategies. The second research question is addressed through two empirical studies, comprising interviews (Paper 2) and a Delphi-survey (Paper 3) involving a diverse set of actors in the EV battery supply chain. These studies enabled identifying current supply chain structures and assessing the actors' perspectives on likely future developments, resulting in the identification of likely future supply chain structures for circular EV batteries.

The findings emphasise that access to sufficient volumes of returned batteries is a critical condition for the scalability and economic viability of circular pathways. Battery collection emerges as a key enabling activity, with centralised and decentralised collection models likely to coexist. Despite its importance, collection remains underdeveloped in the literature and challenging to implement in practice.

The results further suggest that while OEMs are expected to retain control over batteries and associated data, they are unlikely to have access to all used batteries, creating opportunities for BSPs and independent actors. BSP-led supply chains are expected to expand through decentralised and regional networks for collection, testing, repair, refurbishment for reuse and repurposing. Independent traders, dismantlers and workshops are also gaining importance, although limited access to battery performance data remains a significant constraint.

Ownership and control over EV batteries and associated performance data emerge as central determinants of supply chain structure, coordination, and power relations. OEMs that own the battery normally also control access to battery data, which in turn influence coordination and decision-making regarding circular strategy pathways. Limited access to reliable battery data, particularly for BSPs, constrains the provision of efficient services, highlighting data access as a strategic resource within circular EV battery supply chains.

The thesis also indicates that circular strategy decisions are influenced not only by technical considerations, but by economic viability and regulatory conditions. Current EU battery regulation place strong emphasis on recycling through EPR and recycled content requirements, placing recycling as a prioritise circular strategy for OEMs. At the same time, the findings identify repurposing as a promising alternative within the EV battery supply chain. However, the absence of clear and consistent regulatory support is one of the reasons limiting its broader adoption.

Finally, the findings indicate that EV battery supply chains are in a transitional phase, characterised by experimentation, pilot projects, and evolving collaborations. Two dominant yet interconnected supply chain structures are identified: OEM-led and BSP-led supply chains. In OEM-led supply chains, circular strategy decisions are commonly made after battery return, based on testing and diagnosis. In contrast, BSP-led supply chains often operate with predefined circular strategies established through contractual arrangements with customers. These structures both compete and collaborate through interconnected circular battery flows.

Overall, the thesis understands circular EV battery supply chains as dynamic, multi-actor, and multi-pathway systems that is influenced by economic viability, regulatory priorities, ownership models, and actor's collaboration.

7.1 Theoretical contribution

This licentiate thesis advances a more integrated understanding of circular EV battery supply chains through the combined lenses of circular economy, circular supply chains, and supply chain structures. Addressing the need for greater conceptual clarity in CSC research within the EV battery context (Slattery et al., 2024; Zhu et al., 2025), the thesis synthesises fragmented literature into a comprehensive CSC perspective. By explicitly connecting activities, actors, and flows across multiple circular strategy pathways, it provides a holistic understanding of how circular value is created, retained, and redistributed within EV battery supply chains.

First, the thesis contributes to CSC theory by systematically connecting supply chain activities to circular strategy pathways in the context of EV batteries. Through a SLR, it clarifies how activities such as collection, testing and diagnosing, sorting, disassembly, remanufacturing, repurposing, and recycling function as interconnected enablers of circular value retention. This perspective moves beyond isolated activity-level descriptions and offers a structured understanding of how circular strategies are established across supply chains, addressing a key gap in existing CSC literature (Gebhardt et al., 2022; Schulz-Mönninghoff et al., 2023; Slattery et al., 2024).

Second, the thesis advances theoretical understanding of supply chain structures in circular contexts. While prior research on supply chain structures has predominantly focused on linear and closed-loop models, this thesis demonstrates how structures evolve in response to circular strategy requirements, ownership models, and economic and regulatory conditions. By integrating supply chain structure with CSC principles, it provides conceptual grounding for analysing how actors, activities, and flows are coordinated across both closed-loop and open-loop configurations in circular EV battery supply chains.

Finally, the combination of a SLR with empirical insights from interviews and a Delphi study connects conceptual CSC frameworks with real-world supply chain configurations. This integrated approach strengthens the literature development by offering an empirically informed and analytically structured foundation for future research on circular supply chain structures and design, coordination mechanisms, and governance.

7.2 Practical implication

This thesis provides practical insights to support managers and decision-makers in designing circular EV battery supply chains. It provides a comprehensive overview of the challenges, constraints, and limitations currently influencing the development of circular EV battery supply chains, drawing on perspectives from multiple supply chain actors. Particularly, the findings support practitioners' understand of how battery ownership models, restricted access to battery data, regulatory complexity, logistical challenges, and coordination difficulties directly affect the effectiveness of circular battery flows and the alignment of activities across reuse, repurposing, and recycling pathways.

The thesis also outlines likely future developments in circular EV battery supply chains, therefore supporting strategic decision-making related to supply chain configuration and investment priorities. By highlighting expected developments, such as increasing demand for battery reuse, refurbishment, and recycling, the expansion of repurposing markets, growing OEM ambitions regarding battery ownership and control, and the emergence of new actors (e.g. independent traders), the thesis enables organisations to anticipate future requirements. These insights are relevant for planning infrastructure investments, forming partnerships, developing data governance practices, and building organisational capabilities to remain competitive and in accordance with regulatory and market conditions.

Finally, the thesis identifies crucial aspects of circular EV battery supply chains, supporting organisations in assessing their current position within the circular EV battery ecosystem. By clarifying interdependencies, gaps, and improvement opportunities, the findings assist organisations in designing and adapting supply chain structures that are better aligned with both current practices and likely future developments in the EV battery supply chain. Therefore, the thesis contributes to more effective coordination and implementation of circular EV battery flows.

7.3 Limitations and future research

This thesis has some limitations that should be considered when interpreting the findings. The empirical studies, comprising interviews and a Delphi survey, did not include participants from all European countries. The regional focus of the interviews and Delphi survey might have influenced the findings, as regulatory conditions, market maturity, infrastructure, and organisational practices vary across Europe. Consequently, the conclusions drawn in this thesis primarily reflect perspectives influenced by the regional contexts of the participating experts and may be less representative in other European or global settings.

Some experts participated in more than one empirical study, which may have contributed to a degree of continuity in perspectives across the studies. While this overlap supported consistency in the analysis, it may also have resulted in certain viewpoints being more strongly reflected in the findings. Moreover, although some OEMs are increasingly engaging in energy storage systems through internal development or strategic joint ventures, actors with this specific profile were not represented in the interview study. As a result, perspectives related to the integration between automotive and energy value chains are less explicitly addressed in the current mapping of supply chain structures.

The thesis identifies several directions for future research. One particularly important area concerns battery collection models. Although centralised and decentralised collection models are sometimes mentioned in the literature, their definitions, operational boundaries, and implications remain unclear. Empirical research examining how these models are designed, managed, and integrated within circular EV battery supply chains would provide valuable insights into their efficiency, scalability, cost implications, and effects on reuse, repurposing and recycling outcomes.

Another important topic for future research concerns the impact of battery ownership and control in circular EV battery supply chains. Ownership models strongly influence access to batteries, data availability, decision-making power, and value capture; however, their implications for coordination and circular strategies are not fully understood. Comparative studies examining OEM and BSP-led ownership and control structures could therefore provide deeper insights into how these configurations influence current and future supply chain structures. Closely related is the need for research on ownership transitions across battery life-cycle stages, including how ownership is transferred from OEMs to BSPs and second-life providers, under which contractual, regulatory and organisational arrangements, and what implications these transitions have for responsibility, liability and control. Understanding who owns, uses, and is accountable for batteries at each stage is critical for enabling more effective coordination and scalable circular EV battery supply chains.

As interest in repurposing and second-life applications continues to grow, further research is also needed to investigate the supply chain implications of this shift. This includes developing a better understanding of demand for second-life batteries and analysing how repurposing priorities will impact recycling and reuse pathways. Such research is relevant for anticipating future infrastructure, logistics and coordination requirements.

Finally, future studies can investigate the evolving roles of established and emerging actors, including insurance companies, BSPs and independent traders, as they will likely have influential roles in the future circular EV battery supply chains. Research that investigates how these actors interact, collaborate and shape power dynamics within the supply chain would contribute to a more comprehensive understanding of their roles in the circular EV battery ecosystem.

To conclude, this thesis shows that circular EV battery supply chains constitute dynamic, multi-actor systems. It integrates literature and empirical data to understand collection, testing and diagnosing, disassembly, remanufacturing, repurposing, and recycling within OEM- and BSP-led supply chains. The findings describe crucial aspects of circular EV battery supply chains and propose a mapping of their likely future structures.

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