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Circular Business Models for Electric Vehicle Lithium-Ion Batteries

An analysis of current practices of vehicle manufacturers in the EU and the potential for innovation at Volvo Group

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Abstract

With the transition towards an electrified vehicle fleet, lithium-ion batteries (LIBs) have come into focus for different stakeholders due to their high costs, resource, and energy demands for production as well as connected environmental concerns and supply risks. Circular economy (CE) strategies to slow and close resource loops and circular business models (CBMs) are discussed as solutions to these issues. This research uses a combined multiple and single case study approach to explore how a vehicle manufacturer could innovate its business model to incorporate an environmentally responsible life cycle management of LIBs. An ideal CE strategy for LIBs is identified by reviewing existing environmental assessments. Current CE strategies amongst vehicle manufacturers, their operationalisation and underlying influencing factors are identified by analysing companies' websites and interviews with representatives from six different companies. Finally, the potential for CBM innovation and implementation at Volvo Group is explored through interviews with eight employees that are involved in the LIB life cycle. The results demonstrate that an ideal CE strategy for LIBs follows the EU's waste hierarchy as translated into the technical cycle of the CE. It was found that vehicle manufacturers focus most on repair, refurbishing, and repurposing to slow the loop while remanufacturing is rarely deployed. Most repurposing projects are still in their piloting phase and only a few closed-loop recycling initiatives involving vehicle manufacturers were found. While the CE strategies are very similar, the specific CBM designs vary especially with regards to the involvement of vehicle manufacturers indicating they are context-specific and depend on internal factors. All CBMs were found to require close collaboration between different stakeholders to build trust and reduce uncertainties. Furthermore, the necessity to design for disassembly and to build expertise to thoroughly diagnose the state of health of LIBs to enable strategies that slow the loop was highlighted.

Keywords: circular economy; circular business models; business model innovation; lithium-ion batteries; electric mobility

Executive Summary

Background

The electrification of road transportation is widely considered as a viable strategy to achieve decarbonisation of the transport system. With the transition towards an electrified vehicle fleet, lithium-ion batteries (LIBs) have come into focus for different stakeholders due to their high costs, resource, and energy demands for production as well as connected environmental concerns and supply risks. The rising electric vehicle (EV) adoption leads to increased numbers of returning LIBs, which requires the development of a life cycle strategy and management for LIBs with consideration of social and environmental criteria. Circular economy (CE) strategies to slow and close resource loops and more specifically circular business models (CBMs) are discussed as solutions to these issues. However, there is a lack of research discussing the non-technical aspects of LIB's life cycle management related to how CE strategies for LIBs are deployed by automotive original equipment manufacturers (OEMs) and operationalised from a business model perspective. Research is needed to understand internal factors and the role and opportunities of automotive OEMs in the adoption of CBMs for LIBs to reduce environmental impacts from EV road transport.

Research aim and approach

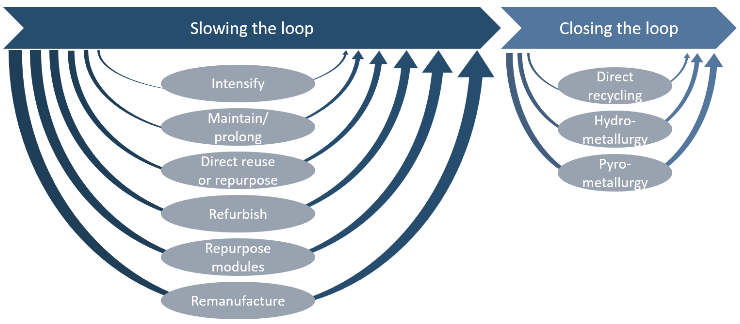
The aim of this study was to explore how an automotive OEM could innovate its business model to incorporate an environmentally responsible life cycle management of LIBs through the utilisation of CBMs using Volvo Group as a case. To contribute to this aim, the following research questions (RQs) were examined:

1. *What is an ideal CE strategy for a LIB life cycle from an environmental perspective?*
2. *Which CE strategies for LIBs are deployed by automotive OEMs in the EU, how and why?*
3. *Which CBMs could Volvo Group implement for LIBs in the EU?*

This thesis used a combined multiple and single case study approach. *RQ2* was informed by multiple cases in the automotive industry with the aim to detect patterns and themes regarding the adoption of CE strategies and CBMs. Then, Volvo Group served as the single case study for the ideation of potentially applicable CBMs in the respective context. Methods of data collection were triangulated and included a comprehensive literature review of academic and grey literature, document analysis, and interviews with six representatives from external companies and eight employees at Volvo Group. A conceptual framework for analysis was developed based on the academic literature regarding CBMs.

Findings

RQ1: What is an ideal CE strategy for a LIB life cycle from an environmental perspective?



The findings indicate an ideal CE strategy for LIBs follows the EU's waste hierarchy as it is translated into the technical cycle of the CE (see figure on the right). Accordingly, slowing the loop of LIBs is preferred before closing it. Opting for activities that preserve the integrity of the product or component for as long as possible reduces the need to produce new batteries and enables a longer and more efficient use of resources. The existing life cycle assessments especially pointed out the environmental benefits of second life applications that are combined with renewable energy production, and where little changes are made to the original product. However, more comprehensive, and dynamic assessments are needed to verify the proposed CE hierarchy.

RQ2: Which CE strategies for LIBs are deployed by automotive OEMs in the EU, how and why?

The industry overview has shown that OEMs focus mostly on repair, refurbishing, and repurposing to slow the loop while remanufacturing is rarely deployed. Some OEMs are involved in all these activities, including a utilisation of replacement LIBs in stationary energy storages before the use in a vehicle. Nevertheless, very few full-scale repurposing CBMs exist as of today because most projects are still in their piloting phase. Furthermore, only a small number of closed-loop recycling initiatives with the involvement of automotive OEMs were found and mostly limited to valuable materials such as cobalt and nickel. Other than that, the standard recycling practice does not include the tracing of materials by the OEMs but can just as well result in closed-loops arranged by the recycler in collaboration with cell producers. The results highlight that the different CE activities are not mutually exclusive, but complementary.

Different CBM designs were observed especially for repurposing and closed-loop recycling with varying involvement of OEMs. OEMs may simply sell their LIBs for repurposing to a third party. Alternatively, several OEMs have expanded in the second life and energy storage business by setting up a specific subsidiary or joint venture. Most often, repurposing models were characterised by close collaborations with partners such as energy utilities or repurposing companies. The findings suggest that the environmental value proposition of a repurposing CBM is not sufficient to compensate for the product's lower functionality and warranty. It needs to offer a competitive economic value to the customer as well.

For closed-loop recycling, the cooperation between cell producers, or their active materials manufacturers, and recyclers is crucial to building trust regarding the quality of secondary raw materials. Moreover, closed-loop recycling is expected to increase with rising raw material prices and the development of a cell production industry in the EU because of the geographical proximity which was found to be relevant to this CBM. It can also be supported by initiatives involving OEMs, but the currently existing closed-loop recycling initiatives only involve OEMs if they are (starting to get) involved in cell production. Overall, design for disassembly and efficient diagnostics through the battery management system have been identified as key enablers for any CBM. In contrast, the rapid technological advancements explain the project-based approach of many OEMs as they seem to hinder upscaled CBMs that benefit from large volumes, a stable technology, and standardised designs.

RQ3: Which CBMs could Volvo Group implement for LIBs in the EU?

Based on an analysis of the current situation at Volvo Group and the learnings from *RQ2*, several opportunities for improvement were identified to support and enable the adoption of CBMs in the future. These opportunities revolved around diagnostics, LIB design, organisational capabilities, and the closed-loop supply chain. In particular, the necessity to build expertise to diagnose the state of health of LIBs and their modules thoroughly and efficiently, as well as to design for disassembly was identified. Overall, CBM innovation for LIBs within Volvo Group could be further supported with strong leadership, a clear vision and strategy, as well as a commitment to incorporate more responsibilities at Volvo Group to navigate the existing uncertainties. While it is possible to outsource CE activities to external partners, it could mean missing out on a business opportunity and losing control of the LIB and its integrated materials.

Volvo Group's potential for repair, refurbishing, and repurposing CBMs was found to be high. In line with the findings from *RQ2*, the specific design for these CBMs could vary but close customer relations were highlighted as crucial to reduce existing uncertainties and concerns. Furthermore, the utilisation of replacement LIBs in stationary energy storages before the use in a vehicle was identified as a potential business case to maximise the use of LIBs as well as secure the accessibility and compatibility of spare parts. For high-cobalt LIBs, a closed-loop recycling model may also be applicable for a few metals such as cobalt and nickel. This, however, is contingent on the active materials and cell production being based in the EU and Volvo Group's suppliers agreeing to the integration of recycled materials. A decentralised disassembly down to module level has been identified as a promising solution to lower costs in this case.

Recommendations

Based on the findings of this research, several recommendations for Volvo Group and other companies that aim to develop an environmentally responsible life cycle management for LIBs and implement CBMs are formulated:

1. **Use the CE hierarchy to inform the life cycle strategy development for LIBs.**

An OEM's CE strategy should be guided by the proposed CE hierarchy for LIBs if the aim is to develop an environmentally friendly life cycle management. This means preserving the product's and component's embodied value for as long as possible and potentially prioritising repurposing over refurbishing and remanufacturing. Additionally, environmental criteria such as GHG emissions and recycling rates should be regarded when selecting a recycler.

2. **Engage in an innovation process to incorporate CBMs for LIBs.**

LIBs offer much potential from a CE perspective and are one of the most valuable parts of EVs. Hence, it is recommended to facilitate a strategic CBM innovation process for LIBs. Making this a strategic priority instead of reacting upon short-term opportunities would benefit an automotive OEM.

3. **Develop expertise on LIB diagnostics and ageing behaviour to enable slowing the loop.**

Assessing whether LIB modules and cells used in the specific OEM's LIB normally age homogenously or heterogeneously could help the overall strategy selection. The operational decision of which CE activity to deploy for a specific LIB requires a thorough diagnosis of its SOH. Practitioners would highly benefit from developing a (standardised) method to estimate the SOH and remaining useful life of LIBs to support CE strategies that slow the loop and that rely on these metrics.

4. **Accelerate the CE transition in the automotive industry by influencing policymakers.**

OEMs can use their voice in industry associations such as ACEA to influence policymakers to develop a clear regulatory framework that supports environmentally favourable CE strategies and improves the economic viability of respective CBMs. This is important because this research has shown there is a misalignment between environmental and economic value. In particular, measures that promote the adoption of repurposing CBMs, which do not seem to have a clear business case despite the environmental value and being the most promising CE activity, should be a focus of a future CE framework for LIBs. Furthermore, OEMs can stress the need to support the development of a European LIBs value chain because the geographical proximity between recyclers and producers is an enabler for closed-loop recycling.

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Abbreviations

BMS – Battery Management System
CBM – Circular Business Model
CE – Circular Economy
EPR – Extended Producer Responsibility
EV – Electric Vehicle
GHG – Greenhouse Gas
LFP – Lithium Iron Phosphate
LIB – Lithium-Ion Battery
NMC – Lithium Nickel Manganese Cobalt Oxide
OEM – Original Equipment Manufacturer
SOH – State of Health

1 Introduction

Road transport is responsible for three quarters of the EU's transport-related greenhouse gas (GHG) emissions (European Environment Agency, 2019a). Despite sectoral climate goals on EU and national levels, the absolute emissions from transport have been increasing since 2014 and account for around a quarter of the EU's GHG emissions (European Environment Agency, 2019a). Moreover, road transport is also a major contributor of harmful air pollutants such as particulate matter and nitrogen oxides, thus threatening human health and the environment (European Environment Agency, 2016). Due to these negative impacts and trends, the future of mobility, and road transport in particular, has come into focus of political discussions in the EU. One measure to address this problem was the introduction of stricter CO_2 emission performance standards by the EU Commission in 2019. These standards aim to reduce the average annual CO_2 emissions of the EU's fleet of new cars, vans and heavy-duty vehicles by 15% by 2025 compared to the reference in 2019 (Art. 1 Regulation (EU) 2019/1242; Art. 1 (4) Regulation (EU) 2019/631).

The electrification of road transportation is widely considered as a viable strategy to achieve a decarbonisation of the transport system and reduce GHG emissions to mitigate climate change (Alonso Raposo et al., 2019). Vehicle manufacturers' investments for electric vehicles (EVs) have increased rapidly in 2017 and 2018, especially due to German producers such as Daimler, BMW and VW (Ernst & Young, 2019). Politically, the electrification of road transport is supported with subsidies for EV purchases such as the environmental bonus for EVs in Germany (Bundesamt for Wirtschaft und Ausfuhr, 2019) and investments in charging infrastructure to accelerate the uptake of EVs. The number of EVs in the EU has increased almost exponentially, with a small drop in 2016, and reached a share of 2% of the total vehicle fleet in 2018 (European Environment Agency, 2019b). This trend is expected to persist and accelerate with further regulation on direct vehicle emissions and targets for adoption set by governments (International Energy Agency, 2019).

In the process of moving towards an electrified vehicle fleet, two aspects have been identified as key to ensure the minimisation of EVs' environmental impact. First, even though EVs do not emit any direct GHG emissions, the production of the electricity stored in the lithium-ion traction batteries (LIBs)[1] can cause massive GHG emissions if it is based on fossil fuels such as coal or oil. Thus, an EV needs to be charged with renewable energy to not shift the problem to energy production (Faria et al., 2013; Hawkins et al., 2013). Secondly, the LIBs needed for EVs contain high amounts of raw materials such as lithium, cobalt, nickel and graphite that are only mined in a few countries and pose a challenge from a material supply risk perspective (Alonso Raposo et al., 2019). The extraction processes for these raw materials are connected to social and ecological risks (Öko-Institut, 2018) and the production of LIBs demands a lot of energy, subsequently emitting high amounts of GHG emissions (Emilsson & Dahllöf, 2019). Moreover, LIBs are considered dangerous goods because the contained metals like lithium, aluminium, cobalt, manganese, nickel, and copper, could potentially slowly leach into the soil, groundwater, and surface water if not disposed of properly (Kang et al., 2013).

However, LIBs do not necessarily need to be disposed of straight away as they can potentially be refurbished, remanufactured, or repurposed. It is commonly estimated that LIBs usually still

[1] In this thesis the abbreviation LIBs will be used when referring to EV LIBs. If LIBs for or from other application are addressed, it will be indicated.

hold a capacity of 70-80% at the end of their first life in vehicles (Bobba, Mathieux, et al., 2018; Olsson et al., 2018). With this capacity, they could still be used in second life applications, where a lower energy capacity is acceptable (Pagliaro & Meneguzzo, 2019). Hence, scholars have been calling for the development of a life cycle strategy and management for LIBs with consideration of social and environmental criteria and have often connected this to the concept of a circular economy (CE) (Olsson et al., 2018).

1.1 Problem definition

The CE has developed as an alternative economic paradigm to the linear economy with the objective to minimise resource input, waste, emissions, and energy leakages while providing economic value (Geissdoerfer, Savaget, Bocken, et al., 2017). CE strategies are centred around slowing resource loops by extending the life of a product, part, or component to preserve its embedded product value, and closing resource loops to retain the material value of the product (Bocken et al., 2016). Products whose environmental impact is mainly caused in the production phase have a lot of potential to benefit from CE strategies (Nußholz, 2017), which is why LIBs have been discussed as a promising product from a CE perspective.

On a political level in the EU, LIBs have been recognised as an important product for the CE and its waste management is currently governed by the Batteries Directive 2006/66/EC. This imposes the legal responsibility for recycling and disposal of LIBs on the producer and sets a recycling target of 50% by weight. In the recent CE Action Plan of the European Commission (European Commission, 2020), LIBs are included as a key product value chain, and the development of a new regulatory framework for batteries was announced with consideration of reuse, repurposing, and recycling, thus underpinning the political CE ambitions for LIBs. Practitioners have also shown a high interest in CE strategies for LIBs due to business opportunities and risks. LIBs represent the costliest part and a major share of the total costs of an EV (International Energy Agency, 2019; Reinhardt et al., 2020). Hence, there is a high interest amongst business stakeholders to capitalise on the embedded value of the battery after its first use in a vehicle. Today, the number of discarded LIBs is still low, but in just a few years volumes are expected to increase, adding up to over six million battery packs by 2030 and a potential remaining capacity of over 275 GWh per year (Jiao, 2019). With these volumes, strategies and systems need to be put in place now to prepare for environmentally sound practices after the first life of LIBs in vehicles (Olsson et al., 2018). Investigating the end-of-use[2] and end-of-life[3] phases as well as identifying best practices for LIB's life cycle management is, thus, relevant to lower costs, the environmental impact and to potentially contribute to the supply of critical raw materials (Idjis & da Costa, 2017). Therefore, this research area is relevant for policy, and businesses as well as for academia.

Previous academic literature on CE with regards to LIBs has been focusing most intensively on closing the loop through material recovery at the end-of-life (D'Adamo & Rosa, 2019; Huang et al., 2018; Melin, 2019), with a significant body of research exploring technological processes (L. Chen et al., 2011; Georgi-Maschler et al., 2012; Li Li et al., 2013, 2018; Diekmann et al., 2017), analysing their environmental benefit (Dewulf et al., 2010; Dunn et al., 2015; Hendrickson et al., 2015; Lv et al., 2018) and estimating the economic potential of recycling

[2] Referring to the point at which a product is discarded by its current user because it is not needed anymore or does not provide the function as required, but where it or components may still be kept within the market (Nasr et al., 2018).

[3] Referring to the point at which a product does not provide the function as required and no other option than recycling or disposal are possible (Nasr et al., 2018).

(Idjis & da Costa, 2017; Kochhar & Johnston, 2018; Wang et al., 2014). Since recycling of LIBs has not yet proven to be profitable (Idjis & da Costa, 2017; Lin Li et al., 2018; Mayyas et al., 2019) and life extension strategies are expected to yield higher economic, environmental and social value among many sectors (Nasr et al., 2018), strategies for slowing the loop have come into focus for LIBs. While little research can be found on remanufacturing or refurbishing, an increasing amount of academic papers have recently been published on second life applications for LIBs. Different second life applications have been investigated with regards to the technological possibilities (Assunção et al., 2016; Cusenza, Guarino, Longo, Mistretta, et al., 2019; Martinez-Laserna et al., 2018; Sanghai et al., 2019; Schulte et al., 2015), the economic potential and advantages (Assunção et al., 2016; Debnath et al., 2014; Foster et al., 2014, 2014; Jiao & Evans, 2016a; Lebedeva et al., 2018; Neubauer & Pesaran, 2011; Rehme et al., 2016; Sanghai et al., 2019), and the environmental impacts (Ahmadi et al., 2017; Bobba, Cusenza, et al., 2018; Cusenza, Guarino, Longo, Ferraro, et al., 2019; Genikomsakis et al., 2013; Ioakimidis et al., 2019; Richa et al., 2017; Yang et al., 2020). Moreover, general drivers and barriers for different CE strategies for LIBs have been researched (Hill et al., 2019; Kurdve et al., 2019; Olsson et al., 2018).

However, there is a lack of research discussing the non-technical aspects of LIB's life cycle management related to how CE strategies for LIBs are deployed by automotive OEMs and operationalised from a business model perspective. The concept of circular business models (CBMs) has emerged to support businesses operationalise the CE to provide social, environmental, and economic value (Nußholz, 2017). Along with circular design, enabling factors and reverse logistics, business models are considered one of the levers to accelerate the transition to a CE (Ellen MacArthur Foundation, 2015; Urbinati et al., 2017; Vence & Pereira, 2018), which is why they should be in focus of research as well. Despite the importance of CBMs, only very recent and limited literature has investigated them for LIBs. Hill et al. (2019) discussed nine examples of CBMs along the EV LIB value chain, while Olsson et al. (2018) explored CBMs for extended LIB life and Reinhard et al. (2020) analysed sustainable business model archetypes for a second life. However, no comprehensive and systematic overview of the utilised CBMs and their design along the entire LIB life cycle has yet been provided.

Specifically, the stakeholders' interactions, relations, and roles within these CBMs and their reverse supply chains have not been assessed sufficiently (D'Adamo & Rosa, 2019; Mayyas et al., 2019; Melin, 2019). This value network (i.e. the organisation's internal activities and relations with partners) has been identified as one of two internal factors explaining the varying integration of circular principles into the business model amongst companies (Urbinati et al., 2017). Nevertheless, no prior research has focused on the internal organisational capacities needed for an automotive OEM to implement CBMs for LIBs. This, however, is important since automotive OEMs usually end up as the physical owners of the battery packs when they are returned (Reinhardt et al., 2020) and decide upon their fate. Automotive OEMs have the potential to integrate strategies to prolong the life of the LIB in the first use, have been in charge or collaborating for all major second life energy storage systems (Melin, 2020), and hold the responsibility for the end-of-life management of LIBs. Thus, further research is needed to understand internal factors and the role and opportunities of automotive OEMs in the adoption of CBMs for LIBs to reduce environmental impacts from EV road transport.

1.2 Research objective and questions

In order to address the described problem, the aim of this study is to explore how an automotive OEM could innovate its business model to incorporate an environmentally responsible life cycle management of LIBs through the utilisation of CBMs using Volvo Group as a case. To contribute to this aim, the following research questions (RQs) are examined:

RQ1: What is an ideal CE strategy for a LIB life cycle from an environmental perspective?

RQ2: Which CE strategies for LIBs are deployed by automotive OEMs in the EU, how and why?

RQ3: Which CBMs could Volvo Group implement for LIBs in the EU?

1.3 Audience

The primary audience for this thesis is practitioners and researchers in the field of CE and LIBs. On a micro-level, the case company Volvo Group, which sought to investigate its opportunities associated with the implementation of CBMs for LIBs, and other automotive OEMs are expected to be the main audience for the results of this work. The results should also be useful to other industries along the LIBs value chain who are interested in adopting CBMs. Additionally, this thesis contributes to the emerging academic research on CBMs by focusing on the current deployment of CBMs for LIBs in the automotive sector and delving into the non-technical aspects of the closed-loop supply chains. On a macro-level, the results provide an enhanced understanding of the interplay between policy and CBM initiatives for LIBs. This knowledge may be beneficial for policymakers who can improve and adapt policy to incentivise environmentally friendly life cycle approaches for LIBs amongst OEMs.

1.4 Disposition

Chapter one introduced the background to this research, defined the problem and research questions as well as the targeted audience.

Chapter two presents and justifies the methodology, research design, and case study approach in this thesis. Then, the process of data collection and analysis as well as the scope and limitations and ethical considerations are discussed.

Chapter three provides a literature review of the most relevant theoretical concepts for this study and the current state of research regarding LIBs in relation to the CE. The chapter closes with a summary of identified knowledge gaps and the conceptual framework developed for the presentation and analysis of findings following in *Chapter four*.

Chapter five discusses and contextualises the findings by relating them to the existing literature and highlighting this research's contribution to the state of knowledge. Furthermore, methodological reflections are provided.

Chapter six concludes this thesis with a summary of the findings and recommendations for practitioners, policymakers, and for future research.

2 Methodology

This chapter explains the methodology of this thesis used to produce knowledge and answer the previously established research questions. It introduces the research design and case study approach in section 2.1, methods for data collection and analysis in sections 2.2 and 2.3, discusses the scope and limitations in section 2.4 and ethical considerations in section 2.5.

2.1 Research design

The research approach taken in this thesis is of a transdisciplinary nature and reflects the researcher's interdisciplinary background. An interdisciplinary perspective is necessary to study CBMs because they are connected to different disciplines (i.e. business, environment, or political aspects). This research is, furthermore, reflective of a transdisciplinary research approach, which is characterised by a collaborative framing of the problem, the aim to co-produce *"solution-oriented and transferable knowledge through collaborative research"* and the integration of this knowledge into scientific and societal practice (Lang et al., 2012, p. 27). This approach has been found to be useful for contributing to solving a "real-world" sustainability problem as it produces knowledge more suitable for addressing the problem (Lang et al., 2012; Mobjörk, 2010).

2.1.1 Conceptual design

The framing of the problem was facilitated in collaboration with stakeholders from Volvo Group and the author. The conceptual research design (see Figure 2-1) to address the problem is guided by the business model innovation process and incorporates its first two steps as outlined by Wirtz, & Daiser (2018), namely the analysis of the current situation (i.e. the adoption of CE strategies, their operationalisation in CBMs and influencing factors at Volvo Group and other automotive OEMs in the EU that have sold EVs in the past) and then the ideation of new CBMs along the entire life cycle of Volvo Group's LIBs. Supplementing the traditional business model innovation process, the author first integrates the initial step of the process towards a circular business as proposed by Kraaijenhagen et al. (2016) by establishing a vision for an ideal CE strategy for LIBs' life cycle based on existing environmental assessments.

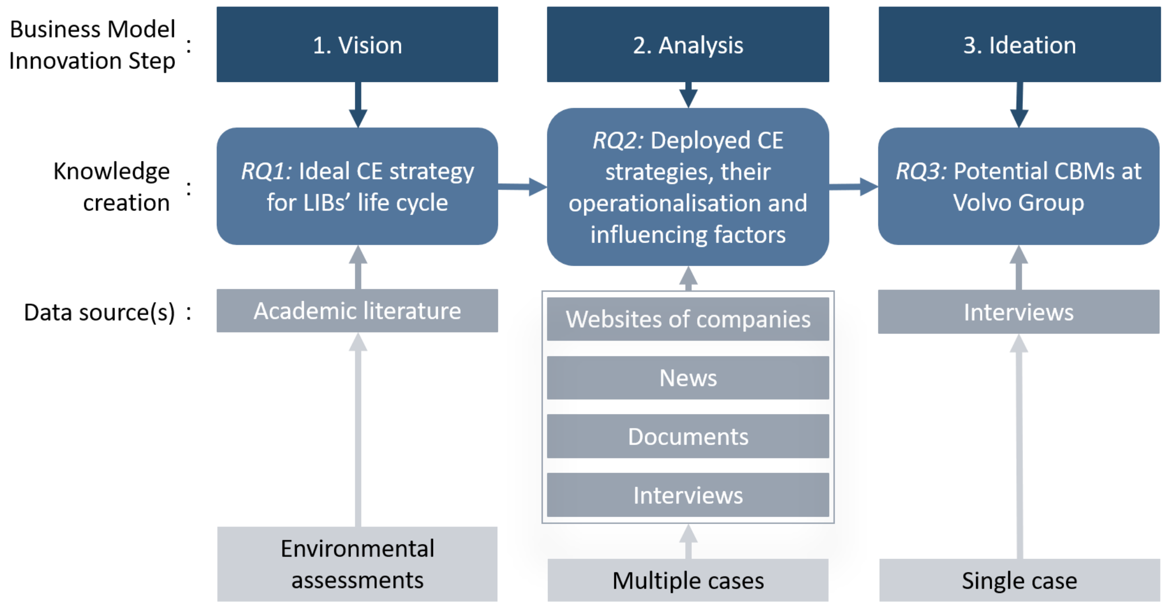

Figure 2-1. Conceptual research design

2.1.2 Case study approach

Case studies are especially suited for answering "why" and "how" research questions and for providing an in-depth understanding of a contemporary phenomenon in a real-world context (Yin, 2014). Multiple case studies test or aim to generalise theoretical constructs (Eriksson & Kovalainen, 2008), while a single case study approach is appropriate when focusing on an emerging topic that requires extensive research and contextualised knowledge (Creswell, 2014; Gerring, 2004). In this thesis, both approaches are used to complement each other. First, answers to *RQ2* are informed by multiple cases in the automotive industry with the aim to detect patterns and themes regarding the adoption of CE strategies and CBMs that may be generalisable. Then, Volvo Group serves as the single case study for the business model innovation process and ideation of potentially applicable CBMs in the respective context. Thus, this research combines knowledge derived from several less in-depth cases and a detailed single case study.

There are two main reasons for the adoption of this combined multiple and single case study approach to fulfil the objective of this thesis. Firstly, single case study approaches have been widely used in academic literature to provide examples and study how companies innovate their business models to incorporate CE activities (Bocken & Antikainen, 2019; Hart et al., 2019; Zucchella & Previtali, 2019). CBMs and closed-loop supply chains are highly dependent on the product type as well as contextual factors (Wells & Seitz, 2005) and also business model innovation is contextual (Kringelum & Gjerding, 2018), which is why a single case study providing a real-life setting and context-dependent knowledge (Flyvbjerg, 2006) is most suitable here. Secondly, CBMs for LIBs in the automotive industry remain insufficiently understood (Walliman, 2006) as will be shown in chapter 3. It has been argued that a lack of case studies impede companies in understanding how to determine, develop, and evaluate alternative business models such as CBMs (Evans et al., 2017). Because of this insufficient knowledge, the chosen qualitative and explorative multiple case study approach is suitable in helping to test existing theories with multiple cases in *RQ2* and to generate new concepts and theories by the *"force of example"* (Flyvbjerg, 2006, p. 228) of a single case study in *RQ3*.

The selection of cases for *RQ2* follows a purposeful sampling method (Blaikie & Priest, 2019) and is guided by the aim to learn from cases that successfully deploy CE strategies for LIBs. The industry overview served as a base for this selection. For this, all automotive OEMs that have sold EVs in the EU in the past were considered. Out of these OEMs, a total of five companies were identified and contacted as potential case studies because they seemed more mature in their process of introducing CBMs for LIBs. Four of these responded positively and were included in this research. Another four companies with comparable characteristics to the Volvo Group were contacted, but none of them were able or willing to participate. The single case study was selected because of the existing collaboration between the author and Volvo Group, and their current investigation of the potential integration of CBMs for LIBs at the group's commercial vehicle manufacturing companies. The collaboration offered the opportunity to access people and information needed to make a single case study approach viable and useful.

2.2 Data collection

Multiple sources of data were triangulated in this research to construct internal validity (Yin, 2014): academic and grey literature, company documents, and interviews.

2.2.1 Literature review

The literature review used both academic and grey literature. Academic literature included peer-reviewed journal articles, conference papers, and books published in English and German and accessible by the end of April 2020. First, the author identified relevant keywords for the literature search outlined in Appendix A. Then, the literature search included variations (e.g. singular, plural) and combinations of the keywords. Typical examples of such combinations are "electric vehicle" AND "lithium-ion battery" AND "circular economy" OR "circular business model" OR "reuse" OR "second life". The titles, abstracts, keywords, and, if necessary, the full paper were examined for relevance to the topics (i.e. synonyms and comparable constructs, not simply keywords). Because of the rapid developments regarding LIBs and related technologies, only literature published after 2010 was considered and more recent literature from after 2015 was prioritised as it reflects the current discourse and technological standard better. This cut-off criterium does not apply to literature on key concepts such as CE, CBMs, business model innovation, and closed-loop supply chains. From this initial sample, additional literature was identified through the snowballing approach, which entails reviewing the references of selected papers (Wohlin, 2014).

The aim of the academic literature review was to define key concepts and summarise previous research on the topic at hand. This was used to develop an analytical framework to answer the research questions, as well as to gather data to answer *RQ1*. Hence, the reviewed **academic literature** provided information on:

1) a current understanding of CE,
2) key dimensions and characteristics of CBMs in comparison to conventional business models,
3) the process and challenges of business model innovation for a CE,
4) previous research on CE strategies and CBMs for LIBs including the identified influencing factors and challenges, and
5) environmental assessments for different CE strategies for LIBs.

Limited information was provided in academic literature on the regulation for LIBs and specific CE strategies for LIBs utilised by automotive OEMs to answer part of *RQ2*. Hence, additional grey literature was used. Legal documents, OEMs' websites, annual reports, and conference presentations as well as business newsletters such as *Electrive* were consulted. Only automotive companies selling EVs in the EU were included in the analysis. Whenever suitable, brands were combined in their parental company groups (e.g. Volkswagen Group). While the focus of the analysis was on their CE activities within the EU, some examples of advanced practices in the production countries of non-EU based automotive companies were provided for comparison. Hence, the reviewed **grey literature** provided information on:

1) the EU's current legislative context for LIBs and its potential future changes,
2) LIB life cycle strategies and CBMs in the automotive industry.

Thus, the literature review not only offered an overview on existing research and theories as a background, but also provided data for answering the research questions.

2.2.2 Documents

Documents and presentations from Volvo Group were consulted to understand and analyse the context of the case study. Furthermore, it served to collect data on their current LIB technologies and specifications and the internal activities around the life cycle of LIBs.

2.2.3 Semi-structured, unstructured, and informal interviews

The third stream of data was collected through semi-structured and informal interviews to inform *RQ2* and *RQ3*. For *RQ2*, the data retrieved from grey literature did not sufficiently convey OEM's motivations (why) and specific implementation (how) of CE activities. Therefore, a purposeful sample (Blaikie & Priest, 2019) of automotive OEMs that seemed more mature in their process of introducing CBMs for LIBs was used to answer these two aspects of the question. Four semi-structured interviews were carried out with representatives from other automotive OEMs. This interview type was selected because it provides a structure to the conversation while allowing for the flexibility needed to capture the attitudes of the participant and to probe for additional details (Creswell, 2014). A list providing details about the interviews including the name of respondents, their position, as well as the interview date and time can be found in Appendix B.

Suitable interviewees were identified by the author through companies' websites or by the companies themselves. The interviews were conducted in English or German and executed either in person or online. The interview guide for automotive OEMs was developed based on the literature review as well as the preliminary results from the grey literature on SQ2 and slightly adapted during the research process based on the learnings from previous interviews. An example of the consolidated interview guide is found in Appendix C. Following the inductive research approach, the interview guide was not strictly followed to allow for new topics or themes to emerge. In addition, two interviews were conducted with representatives from other OEMs within the LIB value chain (a second-life actor and a recycler) to validate CBM ideas and understand (potential) cooperation between OEMs. The interview guide was adapted significantly for these interviews. Because the interviews were used to derive factual knowledge, they were not fully transcribed. Instead, information was summarised in note form and essential quotes. With the consent of the participants, the interviews were recorded electronically on a phone to be used for the adjustment of interview notes. If requested, the notes were sent to the respondents to get their validation and approval.

To gather information on the single case company and understand the real-life setting, the author was placed at Volvo Group in Gothenburg for the first eight weeks of the research period working in CampX, where all electromobility employees sit. This enabled a better collaboration and understanding of the company's current business model, the organisational capacities, and access to data and interviewees. It also offered several possibilities for informal conversational interactions with Volvo Group employees and participation in meetings related to the life cycle management of LIBs. Furthermore, eight employees were selected for further in-depth semi-structured and unstructured interviews to understand the current business model for LIBs, identify Volvo Group's internal factors which influence the creation or integration of CBMs and develop CBM ideas. The selection of interviewees was made in collaboration between the author and the company supervisor, Mélanie Girardot, as well as via "snowballing", by which respondents suggested other colleagues who could be of interest to interview. The selection was based on the interviewee's ability to provide useful information to this study i.e. having a good understanding of the company's initiatives and potential regarding the life cycle management for LIBs (Blaikie & Priest, 2019; Creswell, 2014). It was, furthermore, guided by the aim to achieve a high representation of internal actors involved in Volvo Group's current life cycle management of LIBs. Information from these informal conversational interactions and unstructured interviews were documented by note-taking.

2.3 Data analysis

For the initial literature review, synthesis matrices were used to systematically organise the data on 1) concepts such as CE, business models, CBMs and business model innovation, and 2) existing findings on CE strategies and CBMs for LIBs. Then, influencing factors for the adoption of CE strategies for LIBs were categorised according to the PEST framework, which outlines political, economic, social, and technological factors, as well as internal factors such as the organisational capabilities. The environmental assessments to answer *RQ1* were analysed using a synthesis matrix as represented in Appendix D. The matrices were adapted and completed in an iterative process as additional literature was identified throughout the research process, thus employing an inductive and deductive approach iteratively.

The data for answering *RQ2* and *RQ3* was examined using directed content analysis with a coding scheme based on the conceptual framework presented in section 3.6.2. Hence, a predominantly deductive approach was used for the analysis. However, the author remained open to discovering novel influencing factors for the CE strategy selection and operationalisation that were not represented in the conceptual framework, thus, employing an inductive and deductive approach iteratively. Currently deployed CE strategies were identified in grey literature before analysing and integrating findings from the interviews. The data from the interviews to answer *RQ2* and *RQ3* was analysed with a three-step content analysis: (i) transcription of interviews, though in note form, (ii) a complete peruse of all data to establish a global understanding, and (iii) coding (Creswell, 2014).

2.4 Scope and limitations

As can be seen in the research questions outlined in section 1.2, the geographical scope of this study has been limited to the EU. Furthermore, instead of selecting a few specific CE strategies for LIBs to investigate their operationalisation in a business model in detail, this research explores all business strategies that slow and close the loop along the life cycle of LIBs, thus accepting a potential loss in depth of the study for a gain in breadth.

The selection of the EU as scope is justified because it is the main market for EVs of Volvo Group's brands. The sales could increase even more in the future as automotive OEMs need to reach EU CO_2 targets in 2025 with their sold vehicles and EVs are one way to achieve that (Regulation (EU) 2019/1242). Moreover, there is a high potential for new systems to be set up within the EU with shorter logistics chains and a growing battery manufacturing industry as envisioned by the European Commission (2019b). The focus on all CE strategies along the life cycle of LIBs is motivated by the fact that no consensus exists among academia or industry yet as to whether one is the most beneficial from an environmental or economic perspective. Hence, this research investigates the different possibilities of automotive OEMs regarding the life cycle management of LIBs.

A limitation to this study is the restricted data collection for the single case study due to the coronavirus SARS-CoV-2 outbreak. Most Volvo Group employees were released from work for several weeks, which significantly shortened the period for data collection and inhibited the envisioned collaborative ideation of potential CBMs as well as follow-up interviews to clarify information obtained in unstructured interviews. As a result, *RQ3* was less the focus than originally planned and could not benefit from a joint workshop with relevant employees to provide a stronger ideation of business models and to ensure the co-creation and dissemination of knowledge, which are two goals of a transdisciplinary research approach (Lang et al., 2012).

Moreover, the reliability of results for the deployed CE strategies on repair, refurbishing, and remanufacturing could have been improved by increasing the number of interviews with representatives from other automotive OEMs. The availability of such, however, was limited as the author was dependent on their willingness to cooperate. While nine automotive OEMs were contacted, only the given four agreed to an interview. Hence, it is unlikely to expect that they would have been able to provide several interview partners.

Other limitations relate to the interviews. Most interviews conducted for this research lasted between 40 minutes and close to two hours. In most cases, the time was not sufficient to go into depth with all the different CE strategy possibilities. Thus, the author was not able to include the CBMs for different CE activities equally. In fact, repurposing CBMs were predominantly talked about by interviewees, which is why the results on these are much more substantiated than for other CBMs. The time limitations sometimes also prohibited discussing all components of a specific CBM with interviewees. Another observation was that the terminology of CE activities, as it will be introduced in section 3.1, was not clearly distinguished amongst interviewees. Even though the author tried to define the terms as thoroughly as possible and ask clarifying questions, sometimes it was not clear which CE activity they were referring to. This was especially prominent with the terms repair, refurbishing, and remanufacturing and had to be considered when analysing the interviews.

2.5 Ethical considerations

This project is supported by the Swedish automotive company Volvo Group. Volvo Group provided financial assistance and a workspace for the student while conducting her research in Gothenburg, Sweden. Furthermore, they put the author in contact with several internal as well as external partners and stakeholders for the data collection. In line with the transdisciplinary approach, the research topic and focus were developed in collaboration with Volvo Group. Nevertheless, the analysis and findings were not influenced by this collaboration, which is crucial to ensure the integrity of this research.

Other ethical considerations for this research revolved around the interview process and the collected data. All interviewees participated voluntarily and were informed in written form about the goal of this research, the collaboration between the author with Volvo Group, and the planned use of the information obtained prior to the interview. Interviewees were asked for consent to record the interview and to disclose their name and position within their organisation in this publication. In case interviewees chose to remain anonymous, their own, and sometimes their company's names were replaced. Finally, specific information and quotes from individuals within the thesis draft were shared with the respective interviewees to get verification prior to the publication of this thesis. The collected empirical data is stored electronically on the author's personal laptop and protected cloud system of the university.

3 Literature review

The literature review provides an overview of the concept of CE (section 3.1) and the role of businesses with regards to CBMs and business model innovation (section 3.2). Then, the focus is on the product of LIBs by presenting existing CE strategies and practices (section 3.3) followed by a discussion of the factors influencing the adoption of CE strategies and CBMs (section 3.4), and the challenges for CE approaches (section 3.5). Finally, section 3.6 summarises the literature review, outlines knowledge gaps, and describes the conceptual framework which guided the data collection and analysis.

3.1 Circular economy

The current economic system is primarily based on a linear economy, which is characterised by a take-make-dispose material and energy flow model. However, since the late 1970s an alternative concept has emerged to address the negative effects of this unsustainable use of resources – the CE concept (Ellen MacArthur Foundation, 2013; Geissdoerfer, Savaget, Bocken, et al., 2017; Lüdeke-Freund et al., 2019). It originates from various schools of thought and concepts such as industrial ecology, industrial symbiosis, the limits to growth, cradle-to-cradle, biomimicry, eco-efficiency, and many others (Geissdoerfer, Morioka, et al., 2018; Korhonen et al., 2018; Lewandowski, 2016). Because of these many influences and schools of thought, several definitions and conceptualisations of the CE exist (Kirchherr et al., 2017; Zucchella & Previtali, 2019). Most of them, however, acknowledge the main aim to create a regenerative economic system that decouples economic growth from resource consumption (Ellen MacArthur Foundation, 2013). It is assumed that this new system can offer economic gains through the mitigation of resource price volatility and supply chain risks, cost savings and job creation due to labour-intensive activities (Ellen MacArthur Foundation, 2015; Lewandowski, 2016; Ness & Xing, 2017), as well as environmental gains such as reduced resource consumption, waste, pollution and GHG emissions (Ellen MacArthur Foundation, 2015; Ness & Xing, 2017). An overview of the objectives of the CE is provided in Figure 3-1.

Figure 3-1. CE objectives

Source: Korhonen et al., 2018

The CE is based on materials being recovered and restored in the technical cycle through circular strategies and regenerated in the biological cycle through natural processes such as composting (Ellen MacArthur Foundation, 2015). Overall, resource input and waste should be minimised by keeping *"products, components, and materials at their highest utility and value at all* *times"* (Bocken et al., 2017, p. 476). Value in the CE should not only be understood as economic but also as environmental and social value in order to contribute to a sustainable development (Bocken et al., 2013). While the CE is frequently understood as an operationalisation of sustainable development, this relationship is not necessarily made explicit in its definition (Geissdoerfer, Savaget, Bocken, et al., 2017). Kirchherr et al. (2017) found that amongst 114 definitions only 12% of explicitly mention sustainable development and only 13% refer to all three dimensions of sustainable development – namely environmental quality, economic prosperity, and social equity (Elkington, 1997). Korhonen et al. (2018) proposed a new definition based on the sustainable development paradigm: *"Circular Economy is an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature materials and energy throughput flow. This is done by using cyclical materials flows, renewable energy sources and cascading-type energy flows. Successful circular economy contributes to all the three dimensions of sustainable development. Circular economy limits the throughput flow to a level that nature tolerates and utilises ecosystem cycles in economic cycles by respecting their natural reproduction rates"* (p. 39).

It is, thus, important to note that the relation between the concept of CE and sustainability is not self-evident (Geissdoerfer, Savaget, Bocken, et al., 2017). Potential rebound effects could offset the environmental benefits from circular products or services (Pieroni et al., 2019; Zink & Geyer, 2017) which is why there is a need to measure the impact of the CE through, for example, Material Flow Accounting or Life Cycle Assessment and to identify unintended consequences (Geissdoerfer, Savaget, Bocken, et al., 2017; Kalmykova et al., 2018). If the aim is to operationalise or contribute to sustainability, the decision on a CE strategy must be guided by an analysis of the overall sustainability value offered and not only based on the economic value. As guidance for this, the Ellen MacArthur Foundation (2015), with a mission to accelerate the transition to a CE, generally recommends focusing on activities that preserve the original use and complexity of a product, so-called "inner loop" or value-retention strategies, because this preserves most value, i.e. "*more of a product's integrity, complexity, and embedded labour and energy"* (Ellen MacArthur Foundation, 2015, p. 8). These activities include sharing to intensify the use, repair, reuse and repurposing, refurbishment, and remanufacturing. Only when a product or component cannot be circled in an inner loop anymore, the materials should be recycled and circled as many times as possible in the so-called "outer loop" (see Figure 3-2).

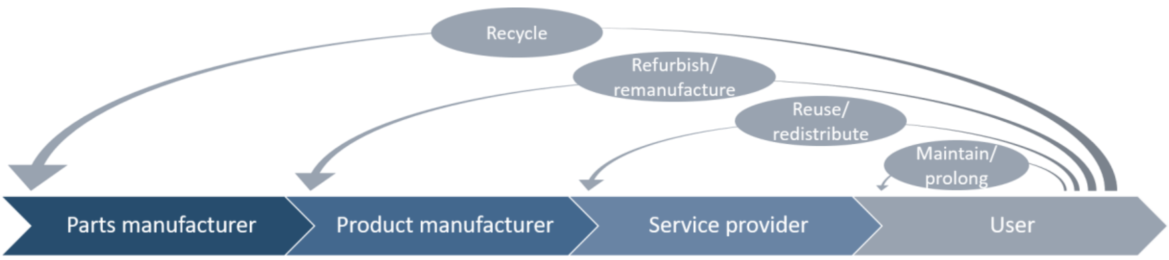

Figure 3-2. Technical cycles of the CE

Source: adapted from Ellen MacArthur Foundation, 2015

Many definitions of CE focus mostly on the principle of recycling and miss the importance of adopting a system shift to ensure the transition to a CE (Kirchherr et al., 2017). From a sustainability perspective, increasing and maximising the resource efficiency beyond the initial production through inner loop strategies and recycling only at last is, thus, the focus of the technical cycle in the CE concept (Ellen MacArthur Foundation, 2013; Korhonen et al., 2018). However, many of the inner and outer loop activities are not clearly defined and are sometimes used interchangeably in both literature and industry. This can lead to misunderstandings in communication and the interpretation of results from previous research. The most common definitions of these terms are provided in Table 3-1.

Table 3-1. Definitions of CE activities

Term	User	Definition
Repair	First user	extends the life of a product during its first use by retaining or restoring its functionalities with minor repairs that can be done by manufacturers or professional service providers (Bocken et al., 2016; Lüdeke-Freund et al., 2019)
Reuse	Second hand	extends the life of a product or part by having a second hand user utilise it for the same original purpose with no or only minor enhancements and changes (Lüdeke-Freund et al., 2019);
Refurbish	Second hand	extends the life of a product by a replacing a few major components which restores its functionality and provides a good or acceptable performance for a second hand user (Lüdeke-Freund et al., 2019; Nasr et al., 2018); also known as reconditioning (King et al., 2006)
Remanufacture	Second hand	extends the life of a product by a comprehensive restoration and replacement of major components to provide a product with a condition and performance as good as new to a second hand user (Diallo et al., 2017; Nasr et al., 2018)
Repurpose	Second hand in other application	extends the life of a product or part by using it for another purpose than it was originally produced for; sometimes also known as second life, cascaded or second use (European Environment Agency, 2018; Lüdeke-Freund et al., 2019; Richa et al., 2017)
Recycle	-	closes material cycles by retrieving raw materials from the product and returning them to the production process of new products in lower (downcycling or open-loop), similar (closed-loop) or higher (upcycling) quality and functionality (Ellen MacArthur Foundation, 2013; King et al., 2006); **closed-loop** recycling results in the retrieval of recycled materials that can be used in the same type of products as before and, thus, substitute virgin material, whereas **open-loop** recycling provides materials that are only usable for other types of products and substitute other materials (Huysman et al., 2015); energy recovery is not considered recycling (Nasr et al., 2018)

In this work, the focus lies on the micro-level of such an economic system addressing how businesses can implement and operationalise the principles of the CE in their activities. Thus, the upcoming chapter focuses on businesses in a CE

3.2 Businesses in a circular economy

In the following sections, the evolution of the CBM concept as well as the operationalisation of the CE are presented, CBM innovation discussed and barriers and drivers for it reviewed.

3.2.1 Evolution of the circular business model concept

Traditional business models

To understand the concept of CBMs, one first needs to look at traditional business models. As for most concepts, several definitions exist for business models. However, based on comprehensive reviews, Geissdoerfer et al. (2018) propose the unified understanding that business models are *"simplified representations of the elements of a complex organisational system and the* *interrelation between these elements"* (p. 713). As such, business models describe *"the rationale of how an organisation creates, delivers, and captures value"* (Osterwalder et al., 2010, p. 14). The business model canvas by Osterwalder et al. (2010) conceptualises this rationale based on nine elements or building blocks. The *value proposition* describes the offer and value tailored to the needs and problems of the targeted *customer segments*, with whom certain *customer relationships* must be maintained. The ability to create and deliver this value proposition is dependent on a company's physical, intellectual, human, and financial *resources*, their performed *activities*, as well as *key partners*, if some activities are outsourced. Furthermore, *channels* for the distribution, sales, and communication must be defined to be able to capture *revenue streams* from the delivery of the product or service. The financial model is then also influenced by the *costs* occurring for the value creation and delivery. Richardson (2008) incorporated these elements in three main interrelated dimensions: value proposition, value creation and delivery, and value capture (see Table 3-2).

Table 3-2. Core elements of a business model

Value dimension	Key elements	Guiding question
Value proposition	• offer and value proposition • customer segments • customer relationship	What value is provided and to whom?
Value creation and delivery	• key resources • key activities • key partners and suppliers • channels	How is value provided?
Value capture	• cost structure • revenue streams	How does the company make profit and capture other forms of value?

Source: Osterwalder et al., 2005; Richardson, 2008

Circular business models

Based on the business model concept, business approaches that incorporate CE activities have emerged under the term of CBMs. Three main business strategies along resource efficiency are discussed for the operationalising of the CE: (1) *narrowing the loop* by minimising resource use per product, (2) *slowing the loop* by extending the useful life of a product or intensifying its utilisation, and (3) *closing the loop* by recycling materials at the end-of-life (Bocken et al., 2016).

However, Nußholz (2017) points out that a coherent definition is missing of which resource efficiency strategies should be classified as a CBM. Most crucially, there is disagreement on whether production-related strategies that are narrowing the loop are considered as CBMs, because these are already widely used in the linear economy building on the lean philosophy (Bocken et al., 2016). Thus, the main contribution of the CE lies in slowing and closing strategies. This is reflected in the definition proposed by Nußholz according to which *„a circular business model is how a company creates, captures, and delivers value with the value creation logic designed to improve resource efficiency through contributing to extending useful life of products and parts (e.g., through long-life design, repair and remanufacturing) and closing material loops"* (2017, p. 12). Following this definition, a CBM entails business activities that address resource efficiency improvements in the use and end-of-life phase. This way, companies can create commercial value by making use of the embedded economic and environmental value in a product, part, or the materials (Bakker et al., 2014; Den Hollander & Bakker, 2016; Moreno et al., 2016).

Nevertheless, CBMs are not inherently environmentally favourable. The resource efficiency gains in second life cases for example depend highly on the reverse logistic transportation demands as well as the impacts from the use phase during the second life (Cooper & Gutowski, 2017). For products with a high energy consumption in the use phase, for instance, the optimal lifetime should be assessed to account for energy efficiency improvements of new substitute products (Bakker et al., 2014). In contrast, products with low impacts in the use phase have a high potential for resource efficiency gains when extending the life as much as possible. Hence, the CBM should always be guided by a life cycle assessment to ensure the environmental benefit (Östlin et al., 2008). Furthermore, if a CBM wants to claim it is sustainable, it needs to be able to capture *"economic value while maintaining or regenerating natural, social, and economic capital beyond its organizational boundaries"* (Schaltegger et al., 2016, p. 3). In other words, a sustainable CBM must be economically viable while positively contributing to social and environmental forms of capital beyond the borders of their own organisation, thus, taking not only a company perspective but also a systems perspective.

Circular business model frameworks

To date, the categorisation of CBMs in academic literature is inconsistent. Bocken, Short, Rana, and Evans (2014) introduced eight sustainable business model archetypes, with one being to create value from waste under which reuse, recycle, re-manufacture, and closed-loops are listed as examples. In an analysis of 120 case studies, Accenture (2014) identified five main CBMs: circular supplies, resource recovery, product life extension, sharing platforms, and product as a service. Then, Bocken et al. (2016) introduced a classification with six circular business strategies: access/performance model, extending product value, classic long-life model, and encourage sufficiency model for slowing the loop, and extending resource value, and industrial symbiosis for closing the loop. Because of this inconsistency, Lüdeke-Freund et al. (2019) recently consolidated various frameworks by using the business model canvas and specifying potential design characteristics of its dimensions based on 26 CBMs proposed in the literature. Using this morphological framework, they identified six major CBM design patterns for repair & maintenance, reuse & redistribution, refurbishment & remanufacturing, cascading & repurposing, recycling, and organic feedstock, and finally combined these patterns with product design strategies.

Product design has been repeatedly discussed in the literature as a crucial factor to enable a CE and CBMs (Bakker et al., 2014; Bocken et al., 2016; Den Hollander et al., 2017; Ellen MacArthur Foundation, 2016). Design for maintenance and repair, for upgradability and adaptability and design for standardisation and compatibility support the extension of product life, while the design for dis-and reassembly is relevant for both slowing and closing loop activities (Bocken et al., 2016; Lüdeke-Freund et al., 2019).

Most visualisation tools and frameworks for CBMs have been developed on the basis of a single cycle (Nußholz, 2018) and use the business model canvas by Osterwalder et al (2010). Lewandowski (2016) added two elements that are specifically relevant to CBMs: take-back system and adoption factors (organisational capabilities and PEST factors). These factors are also found in Antikainen and Valkokari's (2016) "framework for sustainable CBM innovation" in which an analysis on three levels informs the evaluation of the business model: (1) the business level, represented by the business model canvas including reverse logistics in the element of channels, (2) the business ecosystem level, providing information on trends, drivers and stakeholder involvement, and (3) the sustainability impact, assessing the sustainability requirements and benefits of a business model. However, neither of these frameworks can represent and visualise the specific activities of a business model with several cycles.

While the different CBMs can be designed and implemented individually, a company in a CE should plan the value creation along the entire life cycle of a product. Thus, using a life cycle perspective will potentially lead to the integration of a CBM with several cycles and a dynamic value proposition because it changes throughout the product's life cycle (Den Hollander & Bakker, 2016; Nußholz, 2017, 2018; Spring & Araujo, 2017). Furthermore, each cycle requires different value creation and delivery activities as well as value networks (Wells & Seitz, 2005), and offers its own costs and revenue flows. Because existing business model design tools are not able to represent these potential multiple cycles in the visualisation of the business model architecture, Nußholz (2018) developed a CBM mapping tool that *"systematically integrates lifecycle value management with traditional business model design thinking"* (p. 186). This visualisation is meant to help map, analyse, and design the specific business model elements of a CBM across the entire life cycle of the product (Nußholz, 2018).

Closed-loop supply chains

As it is shown in all these frameworks, the collection and reintegration of a product, part, or material is key to the design and success of CBMs. In comparison to traditional business models, the organisation of efficient reverse logistic systems and closed-loop supply chains is highly relevant (Lewandowski, 2016; Schenkel et al., 2015; Wells & Seitz, 2005). Closed-loop supply chains consist of a forward and reverse logistics chain and can occur in different forms: (1) *post-business*, which entails a material exchange and an alignment of business models between companies involved in the production of a product, part or material, (2) *post-consumer*, which entails the return of a product or part to the original manufacturer via a company-based collection scheme to keep it in the original product or industrial sector, and (3) *post-society*, which entails the return of product and parts to an arbitrary point of manufacture (mostly material recyclers) usually through an independent logistic system (Wells & Seitz, 2005). Therefore, a closed-loop supply chain could, in theory, be organised with different levels of interaction between companies.

Often, reverse logistics activities are understood as instruments to achieving compliance with regulations such as the Batteries Directive 2006/66/EC in the case of LIBs, but Matthews et al. (2016) argue that they can offer a competitive advantage, save costs and help companies and their supply chains to succeed in developing a CBM. Businesses must, thus, arrange take-back and collection systems and decide how they are going to retain ownership of the products, parts or materials that are part of the specific CBM. For remanufacturing, Östlin et al. (2008) identified seven different types of closed-loop supply chain relationships to ensure the used product return: ownership-based (leasing or renting), service-contract, direct-order, deposit-based, credit-based, buy-back, and voluntary-based relationships. Regardless of the relationship, these supply chains are highly dependent on the willingness of customers to return their products and the quality and timing of the returned products are difficult to forecast. Vermunt et al. (2019) suggest that the development of close relationships with supply chain actors or retaining ownership of the product are the most promising strategies to influence the quality of a returned product.

It most often, however, requires setting up a sustainable supply chain network not only with existing suppliers and manufacturers but with other service providers that enable a CE (Winkler, 2011). Within these sustainable supply chain networks, Winkler (2011) argues two planning levels must be considered: First, partners must agree on common environmental goals and other principles for their cooperation on a network level. Then, the individual companies must translate these network goals and agreements into their own strategic and operational decisions (e.g. in purchasing). The importance of shared visioning with existing partners and potential future partners to create a common goal is also highlighted by Kraaijenhagen et al. (2016).

Moreover, in order to compete with traditional linear supply chains and business models, closed-loop supply chains and CBMs must be combined with transformed value creation structures (Wells & Seitz, 2005). These often require new partnerships, channels, and customer relationships. Schenkel et al. (2015) identified six clusters in which innovative value creation concepts in reverse supply chains have been studied and found: (1) partnerships and collaboration (strategic alliance, joint ventures, vertical coordination/integration), (2) product design (design for x, standardisation, life cycle view), (3) service concepts (leasing/renting, aftermarket services, deposit fees), (4) IT solutions (tracking, self-monitoring products, dismantling information system), (5) supply chain processes (quality management, value stream mapping), and (6) organisational characteristics (customer education and support, organisational alignment, resource commitment). A particularly positive effect is attributed to vertical integration, while few others also see benefits of collaborations such as horizontal, inter-firm networks or third-party service providers (Schenkel et al., 2015). Furthermore, Schenkel et al. (2015) find that modular design is widely regarded as the best design option for closed-loop supply chains.

Summary

To summarise, Table 3-3 describes the key differentiation in the value dimensions of a CBM in comparison to traditional business models.

Table 3-3. Core elements of a CBM

Value dimension	Key differentiation compared to traditional business models
Value proposition	• product or service offer containing and using a circular strategy to create value • waste streams are transformed to provide useful and valuable input for customers • proactively preserving the embedded economic, environmental, and social value in the product, part, or materials
Value creation and delivery	• designed to realise the value proposition(s) and the embedded circular strategies • innovating and re-configurating key activities, resources, partners, and channels necessary to overcome barriers • (new) partnerships across industries, large value chain alliances and networks needed to enable reverse logistics and activities that slow and effectively close material flows
Value capture	• additional revenue streams e.g. from markets for secondary production, services, or higher sales price for long-life product • cost-reductions e.g. substituting primary production with lower priced secondary production or avoiding disposal costs • non-monetary benefits e.g. risk reduction, customer satisfaction, information value to improve processes and product design

Source: Bocken et al., 2014; Linder & Williander, 2017; Nußholz, 2017; Schenkel et al., 2015; Wells & Seitz, 2005; Whalen et al., 2018

It has been argued that a business in the CE needs to think and design products differently than in the linear economy and innovate their business model to adapt to the new requirements (Ellen MacArthur Foundation, 2015). However, most businesses' strategies, structures, and operations are set up to capitalise on a linear approach (Accenture, 2014). In order to benefit from the opportunities of a CE, businesses must, thus, fundamentally change their way of working. One of the main challenges in integrating CE activities has been found to be rethinking the supply chains and the way value is created and delivered through the company's business model (Lüdeke-Freund et al., 2019; Schenkel et al., 2015; Wells & Seitz, 2005). Thus, business model innovation is seen as key to proceed to integrating CE activities into organisations (Geissdoerfer, Vladimirova, et al., 2018).

3.2.2 Business model innovation

Business model innovation describes the transformation of a company's business model which can either be achieved by radically implementing a completely new business model or by adjusting a few elements (Geissdoerfer, Vladimirova, et al., 2018; Zott & Amit, 2010). Thus, the degree of the business model innovation varies depending on the novelty of changes and whether these changes are architectural or modular (Foss & Saebi, 2017). While there are other forms of innovation such as product, service, and process innovation, a business model innovation perspective is understood to help systematically and holistically reflect upon all business model elements (Wirtz et al., 2016). Research on business model innovation has focused on five main aspects: the conceptualisation, the organisational change process, the outcomes, the implications, and drivers and barriers (Foss & Saebi, 2017; Wirtz et al., 2016).

The process of business model innovation

The process of business model innovation can be natural and gradual over time, known as the *evolutionary business model innovation*, or it can be focused on a novel innovation in one specific area of the business model, known as the *focused business model innovation* (Foss & Saebi, 2017). If a business model is changed to adapt to new market conditions and circumstances, it is known to be an *adaptive business model innovation*, whereas the changes could also disrupt market conditions and bring novelty to the industry, known as the *complex business model innovation* (Foss & Saebi, 2017).

The procedural steps for business model innovation have been discussed by various scholars (Geissdoerfer, Savaget, Bocken, et al., 2017; Geissdoerfer, Savaget, & Evans, 2017; Pieroni et al., 2019; Stampfl, 2016; Wirtz & Daiser, 2018). Wirtz & Daiser (2018) provide a summary of the process based on existing literature (see Figure 3-3).

Figure 3-3. Business model innovation process steps

Source: adapted from Wirtz & Daiser, 2018

As a first step, the current business model, the market, and competition are analysed followed by the ideation phase during which new business model ideas are generated and potentially conceptualised using the business model canvas. Before continuing with the development of prototypes for the different business model innovation alternatives and testing it in field experiments, the feasibility and profitability of such ideas should be estimated. Based on the tests, responsible managers must then decide on whether and how a business model innovation is going to be implemented. The implementation phase is usually defined by testing through a real pilot before full implementation, and the institutionalisation of the required change management to ensure the success of the business model innovation.

While this process can seem straight-forward, business model innovation is lengthy, complex and involves high risks because it is difficult to anticipate the actual performance of a business model in the market (Foss & Saebi, 2017; Wirtz et al., 2016). Experimentation has been identified as key to dealing with the uncertainty of business model innovation outcomes (Stampfl, 2016). Furthermore, it has been suggested that it might take longer than two to three years to facilitate a full-scale business model innovation process (Chesbrough, 2010). Additionally, macro-factors such as technology and regulatory changes, as well as market dynamics, and micro-factors such as customer needs, competition, company dynamics, and management influence the business model innovation and are subject to uncertainty (Stampfl, 2016; Wirtz & Daiser, 2017). Thus, business model innovation is also described as contextual (Kringelum & Gjerding, 2018) and does not necessarily imply a better market performance (Wirtz et al., 2016). The internal capacity to identify opportunities, react to opportunities and threats, and to remain competitive is another decisive factor for the process of business model innovation (Foss & Saebi, 2017).

Circular business model innovation

Business model innovation has been studied for about 20 years (Wirtz et al., 2016) but the research on CBM innovation is very new (Diaz Lopez et al., 2019). Many aspects are thought to be similar to traditional business model innovation (Antikainen et al., 2017; Antikainen & Valkokari, 2016; Bocken et al., 2019; Guldmann et al., 2019). However, in CBM innovation, the business model elements must be adapted with regards to the different cycles and circular strategies (Nußholz, 2017), which usually requires a fundamental change in the set-up of an organisation’s economic value creation for all stakeholders (Bocken et al., 2014; Zott & Amit, 2010). Thus, CBM innovation demands a more holistic process that needs to ensure the integration of customers’ and stakeholders’ perspectives through co-creation and collaboration (Bocken et al., 2019; Uusitalo & Antikainen, 2018).

The process of CBM innovation may be similar to conventional business model innovation as described above. However, Kraaijenhagen et al. (2016) specify a 10-step approach towards a circular business, which includes (1) Leadership, (2) Vision and purpose, (3) Selecting your pilot, (4) Sketching the system, (5) Visioning with partners, (6) Internal transformation, (7) CBM innovation, (8) Internalising externalities, (9) Contract, and (10) Scaling-up from pilot to circular business. Particularly noteworthy is the authors’ call for the development of a designated, cross-departmental team to manage the internal transformation and to make sure all changes and implications for the company are considered.

The main drivers for companies to engage with CBM innovation include resource efficiency and effectiveness, economic growth, and superior customer value (Geissdoerfer, Savaget, Bocken, et al., 2017; Pieroni et al., 2019). Additionally, competition is an underlying motivator as it might be necessary to innovate the business model to stay competitive (Anderson & Kupp, 2008). Typical changes in CBM innovation involve the introduction of take-back and reverse logistics systems, service-oriented value delivery schemes, increased collaboration amongst value chain actors, and new financial models (Pieroni et al., 2019). Diaz Lopez et al. (2019) found that CBM innovation is likely to affect partnerships, key activities and resources, channels, and customer segments.

Several factors influence the adoption of CBMs in organisations. Internal factors identified in the literature include leadership, business strategy, team commitment, in-house expertise and capabilities, the customer value proposition and interface (i.e. how circularity is integrated and affects the competitive landscape), and the value network (i.e. the organisation's internal activities and relationships with partners) (De Mattos & De Albuquerque, 2018; Lewandowski, 2016; Urbinati et al., 2017). External factors can be mapped along the conventional PEST framework, and include legislation, local government support, geographical proximity for industrial symbiotic practices, technological trends, and customer behaviour (De Mattos & De Albuquerque, 2018; Kurdve et al., 2019; Lewandowski, 2016; Planing, 2015).

Different barriers to sustainable business model innovation have been identified in the literature. Richter (2013) identified the lack of products and services, customer demand, competences, and profitability as four main challenges for the example of a distributed photovoltaic generation. Laukkanen and Patala (2014) summarise barriers to sustainable business model innovation along the categories of regulation (e.g. lack of long-term regulatory frameworks or inconsistent and overlapping regulatory mechanisms), markets and financial issues (e.g. financial risks or short-term management), and behavioural and social issues (e.g. lack of customer acceptance or stakeholder pressure). Moreover, a review by Lüdeke-Freund et al. (2016) revealed various barriers that particularly large and established companies face when developing sustainable business models: the pressure to achieve short-term results, the general aversion to the risk of potentially cannibalising existing business, the lack of capabilities to address social and environmental issues, the lack of integration between the business and sustainability strategy, as well as inertia and resistance to change because of structural and cognitive barriers.

Further barriers particular to CBM innovation include not being able to evaluate hypotheses because of the long timespans and risking a high amount of resources before reaching market validation for complex innovations like product as a service models (Linder & Williander, 2017). A recent publication investigating barriers to CBM innovation in multiple case studies concluded that most companies experience barriers at all four socio-technical levels, i.e. at the market and institutional level, the value chain level, the organisational level, and the employee level, with most barriers found at the organisational level (Guldmann & Huulgaard, 2020).

In order to deal with the barriers and uncertainties of a CBM innovation process, internal and external experimentation is considered a helpful tool to explore different possible CBM configurations and to receive feedback on their feasibility (Bocken et al., 2018; Linder & Williander, 2017; Weissbrod & Bocken, 2017). Internal experimentation is usually facilitated through mapping ideas with the business model canvas and discussing their potential and implications within the company (Chesbrough, 2010; Weissbrod & Bocken, 2017). In comparison, external experimentation includes customer interviews and the development and testing of a prototype with a trusted partner (Bocken et al., 2018; Linder & Williander, 2017). While the process of CBM innovation may differ depending on the company's context and setting, it always requires an open-minded search, generating several CBM alternatives, and the exploration and testing of some of these alternatives through experiments (Bocken et al., 2018; Guldmann & Huulgaard, 2019, 2020; Linder & Williander, 2017).

3.3 Circular economy strategies and electric vehicle lithium-ion batteries

With the increasing electrification of the transport sector and the subsequent growth of LIB production, scholars have been calling for the development of a life cycle strategy and management under consideration of social and environmental criteria (Olsson et al., 2018). This can be achieved by using a CE perspective. LIBs have been identified as a promising product with a high potential to benefit from CE strategies because their environmental impact is mainly caused in the production phase. CE strategies for LIBs, as they are discussed in the literature, are presented in Figure 3-4.

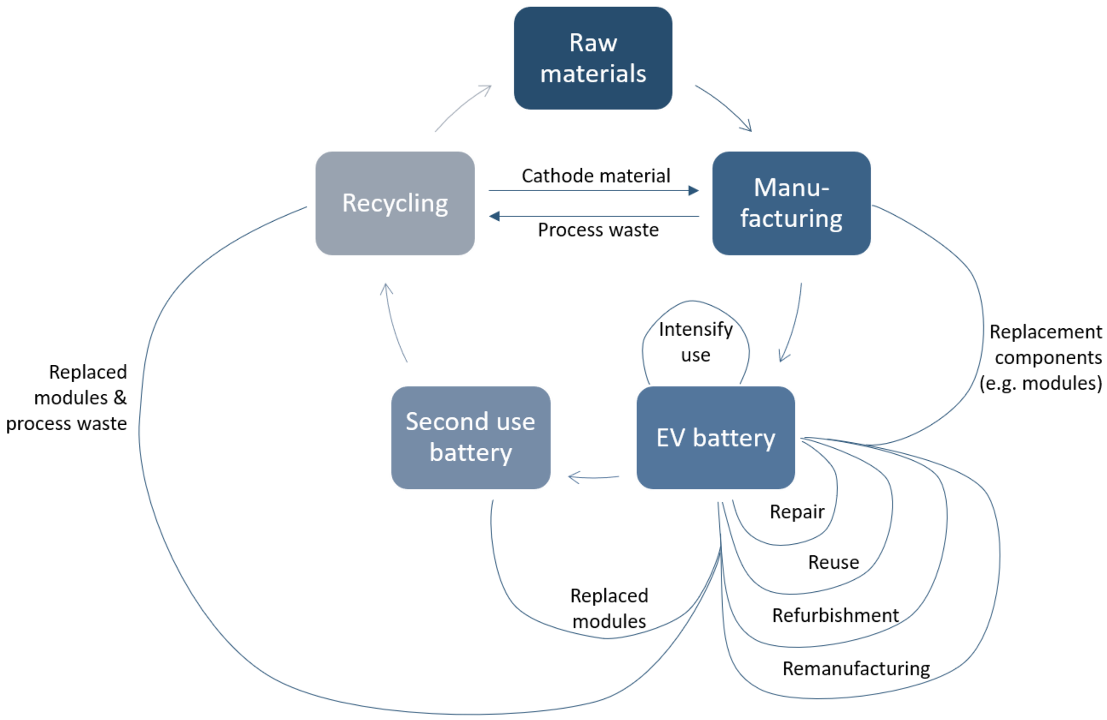

Figure 3-4. CE strategies for LIBs

Source: Kurdve et al., 2019; Nasr et al., 2018; Richa et al., 2017

Slowing the loop of LIBs can be achieved through intensifying the first use by utilising the idle capacity of a vehicle through sharing, prolonging the first use through repair, and extending the life of a LIB at its end-of-use through activities such as reuse, refurbishment, remanufacturing, or repurposing (Kurdve et al., 2019; Nasr et al., 2018; Richa et al., 2017). Recycling a cathode mix or single raw materials are discussed as methods to close the loop (Harper et al., 2019; Velázquez-Martínez et al., 2019). The current state of knowledge regarding the different CE strategies for LIBs is further introduced in the following sections.

3.3.1 Slowing the loop

Repair, reuse, refurbish, remanufacture

Little research is found on repair, reuse, refurbishing, and remanufacturing activities. Nevertheless, refurbishing has been described as the most prominent end-of-use strategy because of its value recovery and cost benefits (Qiao et al., 2017). It is claimed that most vehicle manufacturers are involved in repair and refurbishing within their own organisation or via third party suppliers (Melin, 2020). One study assumed, based on their experience in handling one particular LIB, that for a good performance 10% of the cells must be replaced on average (Standridge & Corneal, 2014). The replacement cells or modules, however, need to have similar characteristics to the remaining cells or modules.

While the automotive remanufacturing industry is the largest remanufacturing sector in the world for parts such as engines, transmissions, starters, alternators, and brakes (Matsumoto et al., 2016), it has not been found to be a promising option for LIBs yet (Kampker et al., 2016). Remanufacturing is said to be enabled by the presence of serial production, replaceable components, and a mature technology without disruptive changes (Sundin, 2004). With LIBs, the potentially disruptive technological advancements are described as the main reason why remanufacturing has not evolved as a major strategy amongst automotive OEMs (Kampker et al., 2016). Product design with modular interfaces, replaceable components, and the avoidance of glue could help overcome this barrier, but the current developments in LIB design are not found to focus on this (Michaelis et al., 2018). At the same time, remanufacturing is seen as a potential solution to provide spare parts even after the series supply of LIBs, especially for vehicles with a long lifetime such as buses (Kampker et al., 2016).

Repurpose

A lot of research has focused on the potential of repurposing LIBs after their first use in a vehicle for a second life in a different application. Automotive OEMs are investigating repurposing as support for their EV programme (Jiao & Evans, 2016b). Melin (2020) found that existing investment by companies, partnerships for second life solutions, the increasing availability of end-of-use LIBs, and a limited supply of new LIBs are the main drivers for the second life investigations and involvement. Furthermore, an increasing amount of distributed and fluctuating electricity production from solar and wind accelerates the demand for (local and regional) energy storage solutions to reduce the stress on the electricity grid (Dusonchet et al., 2019; Vattenfall, 2020). Grid-connected battery storage systems are seen as one solution to support the transition to a system of renewable energy production (European Commission, 2019b). These battery storage systems could be based on new batteries but may as well use repurposed LIBs from EVs.

Many publications refer to the fact that, when removed from the vehicle, LIBs usually retain a capacity of 70-80% and could still be sufficient for use in a less demanding second life application (Ahmadi et al., 2014; Bobba, Mathieux, et al., 2018; Neubauer & Pesaran, 2011; Olsson et al., 2018; Pagliaro & Meneguzzo, 2019; Richa et al., 2017). Neubauer et al. (2015), however, note that in several cases LIBs have been found to have degraded more than the typically assumed 80%. This is because there is no strict rule that a LIB must be decommissioned at a certain capacity level but instead is dependent on the user demand (Sanghai et al., 2019). A recent report by Jiao (2019) providing a global second life battery availability forecast shows that LIBs from buses and trucks will already be available in larger numbers by mid-2020. By 2030, the report expects the available capacity to rise to 275 GWh per year with more than half coming from buses and light, medium- and heavy-duty trucks.

There are several possible applications that have been identified as suitable for a second life of LIBs. Olsson et al. (2018) listed the following: storage of solar or wind power, peak shaving, EV charging, increased grid capability and stability, backup, electricity trading, or vehicle propulsion (such as ferries or forklifts). Research has focused mostly on the integration of second life batteries into larger systems that support national power grids (Gladwin et al., 2016; Saez-de-Ibarra et al., 2016), as well as smaller applications such as mobile charging stations, or small-scale energy storages for solar photovoltaic systems (Assunção et al., 2016; Cusenza, Guarino, Longo, Mistretta, et al., 2019; Ioakimidis et al., 2019).

Despite the environmental benefits of repurposing LIBs, it is claimed that the market is currently undeveloped (Bobba, Mathieux, et al., 2018). Recent data on the second life market shows that 158 MWh of energy storage capacity using EV LIBs are installed in Europe, half of which is provided by replacement LIBs, and the other half by second life LIBs (Melin, 2020). Melin (2020) additionally noted that all larger projects have been carried out or been supported by OEMs. Hence, the involvement of OEMs seems to differ. One research suggests limiting the role of the OEM to the collection and repurposing of LIBs, and outsourcing the service and maintenance of the second life application to a partner such as an energy system integrator (Larsson, 2016).

The repurposing process for the second life can include a certain degree of disassembly, testing for degradation and failure, packaging the batteries for second life, as well as adding electrical hardware, control, and safety systems (Ahmadi et al., 2014; Sanghai et al., 2019). Some authors assume that dismantling down to cell level is not feasible from a technical or economic perspective (Ahmadi et al., 2014; Casals, García, & Cremades, 2017). Instead, it is possible to use the entire battery pack without refurbishing. Faulty LIBs, however, must be examined on a module level to then select and assemble modules with similar characteristics together to a new battery pack for a second life application (Sanghai et al., 2019).

In general, it has been stressed that advanced methods of monitoring and testing are required to identify the potential of a pack, module, or cell for an extension of life (Harper et al., 2019). A number of articles discuss new methods for monitoring cells via the battery management system (BMS) to gain a better knowledge of how the battery has been used and inform the decision on life extension (Christensen & Adebusuyi, 2013; Monhof et al., 2015). Still, feasible, reliable, and automated solutions to assess the battery's performance and predict its remaining useful life are yet to be developed (W. Chen et al., 2019; Kurdve et al., 2019). Little research takes into account how quickly LIBs degrade when they are actually used in the second life application (Martinez-Laserna et al., 2018). The potential lifetime of LIBs in second life applications is, thus, subject to uncertainty and estimation.

3.3.2 Closing the loop

In comparison to activities that prolong the life of LIBs, recycling is not a voluntary activity in the EU but required by law. Currently, the Batteries Directive 2006/66/EC does not specify recycling efficiencies for specific materials, which is why recycling processes mainly focus on the recovery of materials with high economic value or those that are easy to recover such as cobalt and copper (Gaines et al., 2018; Velázquez-Martínez et al., 2019). Nevertheless, various reports highlight the potential of LIB recycling to contribute to securing the raw materials supply for future LIBs in the EU (Dias et al., 2018; Elwert et al., 2019; Öko-Institut, 2018). With a growing battery value chain, this may become more important from a supply perspective and is repeatedly presented as a major driver towards a closed-loop recycling system in the EU.

Much research is on-going to make recycling more efficient and to find the optimal process that is economically feasible on a large scale (Dahllöf et al., 2019). So far, however, there has been no indication in research reviews as to which process could be considered state-of-the-art (Melin, 2019). The recycling process and its material recovery performance can vary significantly based on the combination of different operations (D'Adamo & Rosa, 2019). In general, however, it can be divided into the phases of pre-treatment, metal extraction, and product preparation (Dahllöf et al., 2019; Lv et al., 2018).

During the pre-treatment phase, LIBs are potentially disassembled to module or cell level and discharged. Because of the lack of a standardised battery pack, the disassembly is currently done manually, which is time-consuming and uneconomic in countries with high labour costs (Harper et al., 2019). Nevertheless, LIBs are usually dismantled to module level to avoid wasting energy on incinerating or transporting the aluminium or steel casing, which can be recycled elsewhere locally (Quix, 2019). For some metal extraction processes, mechanical processes (also known as physical separation processes) in which LIBs are treated with shredders, sieves, and magnetic separators may be necessary (Harper et al., 2019). The disassembled and discharged parts or the different output fractions from a mechanical pre-treatment can then be further refined through metal extraction processes.

Currently, the most common metal extraction processes are pyrometallurgical and/or hydrometallurgical treatment (Belchí Lorente et al., 2015; Diekmann et al., 2017; Melin, 2019). Pyrometallurgy with subsequent hydrometallurgy or only hydrometallurgy seem to be the most common techniques amongst large-scale recyclers around the world to-date (Dahllöf et al., 2019; Lv et al., 2018). In pyrometallurgy, LIBs are smelted in a furnace at high temperatures of around 1400 °C to afterwards extract and purify valuable metals such as cobalt, copper, and nickel (Belchí Lorente et al., 2015; Lv et al., 2018). The pyrometallurgical process provides three outputs: (1) the metallic alloy fraction containing nickel, cobalt, copper, and iron, which requires hydrometallurgy to extract the single metals, (2) the slag containing aluminium, manganese, and lithium, which can be an input for other industries such as the cement industry or further processed with hydrometallurgy to extract the metals, and (3) gases (Harper et al., 2019). In contrast, hydrometallurgy uses different acids, bases, or solvents as leaching agents to dissolve the metals (Belchí Lorente et al., 2015). It is eventually combined with a precipitation/filtration step to recover the metals in the product preparation phase.

A third method, direct recycling, is currently not used on an industrial scale but has been successfully tested for laptop and mobile phone batteries (Harper et al., 2019). In this process, cathode or anode materials are removed from the electrode and recovered as a mixture through physical processes instead of separating the metals (Ciez & Whitacre, 2019; Dahllöf et al., 2019; Harper et al., 2019). Only minimal changes are required to recondition the active material for the new LIB, but the lithium content must be replenished to compensate for degradation losses (Harper et al., 2019). Direct recycling requires the new LIB to use the exact same cathode or anode composition as the recycled one. With the rapidly changing cell chemistries and mixtures, this is currently a less suitable approach (Harper et al., 2019). The efficiency of this method has also been found to correlate with the state of health (SOH) of a battery. Hence, it is less compatible with extension of life strategies that reduce the SOH of the battery (Harper et al., 2019). Pyro- and hydrometallurgical processes can recover about 70% of the cathode value of a high-cobalt LIB, but this drops significantly for chemistries such as lithium-iron phosphate (LFP) because of the low material value (Gaines et al., 2018). Hence, direct recycling could be especially relevant for lower-value cathode chemistries and LIBs with a higher SOH because it avoids expensive purification steps (Harper et al., 2019).

There is a discussion as to whether recycled cathode material can be used for LIBs production again, but Li Li et al. (2018) point out that most authors conclude that it can. Otherwise materials would most likely be downcycled in applications with lower quality and functionality (Ellen MacArthur Foundation, 2013; King et al., 2006). Closed-loop recycling of LIBs is seen as a chance to reduce costs, but Gaines et al. (2018) stress that it requires partnerships between the recyclers and the battery producer.

3.4 Factors influencing the adoption of circular economy strategies for lithium-ion batteries

The actual utilisation of the previously outlined life cycle strategies and their operationalisation in business models is dependent on various external and internal factors (Lewandowski, 2016). In the following sections, the findings from existing research will be discussed and organised along political, economic, social, technological, (i.e. PEST) and internal factors (Kurdve et al., 2019).

3.4.1 Political and legal background

Currently, the share of European LIB cell production is 3%, while Asia provides 85% of all LIB cells (Tsiropoulos et al., 2018). However, in the transition to a decarbonised transport sector, the European Council and Commission have identified batteries as a strategic value chain in the EU to ensure sustainable production practices and the competitiveness of the European automotive sector (European Commission, 2019b). In October 2017, the European Battery Alliance, an industry-led initiative backed by the European Commission, was launched with the objective to create a sustainable and competitive battery cells manufacturing value chain (European Commission, n.d.-a). Moreover, the Commission adopted a "Strategic Action Plan on Batteries" in May 2018, which reinforces the focus on building a European battery value chain. Recycling raw materials from existing LIBs and second life applications are repeatedly mentioned as a way to reduce the dependency on imported raw materials (European Commission, 2017, 2019b). In this section, the regulatory framework for LIBs applicable in 2020 and an outlook are introduced.

The Batteries Directive 2006/66/EC

LIBs fall under an Extended Producer Responsibility (EPR) legislation with the Batteries Directive 2006/66/EC. Batteries are divided into portable, industrial, and automotive batteries, whereby LIBs belong to the category of industrial batteries (Art. 3(6) 2006/66/EC). This puts the burden of organising and paying for the collection and recycling of waste industrial batteries onto the producer of these products (Kunz et al., 2018; Lifset, 1993). According to Art. 3(12) 2006/66/EC, producers are defined as any person that *"places batteries or accumulators, including those incorporated into appliances or vehicles, on the market for the first time within the territory of that Member State on a professional basis"*. Hence, this applies to vehicle manufacturers or the importers in the respective countries. The shift of the responsibility for end-of-life management away from municipalities to the producers aims to provide incentives to improve the design of their products and packaging, to decrease waste, as well as to increase reuse and recycling (Kunz et al., 2018; Lifset, 1993; OECD, 2016). Thus, EPR is recognised as a policy instrument that encourages companies to engage with CBMs.

For industrial batteries, the collection does not have to be organised via a specific scheme. The directive only specifies in Art. 8(3) 2006/66/EC that producers or third parties acting on their behalf *"shall not refuse to take back waste industrial batteries and accumulators from end-users, regardless of chemical composition and origin."* Thus, producers can decide individually how to take back LIBs. Independent third parties may, however, also collect industrial batteries and are not obliged to return them to the producers. According to Art. 3 (7) of the Batteries Directive, batteries are defined as waste when Art. 3 (1) of the Waste Directive 2008/98/EC applies[4], whereby any

[4] The original Waste Directive 2006/12/EC which is referred to in the Batteries Directive was repealed by the new Waste Directive in 2008.

substance or object is a waste, when its holder *"discards or intends or is required to discard it"*. A holder is *"the waste producer or the natural or legal person who is in possession of the waste"* (Art. 3 (6) 2008/98/EC). If the LIB is prepared for reuse in the same application through checking, cleaning, and repairing, it is not regarded as waste according to Art. 3 (16) 2008/98/EC. There are currently no clear definitions and rules for remanufacturing and repurposing of LIBs. Once the LIB can no longer be used in the application for which it was designed it is considered waste even if it could be repurposed for a different application (Timmers, 2019).

The treatment of LIBs needs to achieve a recycling efficiency of 50% by average weight (Annex III, Part B, 3(c) 2006/66/EC). This recycling efficiency has to be calculated according to the rules specified in the Commission Regulation (EU) No 493/2012 of 11 June 2012 pursuant to the Batteries Directive. Overall, EV LIBs shall not be disposed in landfills or by incineration, but residues from treatment and recycling processes may be landfilled or incinerated (Art. 14 2006/66/EC). This could be understood as an indirect collection requirement of 100%, but it is not an explicit binding requirement like the collection targets for other batteries, thus leaving room for interpretation. The original producer remains legally responsible for recycling until the LIB is no longer waste, which can only be achieved when it is processed by a facility with an end-of-waste ruling of the national authorities (Timmers, 2019). The documentation on the marketing, collection, and recycling of LIBs is provided annually to the national authorities by the producers.

Future of the regulatory framework for LIBs

The Batteries Directive has recently been evaluated and several limitations were identified both in legal provisions and its implementation that prevent the fulfilment of its objectives to minimise the negative impact of batteries on the environment (European Commission, 2019a). With regards to extending the life of LIBs it was *"agreed that the current legislation is not sufficient to deal with the new situation of the re-use/second use"* (European Commission, 2019a, p. 86). Moreover, the European Commission signed an Innovation Deal[5] in March 2018 with several French and Dutch ministries as well as innovators such as Renault. The goal was to investigate the regulatory constraints for reuse and second life of LIBs as well as possibilities to overcome potential barriers (European Commission, 2018). The final report of the results has yet to be published. Nevertheless, it shows the interest and demand for clear guidelines on the transfer of ownership of the EPR when LIBs are repurposed for a second life (Lebedeva et al., 2017).

Because of the missing European rules regarding the legal responsibility for repurposed LIBs, the Netherlands have introduced an end-of-waste verdict that enables the transfer of the legal EPR to companies that convert and repurpose waste LIBs if they have successfully applied for the verdict (H. Timmers, personal communication, 4 March 2020). To be granted the verdict, companies need to demonstrate they possess a fixed supply chain, a fixed treatment process, and a demonstrable customer base (e.g. by a letter of intent). They must also have an environmental permit to take in external waste from outside the own production process and notify the authorities (either collective or individual) to register the repurposing company as a producer of the repurposed "new" LIB. It is not clear whether similar rulings exist in other European member states today.

[5] Innovation deals are voluntary cooperation agreements between the EU, innovators, and national, regional, and local authorities with the objective to gain an in-depth understanding of the practical implications of an EU regulation (European Commission, n.d.-b).

The Batteries Directive is currently under review and it is assumed that an updated legal framework, which is expected to be proposed in 2020, will include new provisions specifically for EV LIBs and provide *"an adequate legal framework for second life applications"* (European Commission, 2017, p. 30). According to the recently published CE Action Plan of the European Commission (2020), a new regulatory framework to help the emerging battery industry in Europe to become more sustainable and competitive will be adopted. As part of this new framework, rules on recycled content and measures, by which the recovery of valuable materials and the collection and recycling rates of all batteries are improved, are discussed (European Commission, 2020). With regards to rechargeable batteries in EVs, the plan mentions the consideration of potential sustainability and transparency requirements regarding *"the carbon footprint of battery manufacturing, ethical sourcing of raw materials and security of supply, and facilitating reuse, repurposing and recycling"* (European Commission, 2020, p. 8). In a current assessment of options to improve the regulatory framework on batteries, the following LIB-relevant topics are investigated: second life of industrial batteries, minimum levels of recycled content, deposit and refund systems, removability, replaceability, and interoperability of batteries (European Commission, 2019c). Thus, it can be expected that a new regulation will include a stronger focus on CE and the environmental performance of LIBs.

Storage and Transport

Currently, there is no regulation concerning the storage of LIBs (Timmers, 2019), which is why some OEMs introduce their own voluntary standards. In contrast, strict regulations exist for transportation. LIBs are classified as class 9 dangerous goods, which is why they are mostly transported on trucks (Ciez & Whitacre, 2019). For road transport of LIBs, the United Nations treaty *European Agreement Concerning the International Carriage of Dangerous Goods by Road* (ADR) applies (United Nations et al., 2016). Depending on whether the LIB is new, waste, or damaged, different transportation and packaging instructions apply. When LIBs are returned to the dealer, the ADR regulation requires them to classify the batteries for transport (Timmers, 2019).

Repair and Information

The EU aims to guarantee a free competition on the vehicle aftermarket and does not allow discrimination with respect to authorised dealers and repair workshops. In order to ensure this, several EU regulations have been implemented on access to vehicle repair and maintenance information. For heavy-duty vehicles, this is specified in Art. 6 Regulation (EC) No 595/2009 (EURO VI), according to which manufacturers have to *"provide unrestricted and standardised access to vehicle OBD information, diagnostic and other equipment, tools including any relevant software and vehicle repair and maintenance information to independent operators."* Vehicle repair and maintenance information is defined as *"all information required for diagnosis, servicing, inspection, periodic monitoring, repair, re-programming or re-initialising or the remote diagnostic support of the vehicle and which the manufacturers provide for their authorised dealers and repairers, including all subsequent amendments and supplements to such information. This information includes all information required for fitting parts or equipment on vehicles"* (Art. 3 (11) Regulation (EC) No 595/2009).

3.4.2 Economic background

Economic potential of repurposing

It is argued that the total cost of ownership of LIBs contributes to the slow uptake of EVs. The extension of the life of LIBs through reuse and repurposing is frequently discussed as an option to provide new revenue streams by which the LIBs and vehicles could be offered to the first customer at a lower price (European Commission, 2018). The actual economic benefit and potential of second life applications with repurposed LIBs, however, remains a point of discussion in academic literature. Many studies acknowledge great economic opportunities from second life applications for LIBs, especially from energy storage applications (Debnath et al., 2014; Jiao & Evans, 2016a; Lacey et al., 2013). Both selling used LIBs and earning money from actively using them in a different application have been identified as potential revenue models (Jiao & Evans, 2016a).

A previous master thesis investigating how Volvo Group could create a sustainable and economically profitable business case for second life batteries from trucks and buses found that the main expense for repurposing are labour costs for the technicians (Larsson, 2016). These labour costs are mainly related to the time needed for manual module testing. Thus, efficient testing measures are crucial for lowering costs. A large benefit is also found in postponing the recycling costs (Jiao & Evans, 2016b; Larsson, 2016; Sun et al., 2018). However, with the advancements of recycling practices and volatile raw material prices, this is subject to change. Nevertheless, LIB reuse and repurposing have been found to be much more economically attractive options for LIB owners for the foreseeable future compared to recycling (Kelleher Environmental, 2019).

Moreover, Martinez-Laserna et al. (2018) note that the constantly reduced price for new LIBs will reduce the economic advantage of using repurposed LIBs. With the market expansion of EVs and technological progress, the unit price of a new LIB continues to decline while its performance will be improved (Zhu et al., 2017). Because the repurposing costs of the spent LIBs remain high, it may not be economically competitive in comparison to new LIBs in the future (Yang et al., 2020). Sun et al. (2018) also conclude that the viability of the second life market is questionable if the price of a second life battery is too close to the one of a new one that is more efficient and potentially lasts longer. Richa et al. (2017) expect no economic benefit from second life applications if costs for new LIBs reach $132/kWh. Since costs for new LIBs have decreased faster than projected, another report concludes that the business case for second life applications needs to be explored with costs for new batteries of $100/kWh (Kelleher Environmental, 2019). This is supported by Melin (2019), who acknowledges that the rapid industrial and technological development leads to outdated cost (for logistics, dismantling, repurposing, and testing) and revenue (returns from sales or operations) calculations, which can affect the actual dynamics in the market. However, Jiao, & Evans (2016b) argue that repurposed batteries may not be able to compete with new batteries in a product-based "business-as-usual" scenario, but by developing a service-based business model, which reduces risks for customers, they may be more attractive. Furthermore, experts at McKinsey estimate that repurposed LIBs will be 30 to 70% less expensive than new LIBs in 2025, but that this cost advantage could drop to 25% by 2040 (Engel et al., 2019).

Economic potential of recycling

Recycling has not yet proven to be profitable and remains a cost for producers (Idjis & da Costa, 2017; Lin Li et al., 2018; Mayyas et al., 2019). These costs are expected to decrease in the future (Timmers, 2019). Nevertheless, it is not certain whether the recycling of LIBs will ever be a profitable business. An analysis by Idjis & da Costa (2017) concluded that recycling will remain a net cost for producers in all tested scenarios. The current economic conditions, Harper et al. (2019) note, favour the second life of LIBs because it could result in additional income and avoid recycling costs today. Only if the additional income were to be less than the refurbishment cost and the avoided recycling costs together, recycling would be economically favourable. However, it requires in-depth modelling of future cost developments for all life cycle activities (including refurbishing, repurposing, and recycling) to make a life cycle management decision based on economic aspects.

Despite larger volumes returning in the long-term, the uncertainty of the future composition of LIBs presents a challenge for the economic viability of recycling. In a recent patent, seven main raw materials were reported to make up more than 90% of the economic value for recycling, out of which 39% originated from cobalt (Kochhar & Johnston, 2018). The current trend in LIBs development, however, is to move away from high-cobalt battery chemistries and to use lower cost-chemistries with manganese or iron and less rare materials (Kurdve et al., 2019; Mayyas et al., 2019; Richa et al., 2014; Wang et al., 2014). This could endanger the economic viability of LIB recycling in the long-term because cobalt drives the economic revenue of recycling. Then, the recycling of LIBs would rely on other incentives such as legislation or good-will (Kurdve et al., 2019).

At the same time, increasing costs for other raw materials and supply shortages of LIBs could make the recycling of other materials such as lithium and manganese more profitable (Kurdve et al., 2019; Pagliaro & Meneguzzo, 2019). Hence, there is a lot of uncertainty around the economic feasibility of recycling in the long-term and the main factors influencing it are the battery chemistry, battery volumes, commodity prices, and recovery targets set by policy (ElementEnergy, 2019). However, there is no evidence that recycling of LIBs will be profitable in the next five years because the most promising technologies have not been developed at commercial scale yet (Kelleher Environmental, 2019).

3.4.3 Socio-cultural background

There is little research and emphasis in research on the socio-cultural influences on a CE approach and LIBs. Nevertheless, end-user behaviour with regards to the disposal of EVs and their incorporated LIBs as well as a potential customer demand for certification of ethical and conflict-free products have been identified as potential influencing factors (Kurdve et al., 2019). Furthermore, increasing environmental consciousness among the public may be relevant for policy development (Weng et al., 2019) as well as the adoption of CE strategies amongst companies. The focus of public concern can potentially vary and lean more towards impacts on climate change, raw material degradation, or social justice, which can impact the choice of a CE strategy for LIBs.

3.4.4 Technical background

The technological development with regards to cell chemistries is frequently mentioned as an important factor influencing the adoption of CE strategies (Kurdve et al., 2019; Mayyas et al., 2019). To date, LIBs in EVs use different cell chemistries because of rapid technological advancements. The battery chemistries are usually differentiated based on the cathode materials (Saw et al., 2016). The most commonly applied chemistries for commercial EVs are LFP and lithium nickel manganese cobalt oxide (NMC) cathodes (Harper et al., 2019; Hottenroth et al., 2018). Other, less popular cell chemistries for EVs include lithium-manganese-oxide and nickel-cobalt-aluminium-oxide (Harper et al., 2019). NMC has a much higher energy density than LFP, which is why automotive OEMs have predominantly focused on this cell chemistry for fully electric vehicles. Because of the high price volatility of cobalt and its social and environmental risks related to mining, substantial efforts have been put into research and development to reduce its share in NMC batteries (Mayyas et al., 2019; Nitta et al., 2015; Wang et al., 2014). Whereas development once started with a Nickel-Manganese-Cobalt ratio of 1:1:1, nowadays NMC batteries with a ratio of 8:1:1 have reached a high market share (Adamas Intelligence, 2019). Further cell development is focused on the commercialisation of no-cobalt chemistries with equally high energy densities, lithium-sulphur, and solid-state batteries (Bernard, n.d.). However, it is expected that LIBs will dominate the market for the next 10 years.

LIB cells can be designed as cylindrical, prismatic, or pouch cells. A given number of cells are combined and a casing, terminals, as well as a few electronics are added to create a battery module. These modules are the basis for a battery pack, which additionally needs electronics, a cooling system, and a BMS. The BMS provides monitoring and management of the charge/discharge processes of the modules to ensure the safety of the battery pack as well as to prevent overcharging and overvoltage of modules (Yang et al., 2020). Design specifications have been identified as to enabling the adoption of CE strategies for LIBs (Gaines et al., 2018; Kurdve et al., 2019; Pagliaro & Meneguzzo, 2019). Cells and modules may, for example, be designed to allow a potential exchange during refurbishment and modularisation (Saw et al., 2016). Recycling may also be simplified through product designs (Pagliaro & Meneguzzo, 2019). While there is little research on design for recycling (Melin, 2019), Gaines et al. (2018) provide four main suggestions: (1) similar packs and modules enabling the construction of automated disassembly lines, (2) standardisation of cell designs (i.e. material compositions even within one cell chemistry e.g. NMC) to avoid sorting needs and enable direct cathode material recycling without recovering separate metals (direct recycling), (3) fewer components (different materials), and (4) joining methods that enable an easy disassembly (i.e. using nuts and bolts to assemble the pack instead of welding or glue or holding cells in place with means other than potting or thermo-setting compounds). Moreover, the further development of recycling technologies will influence the economic feasibility and, thus, the large-scale adoption of closed-loop recycling in the industry (Dahllöf et al., 2019).

In order to decide whether a battery pack, module or cell can be reused, refurbished, repurposed, or must be recycled when it has been returned by the customer, a comprehensive diagnosis of its status is required. The SOH, a metric that indicates the ageing level of a LIB i.e. to which degree the condition of a LIB compares to the initial specifications (Berecibar et al., 2016; Harper et al., 2019), is most commonly used as the basis for this decision. The SOH can be monitored by the BMS and determined on a cell, module, or pack level. It can be based on a combination of parameters such as capacity, voltage, temperature, and internal resistance. However, there is no consensus yet on what exactly the SOH is and, consequently, how it is supposed to be assessed (Berecibar et al., 2016). Thus, every battery producer and automotive OEM currently defines their own way of measuring it. Ideally, the SOH is monitored continuously during the use of the batteries to identify and predict whether a battery, a module, or a cell need replacement (Harper et al., 2019). This can, for example, be achieved through data-driven machine learning (Ng et al., 2020). It is argued that the BMS should store data on temperature, voltage, depth of discharge, state of charge, and short circuits at a cell level to support a maximisation of its value throughout the entire lifecycle (Reid & Julve, 2016). Furthermore, the operational history of a battery pack may also provide important information on e.g. operating temperatures, average driving distances, or driving habits (Nenadic et al., 2014; Reid & Julve, 2016).

3.4.5 Internal factors

In contrast to external factors, which are similar for all companies, internal factors vary across different manufacturers by their very nature. Little research deals with specific internal factors, but Olsson et al. (2018) found that many barriers to a second life of LIBs are rooted in organisational and cognitive nature. These relate to internal resources and capabilities needed to support necessary adaptations, the reluctance of decision-makers to invest due to existing uncertainties, and the collaboration along the value chain (Olsson et al., 2018). The closed-loop supply chain (infrastructure) as an aspect of the design of the specific value networks has been identified as another differentiating internal factor (Kurdve et al., 2019). Little research was found on the existing collection and reverse logistic systems for LIBs even though the creation of effective and efficient take-back systems to enable reverse logistics and product returns is already legally required in the EU due to the EPR manufacturers or importers hold according to the Batteries Directive 2006/66/EC.

Generally, a producer can organise the national take-back systems for LIBs either via a Producer Responsibility Organisation, which arranges the waste management on behalf of various producers in a certain country, or by individual contracts between producers, dealers, and recyclers (Monier et al., 2014). No comprehensive report was found on the current organisation for LIBs, but it was claimed that their recovery is mostly enabled by business to business contracts (Monier et al., 2014). While the producers must accept LIBs when they are returned and finance the recycling, they are not entitled to receiving them from dealers or customers if they were sold together with the vehicle. Thus, if an automotive OEM is designing CBMs based on the returns of LIBs, they might have to retain ownership and make an effort to get LIBs back by convenient take-back systems as well as tracing tools (Östlin et al., 2008).

Klör et al. (2015) identified three potential market options for trading used LIBs between owners and second life applicants: (1) an open market in which access to an online marketplace is unrestricted, thus, allowing anyone to become a supplier, buyer or modifier of LIBs, (2) an intermediary-based market in which an intermediary collects LIBs from users and OEMs, potentially modifies them and sells them to a second life applicant, and (3) a closed market in which LIBs are only returned to and modified by the OEM. They found that a closed market was most preferable from a transaction cost perspective. However, experts interviewed by the authors expect an intermediary-based market with support from the automotive industry will form. Adding to this, Kurdve et al. (2019) argue that for a free market infrastructure (i.e. an open market), substantial standardisation and open information are required whereas a regulated system (i.e. a closed market) is defined by closed information and OEM-reliant operations, thus requiring large volumes for a high efficiency of such a system.

Within the current predominant practice, a dealer or dismantler removes the LIB from an end-of-life EV, as required by the ELV Directive, before it is sent to a recycling facility at the cost of the producer (Kurdve et al., 2019). Only a small amount is currently diverted for reuse or repurposing (Kurdve et al., 2019). Removing and handling LIBs requires special training of staff at the workshops on high-voltage energy storage systems and potentially brand-specific training and sometimes even equipment as well (Klör et al., 2015). If the used battery pack should be checked to assess whether it is still good for use, a testing procedure has to be established within the reverse logistics chain, which could be based at the vehicle dealers or somewhere else in the recycling sequence (Ahmadi et al., 2017). They would then need to diagnose the LIB's status to decide whether it should be reused, refurbished, repurposed, or recycled. One proposed solution would require access to the data from the BMS, which is usually encrypted by OEMs for data protection (Klör et al., 2015). Thus, information sharing and collaboration amongst these actors would be needed for this process (Kurdve et al., 2019; Olsson et al., 2018). Moreover, transportation has been identified as one of the cost drivers in end-of-life processes (Idjis & da Costa, 2017). Hence, there is a desire to optimise the logistics of LIBs and to reduce transports wherever possible, which is why the localisation of CE activities such as reuse, repurposing, and recycling is another factor to be considered in the differentiation of adoption (Kurdve et al., 2019).

3.5 Challenges for circular economy strategies for lithium-ion batteries

This section provides a summary of challenges proposed in the literature for repurposing or recycling, some of which are connected to the previously mentioned external and internal influencing factors.

3.5.1 Challenges for slowing the loop

Because of the lack of literature specifically relating to repair, refurbishment, and remanufacturing of LIBs, the challenges will be delineated for repurposing only. Several challenges influencing the large-scale uptake of second life projects have been identified by researchers such as Olsson et al. (2018), who provide an overview of cognitive, organisational and technical barriers, or Bobba, Cusenza et al. (2018), who summarise them in a list of regulatory, technical, and economic barriers, as well as safety and responsibility issues. Figure 3-5 presents some of the most common technical, economic, internal, organisational, and regulatory barriers proposed in the literature that prevent actors from upscaling second life projects.

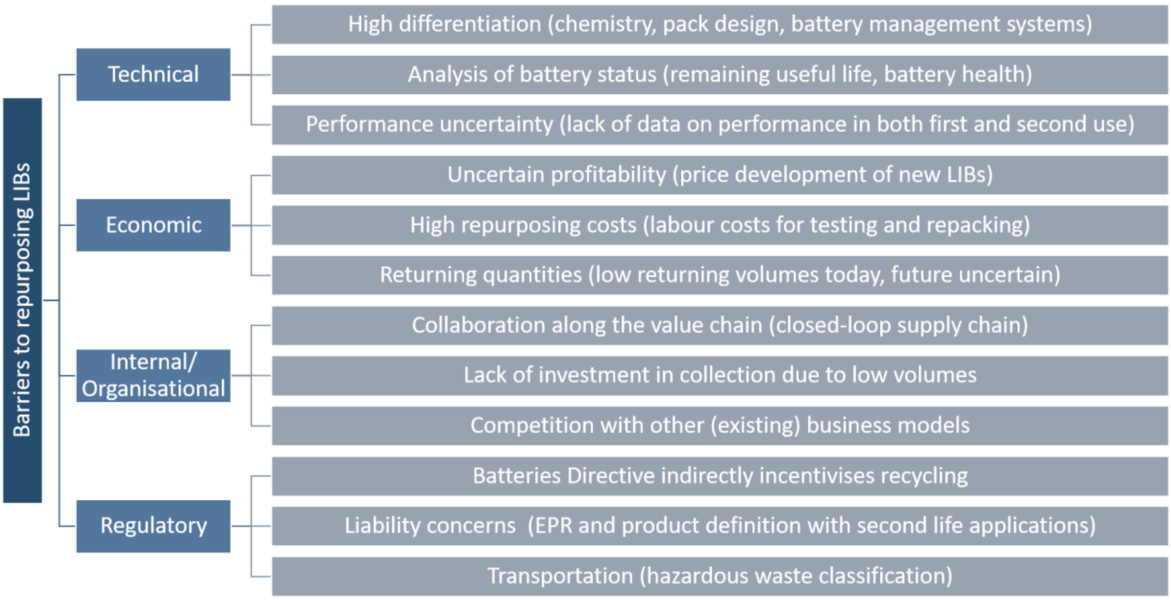

Figure 3-5. Barriers to repurposing business models

Sources: Bobba, Cusenza, et al., 2018; Hossain et al., 2019; Klör et al., 2015; Kurdve et al., 2019; Olsson et al., 2018; Reinhardt et al., 2019

The high differentiation of LIBs in terms of current and potential future chemistries, pack designs and BMS reduces the potential to upscale repurposing CBMs (Olsson et al., 2018). LIBs' designs are highly differentiated due to the rapidly developing battery technologies (Nitta et al., 2015). This leads to high costs and time needed for repurposing LIBs, which requires controlling each module or cell, potentially removing and repacking them within the LIB, and a modification of the BMS for the second life application (Olsson et al., 2018). Hence, overall, the specific qualification and equipment needed for handling, assessing, as well as repurposing the batteries is high and would have to be informed by producers' knowledge on their batteries (Klör et al., 2015; Olsson et al., 2018). This favours a system where second life projects can only be executed in close collaboration or by the companies that hold the knowledge on the batteries and its management system. Some of these companies may, however, not be interested in investigating second life applications if they compete with other (existing) business models (Olsson et al., 2018). One of these competing business models could be a recycling business model. Prolonging the life of a LIB will delay the metal circulation (Bobba et al., 2019; European Environment Agency, 2018), which influences the material supply in the manufacturing sector (Yang et al., 2020). Due to scarce and critical raw materials such as cobalt, producers may be more inclined to recycle LIBs faster to use the materials to produce their new batteries. Thus, these internal and organisational barriers and trade-offs must be considered.

From a business perspective, the profitability due to uncertain revenue streams and high repurposing costs, as discussed in section 3.4.2, is a major uncertainty to be clarified before companies upscale pilot projects to business models. One of the most prominent barriers mentioned in the literature is the high uncertainty regarding the future market conditions because larger quantities of LIBs will only retire by 2025 at the earliest. Other uncertainties relate to the costs of future new batteries and the performance of second life batteries in different applications that influence the feasibility of second life applications (Hossain et al., 2019; Olsson et al., 2018; Sanghai et al., 2019). Furthermore, the currently low quantities of returning LIBs undermine economies of scale for reuse and second life (Klör et al., 2015).

Regulatory barriers revolve around a lack of clear guidance from the current regulatory framework, which indirectly incentivises recycling because it only sets rules for recycling and does not address extension of life activities (Elkind, 2014). Liability concerns exist amongst producers who are registered for the EPR with the first use of the LIB as there is no rule on the transfer of the EPR. Various sources also note an uncertainty regarding the legal status and product definition of second life batteries (Bobba, Cusenza, et al., 2018; Olsson et al., 2018; Richa et al., 2017), which makes second life applications less compelling.

3.5.2 Challenges for recycling

Similar to second life applications, the recycling industry faces several difficulties as summarised in Figure 3-6.

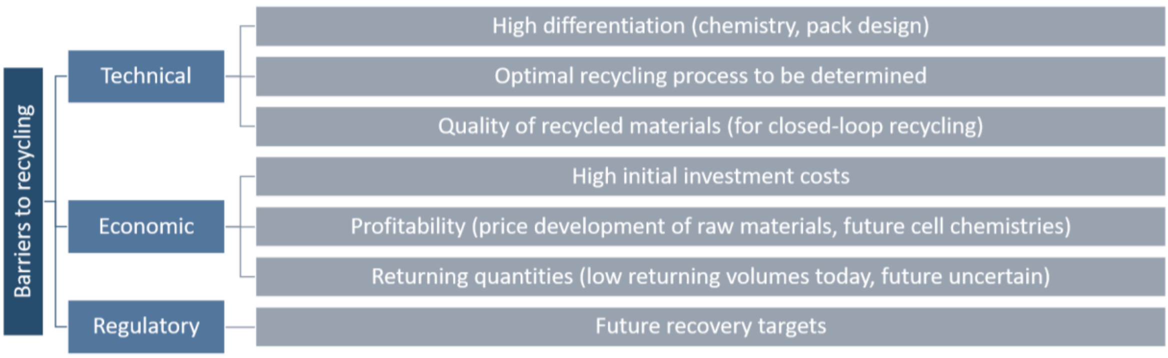

Figure 3-6. Barriers to recycling business models

Sources: ElementEnergy, 2019; Gaines et al., 2018; Harper et al., 2019; Kurdve et al., 2019; Pagliaro & Meneguzzo, 2019; Velázquez-Martínez et al., 2019

The different battery types in the input stream hinder the development of a standardized process and require manual sorting if they are not well-labelled, thus, increasing the costs (Belchí Lorente et al., 2015; Velázquez-Martínez et al., 2019). Different material compositions of cell chemistries (even within NMC for example) are hindering direct recycling processes retrieving cathode materials (Gaines et al., 2018) and the potential for commercial recycling with high quality recycled materials for a closed-loop is questioned. On the economic side, recycling is dependent on high returning quantities to be cost-effective due to high fixed costs (Rohr et al., 2017). However, large numbers (≈200.000) of LIBs for recycling are not expected before 2025 (Gaines et al., 2018). Hence, the profitability of LIB recycling is currently constrained by low volumes, high processing and relatively low raw material costs, as well as inefficient collection mechanisms for waste LIBs (Lin Li et al., 2018; Mayyas et al., 2019).

3.6 Summary

3.6.1 Knowledge gaps in literature

The literature showed that LIBs offer a high potential to benefit from CE strategies. This has been recognised on a political, business, and academic level. A clear idea exists as to what kind of CE strategies could be applicable to LIBs. But the literature review identified a lack of research discussing the non-technical aspects of LIB's life cycle management related to the deployment of CE strategies by automotive OEMs and the operationalisation from a business model perspective. While a few examples of CBMs for LIBs have been discussed in the literature, there is little in-depth empirical evidence and analysis. The current practical and research focus to understand what drives and hinders an automotive OEM to integrate CE strategies into their business model has been mostly placed on external factors and the technological dimension (Olsson et al., 2018). However, challenges in these dimensions are similar for all actors and they cannot explain the differentiation in the adoption of CE strategies and CBMs amongst OEMs. This differentiation is much more likely rooted in internal factors, which have been identified as an underexplored, but crucial aspect to accelerate the adoption of CE strategies and CBMs for LIBs. To give an example, the stakeholder interactions, relations, and roles within existing CBMs and their reverse supply chains have not been assessed sufficiently (D'Adamo & Rosa, 2019; Mayyas et al., 2019; Melin, 2019).

Consequently, there is a need for a comprehensive overview of deployed CE strategies and their operationalisation amongst automotive OEMs as well as an analysis of the influencing factors with a focus on internal factors. This shall support the business model innovation process to integrate CE strategies for LIBs. Automotive OEMs are of special importance for CE strategies for LIBs as they hold the end-of-life responsibility and could integrate inner loop CE strategies. An exploration of the potential implementation of CBMs for LIBs from the perspective of an automotive OEM to accelerate their adoption and to reduce overall environmental impacts from EV road transport is, thus, relevant for both academia and practitioners.

Furthermore, it has been argued that the CE strategy should be guided by an assessment of the sustainability value. However, no literature was found that directly compares different CE strategy options with regards to this. Instead, research has predominantly assessed environmental impacts of single options such as second life or recycling without comparing these (Kelleher Environmental, 2019). Hence, there is a need to analyse and combine the existing findings on environmental impacts to provide guidance for the design of a CE strategy along the entire life cycle of LIBs.

3.6.2 Conceptual framework

Based on the literature review, a conceptual framework was designed to guide the research questions, data collection, and data analysis (see Figure 3-7). It uses the existing framework by Lewandowski (2016) with regards to the *external* and *internal adoption factors* as well as the *operationalisation* reflected by the business model canvas components extended by the take-back system. The *sustainability impact* as discussed by Antikainen and Valkokari (2016) is added as a factor necessary to ensure the sustainability focus of a CE strategy. Moreover, the circular economy strategy block was added to the framework as a pre-step for the operationalisation in a CBM. Even though it is not visualised, the author recognises that the operationalisation in the CBM may also have to represent several cycles as described by Nußholz (2018).

The external factors are organised by *PEST categories* (Kurdve et al., 2019) and the internal factors relate to the *organisational capabilities*, which include leadership, team commitment, as well as in-house expertise, skills, and technology (Lewandowski, 2016), a *company's strategy*, such as the business or sustainability strategy (Kurdve et al., 2019), as well as the *value network*, describing the internal activities and closed-loop supply chain structure (Urbinati et al., 2017). The framework indicates a mutual influence between the CE strategy and the respective factors. These factors directly influence and sometimes inhibit the ability of a company to adopt or select certain CE strategies. Nevertheless, the decision of a company to follow and prioritise a certain strategy may as well shape external trends by influencing policy and technological developments, change the internal organisation by focusing on capacity development, and result in a changed sustainability impact, for example.

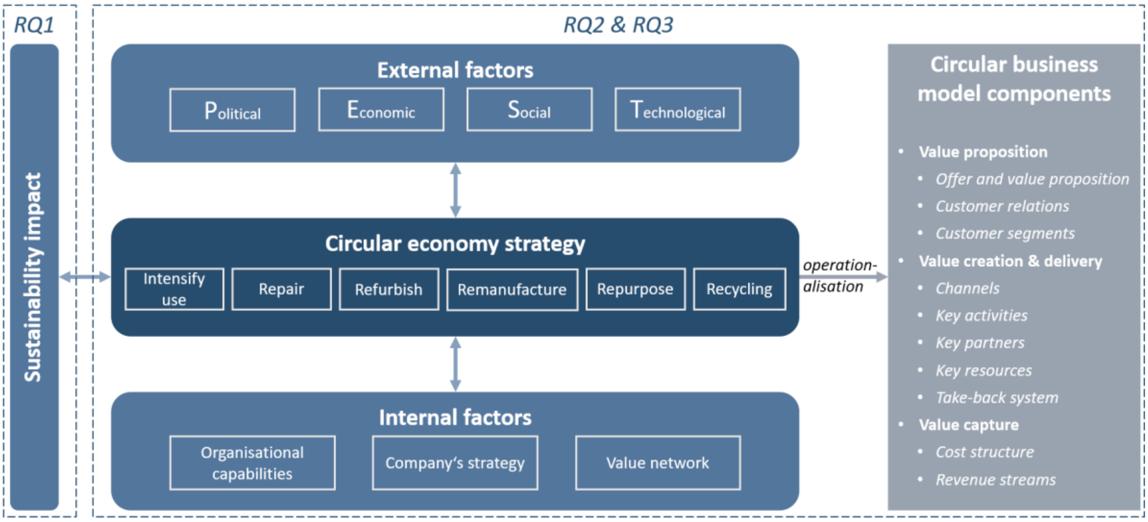

Figure 3-7. Conceptual framework

The research in this thesis is structured along this conceptual framework and focusses on (1) the sustainability impact by providing an approximation of the ideal CE strategy for LIBs from an environmental perspective *(RQ1)*, (2) deployed CE strategies at automotive OEMs in the EU and their operationalisation as well as the influencing factors *(RQ2)*, and (3) the ideation of potential CBMs applicable in the Volvo Group context *(RQ3)*.

4 Findings and analysis

This section presents and analyses findings for *RQ1* in section 4.1., for *RQ2* in section 4.2, and for *RQ3* in section 4.3.

4.1 Ideal circular economy strategy for lithium-ion batteries from an environmental perspective

Decisions on the life cycle management and CE strategy of LIBs should be guided by an assessment of the environmental benefit (Olsson et al., 2018). Life cycle assessments are a commonly used method assessing the environmental impact of a product or service considering different impact categories such as cumulative energy demand, climate change, metal depletion, particulate matter, or human toxicity (Guinée, 2002). Analyses of environmental life cycle impacts from LIBs have focused primarily on climate change and the cumulative energy demand. Only a few investigated wider environmental implications such as other air pollutants or metal depletion (Hill et al., 2019). In the following, results from existing environmental assessments are presented and combined to propose a CE hierarchy for LIBs.

4.1.1 Slowing the loop

To date, there are no academic studies published that assess the environmental benefits of life extension activities such as repair, remanufacturing, or refurbishing for the continued use in a vehicle. Nevertheless, several studies exist focusing on the environmental benefit from different second life applications. A tabular overview is provided in Appendix D.

Most of these studies have focused on LFP batteries. Genikomsakis et al. (2013) found that there is an overall positive environmental impact in all assessed categories when comparing the use of second life LFP batteries in a small-scale energy storage unit in a smart building with solar photovoltaic panels in Spain, instead of using new batteries for the same application. A similar, more recent study by Ioakmidis et al. (2019) analysed four second life scenarios for an LFP battery and came to the same conclusion that there is a significant environmental benefit from second life in comparison to using a newly manufactured battery. Ahmadi et al. (2017) analysed an LFP battery life cycle by comparing the functions (kWh of energy stored) provided during the use in the vehicle and the second life energy storage (cascaded use system) to a conventional system in which the same function is provided by gasoline during the first use and natural gas during the stationary use. The environmental impact categories assessed by the authors were global warming, photochemical oxidation formation, particulate matter formation, freshwater eutrophication potential, metal depletion potential, and fossil-resource depletion. They found that the cascaded use system appears significantly beneficial compared to the conventional system. Only the impact on metal depletion is worse for the cascaded use system. Yang et al. (2020) found that the second life of LFP batteries results in a reduced environmental impact in every category except for metal depletion when compared with an energy storage based on lead-acid batteries. Reasons for the higher metal depletion are the replacement of components such as the battery tray in the repurposing stage and the high recycling rates for lead-acid batteries. This shows that when considering metal depletion only, a repurposed LIBs may not always be preferable in comparison to an energy storage system with lead-acid batteries or using natural gas.

A few studies exist for NMC batteries in a second life application as well. The most renowned study by Bobba et al. (2018) analysed the application of a repurposed NMC battery from a Mitsubishi plug-in hybrid EV for two purposes, one designed for peak shaving in a grid-connected office building and another for increasing the photovoltaic self-consumption of a residential dwelling. The results showed that a second life application for peak shaving has small environmental benefits in all assessed impact categories if it substitutes a new battery (lithium-ion or lead-acid). In the application for photovoltaic self-consumption, higher environmental savings are observed especially if it replaces a diesel generator backup system. Cusenza, Guarino, Longo, Ferraro et al. (2019) identified the energy and environmental benefits of repurposed NMC batteries substituting new LIBs in a stationary energy storage system in residential buildings in combination with renewable electricity generation. Their analysis considered the functions demanded during the entire life cycle of the LIB in the building as well as in the transportation sector. Because of this, the scenario with repurposing uses fewer batteries compared to the scenario in which all functions are fulfilled by new LIBs.[6] The study showed that the environmental impacts decrease by 4% (in cumulative energy demand) to 17% (in abiotic depletion potential) when using repurposed LIBs. Furthermore, results of an analysis of GHG emissions from the use of NMC batteries for different energy storage purposes highlighted that the use of battery energy storages is only advisable in combination with renewable energy sources (Casals, García, Aguesse, et al., 2017). Otherwise the energy losses from the energy storage act as a multiplying factor for the emissions from the polluting energy production.

The previously presented studies focused on the second life application only and compared it to technology that the LIBs potentially replace to assess the environmental benefits of using repurposed LIBs. The only existing analysis that compares benefits from more than one CE strategy option is a well-known study by Richa et al. (2017) for lithium manganese oxide batteries. They assessed the effects on energy demand, eco-toxicity, and metal input from direct reuse in a vehicle, the second life of refurbished LIBs in stationary applications, recycling, and landfilling for lithium manganese oxide batteries. They found that environmental benefits are highest when the battery is refurbished for a second life in a stationary energy storage before being recycled. The benefit of the second life application in this study is based on avoiding the production and use of lead-acid batteries for the energy storage.

Some limitations of the presented studies should be considered. Several of them make assumptions regarding the second life performance and the remaining useful life of LIBs. For the comparison of the second life applications many use lead-acid battery as alternatives. While these have been a widely used technology for stationary and industrial purposes in the past, new storage systems now generally use LIBs (Kelleher Environmental, 2019). Moreover, the studies that compare repurposed LIBs to new LIBs by Bobba, Cusenza et al. (2018) and Cusenza, Guarino, Longo, Ferraro et al. (2019) assume the same technical specifications of the LIBs and, thus, disregard the fact that new LIBs will most likely be using more advanced technology with a potentially lower environmental impact per kWh in comparison to repurposed older ones. Nevertheless, the assessments can still provide guidance for decision making because the general trend of the results is valid despite these limitations.

4.1.2 Closing the loop

It is usually assumed that the energy needed for recycling materials is generally lower than for producing the materials from the ore, and that recycling is, thus, overall environmentally beneficial (Worrell & Reuter, 2014). For LIBs, several assessments show that recycling can reduce many environmental impacts (Ciez & Whitacre, 2019; Elwert et al., 2019; Oliveira et al.,

[6] While there are fewer new LIBs needed to provide the same function for the energy storage in the building, to meet the functional demands for the transportation sector, the same number of additional new batteries are accounted for.

2015; Richa et al., 2017; Yang et al., 2020). With regard to SO_x emissions, Gaines et al. (2018) note that all recycling methods show significant emission reductions with direct recycling saving the most. According to Lebedeva et al. (2017), the recycling efficiencies for lithium, nickel, manganese, and cobalt of an NMC battery in a purely hydrometallurgical process are higher than for a combined pyrometallurgical and hydrometallurgical recycling process. And Cusenza et al. (2019) note that the environmental benefits from recycling could be increased if materials such as graphite, the electrolyte, and aluminium were recovered by designing battery cells for separation of cell components.

Oliveira et al. (2015) assessed the environmental impacts of recycling lithium manganese oxide and LFP batteries, considering climate change, human toxicity, particulate matter, and metal depletion. They concluded that hydrometallurgical recycling with recovery efficiencies of 100% for lithium and cobalt, 75% for iron and steel, and 94% for the remaining non-ferrous materials, results in a net environmental benefit. Richa et al. (2017) find that in their model a 50:50 mix of hydrometallurgical and pyrometallurgical recycling processes for lithium manganese oxide is positive with regards to cumulative energy demand, eco-toxicity, and metal input. Using hydrometallurgy resulted in lower energy demand while pyrometallurgy yielded better results for avoided metal depletion. When comparing the energy efficiency of different recycling processes, direct recycling is most efficient followed by hydrometallurgy and then pyrometallurgy (Lv et al., 2018). A recent study compared the climate impact of pyro-, hydrometallurgical and direct recycling processes for cylindrical and pouch cell batteries of nickel cobalt aluminium oxide, NMC[7], and LFP chemistry in the US (Ciez & Whitacre, 2019). It found that pyrometallurgy and the recycling of LFP cells always result in a statistically significant net increase of GHG emissions when compared with cell manufacturing from virgin materials. Hydrometallurgical and direct recycling, on the other hand, potentially avoid GHG emissions for NMC and nickel cobalt aluminium oxide cells. This reduction, however, is shown to only be statistically significant for the direct recycling of pouch cells. Furthermore, the authors calculated how much of the cathode material must at least be recovered through direct recycling to result in net emissions reductions. For NMC, this has been estimated to be 78% for cylindrical and 59% for pouch cells.

4.1.3 Proposed circular economy hierarchy for lithium-ion batteries

The existing environmental assessments indicate that a CE strategy for LIBs' life cycle should aim to slow the loop of LIBs before closing it and opt for activities that preserve the integrity of the product or component for as long as possible. Measures to slow the loop have been found to result in a decreased environmental impact in all impact categories except for metal depletion in some cases. However, the combination with a subsequent recycling strategy then provides positive results even for this environmental impact category. Hence, a preliminary CE hierarchy for LIBs can be deducted and is presented in Figure 4-1.

Accordingly, the use in the first application should be intensified and prolonged as much as possible because it aligns with the observed positive effect of reducing the need to produce a new LIB to provide the desired functionality. Then, direct reuse or second life in which the LIB with only minor replacements and repairs should be prioritised. To provide significant environmental benefits, the second life application should substitute an alternative system with new batteries or fossil-fuel use and be combined with renewable energy. If direct reuse or repurposing is not possible, reuse with refurbishment would be the next option. The exchanged

[7] With a Nickel-Manganese-Cobalt ratio of 6:2:2.

modules could be repurposed by adding new components such as a casing or BMS. The least favourable option for slowing the loop is reuse with remanufacturing as it requires a lot of new parts and retains little of the embedded value. In general, the number and length of cycles should be maximised because material, energy, and labour for creating a new product or component can be avoided and LIBs require little energy in the use phase, thus not needing to account for energy efficiency improvements (Ellen MacArthur Foundation, 2015).

The outer loop should only follow at the very end of the LIB life cycle and the selection of a recycling technology/process can be guided by environmental criteria as well. From an environmental perspective, pyrometallurgy would not be favourable and, instead, a combined mechanical and hydrometallurgical process or, if possible, direct recycling would be advantageous. There is no indication regarding the optimal recycling rate in the assessed literature. It may be beneficial to maximise the material recycling from a materials perspective, but it may result in negative impacts on other impact categories such as climate change if the required energy is too high at a certain threshold. Hence, the most optimal and balanced recycling rate has not been determined yet.

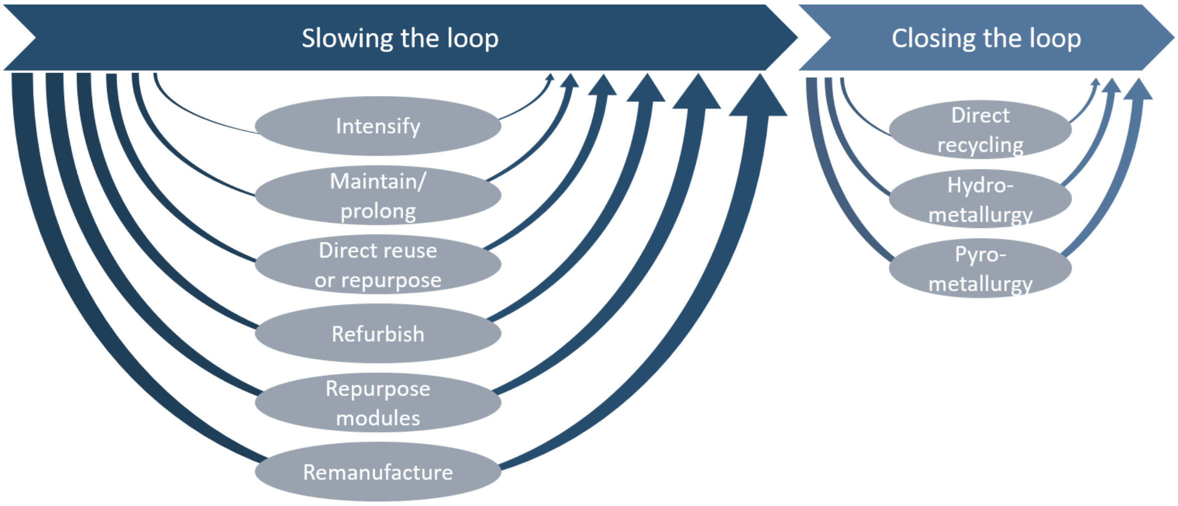

Figure 4-1. CE hierarchy for LIBs from an environmental perspective

4.2 Current circular economy strategy deployment

This section presents results for *RQ2* by first providing an industry overview of the deployed CE strategies at automotive OEMs *(which)*. Then, their operationalisation is presented along the CBM components *(how)*, before identifying external and internal influencing factors for the strategy selection *(why)*.

4.2.1 Industry overview

Table 4-1 offers a summary of the deployed activities corresponding to CE strategies at automotive OEMs in the EU exclusively. For recycling, only closed-loop recycling initiatives are considered because general recycling is required by law in the EU anyway. A full list of automotive OEMs' specific activities and more information on them is found in Appendix E.

The results show that many automotive OEMs provide no public information on activities such as intensifying use, repair, refurbishing, and remanufacturing. This may indicate they are not actively pursuing these CE strategies. However, the interviews revealed that all the interviewed OEMs are repairing and refurbishing their LIBs despite the lack of official communication. In contrast, second life projects are heavily represented in the official communication and deployed or investigated by most automotive OEMs. Most of these projects are pilots to verify the technical and economic feasibility of such applications and to prepare for higher volumes of returning LIBs in the future. The same applies to closed-loop recycling initiatives. Several OEMs are currently investigating potential closed-loop recycling business models, but only Volkswagen Group with their brands Audi and VW has officially set up closed-loop recycling systems for a few valuable metals such as cobalt and nickel.

Table 4-1. Deployed CE activities at automotive OEMs in the EU

Company/ Group	Intensifying use	Repair	Refurbish	Reman	Repurpose	Closed-loop recycling
ADL	*No info*	*No info*	*No info*	*No info*	*No info*	*No info*
BAIC	*No info*	*No info*	*No info*	*No info*	*No info*	*No info*
BMW	*No info*	*No info*	*No info*	*No info*	*Yes*	*Investigations*
BYD	*No info*	*No info*	*No info*	*No info*	*No info*	*No info*
DAF	*No info*	*No info*	*No info*	*No info*	*No info*	*No info*
Daimler AG	*No info*	*Yes*	*Yes*	*Yes*	*Yes*	*Investigations*
Ford	*No info*	*No info*	*No info*	*No info*	*No info*	*No info*
Honda	*No info*	*No info*	*No info*	*No info*	*Investigations*	*Investigations*
Hyundai	*No info*	*No info*	*No info*	*No info*	*Yes*	*No info*
Irizar	*No info*	*Yes*	*Yes*	*No info*	*Planned*	*No info*
Jaguar Land Rover	*No info*	*No info*	*No info*	*No info*	*Yes*	*No info*
LEVC	*No info*	*No info*	*No info*	*No info*	*No info*	*No info*
Mitsubishi	*No info*	*No info*	*No info*	*No info*	*Yes*	*No info*
Nissan	*Yes*	*No info*	*No info*	*No info*	*Yes*	*No info*
PSA Group	*No info*	*No info*	*Unclear*	*No info*	*Investigations*	*No info*
Renault Group	*Yes*	*Yes*	*Yes*	*No*	*Yes*	*Investigations*
Solaris Bus & Coach	*No info*	*No info*	*No info*	*No info*	*Investigations*	*Unclear*
Streetscooter	*No info*	*No info*	*No info*	*No info*	*No info*	*No info*
Tazzari	*No info*	*No info*	*No info*	*No info*	*No info*	*No info*
Tesla	*No info*	*No info*	*No info*	*No info*	*No*	*Envisioned*
Toyota	*No info*	*No info*	*No info*	*No info*	*Investigations*	*No info*
VDL Bus & Coach	*No info*	*Yes*	*Yes*	*No*	*Yes*	*Investigations*
Volkswagen Group	*No info*	*Yes*	*Yes*	*No*	*Yes*	*Yes*
Volvo Cars	*No info*	*No info*	*No info*	*No info*	*Investigations*	*No info*
Volvo Group	*No*	*Yes*	*Investigations*	*Investigations*	*Yes*	*Investigations*

Some OEMs have publicly announced an official life cycle strategy for LIBs and for some others, it can be deduced from their actions (see Table 4-2). Among all OEMs with an official life cycle strategy, Tesla is the only one not involved in or planning second life activities. In contrast, all other OEMs with such a strategy are deploying or investigating repurposing options and BMW, Daimler, Renault, and Volkswagen even use their replacement packs or modules in energy storages before their use in vehicles, hence adding another repurposing stage *before* the actual first life application (pre-1st life utilisation). One respondent described this as a common practice amongst OEMs (Respondent 4). In contrast, remanufacturing of LIBs appears to be the least utilised strategy followed by the intensification of use, which is only currently envisioned and piloted by Nissan and Renault through vehicles with bidirectional charging. These vehicles store energy not only for driving purposes but also to offer services to the electricity grid. One respondent mentioned that several combinations of these activities are possible for the battery packs and even single modules: they may be utilised for all or a couple of CE activities or only for (closed-loop) recycling depending on the SOH and customer demand (Respondent 1).

Table 4-2. CE strategies for LIBs at automotive OEMs in the EU

Company/ Group	Official strategy	Info on CE strategy (incl. non-official strategies)
BMW Group	Yes	Ambition to create a *"closed life cycle loop"* consisting of: → Pre-1st life utilisation of replacement batteries in energy storages → "Possibly" a second life in various applications e.g. stationary energy storage → Recycling: goal to reach >90% overall recycling rate; closed-loop investigations with Umicore and Northvolt to develop "cutting-edge green battery cells"
Daimler AG[8]	Yes	→ Pre-1st life utilisation of replacement batteries in energy storages Processes for end-of-use batteries: *"Reuse, Repair, Remanufacture, ReMat"*: → Reuse (= understood as second life) in large-scale stationary energy storages → Repair with module exchanges → Remanufacturing with tests and exchanges on cell level → Recycling: goal to increase recycling rates continuously - Research projects as well as collaboration with suppliers and waste-disposal partners e.g. sustainability partnership with cell supplier Farasis Energy (Ganzhou) aims to increase the recycled content in the cells
Honda	No	Investigations into second life and potentially closed-loop recycling outsourced via partnership with SNAM
Irizar	No	→ Refurbishing enabled through modular design for disassembly → Repurposing for second life at Repsol service stations for EV charging → High recyclability claims (99%), but no info on closed-loop
Nissan	Yes	EV "ecosystem" vision/Nissan Energy Plan: → Intensifying use: utilise batteries to store and share energy during use phase not only for driving purposes → Remanufacturing (in Japan) with 4R company, no info on EU → Repurposing for second life in various applications e.g. business with Eaton for home and building stationary energy storages
Renault Group	Yes	CE model for LIBs: → Pre-1st life utilisation of replacement batteries in Advanced Battery Storage → Intensify and maximise the lifetime in the vehicle e.g. bidirectional charging → Renault repair centres to repair defective batteries and refurbish them → Repurposing for second life in stationary energy storage applications (domestic and industrial); business e.g. with Connected Energy and Powervault → Recycling partnership with Veolia (not closed-loop yet, but investigated)
Tesla	Yes	→ Decision not to get actively involved in repurposing → Development of a closed-loop battery recycling process for valuable materials (currently only planned for Gigafactory 1 in the US)
VDL Bus & Coach	No	→ Refurbishing at specialised VDL workshop → Investigations into second life as energy storages within a joint venture with VDL Groep and Scholt Energy Control → Actively explore different recycling options

8 This information applies to the electric vehicles of Mercedes-Benz and Smart. However, it is assumed that the group will collaborate across the different brands and harmonise their strategies and activities for LIBs.

Volkswagen Group[9]	Yes	The Group published a battery life cycle strategy early 2019 assuming overall responsibility through the entire life cycle: → Engage in cell production in Salzgitter, and produce battery packs in Brunswick → Pre-1st life utilisation of replacement batteries → Optimal utilisation of batteries via internal analysis of the battery system at end-of-use to decide on refurbishing or repurposing → Second life in mobile charging stations (start of production planned for 2020) → Closed-loop recycling: - Audi partners with Umicore for closed-loop recycling of cobalt and nickel (starting January 2020) - Volkswagen envisions closed-loop recycling of cobalt, nickel, manganese and lithium in newly built pilot recycling facility at the "Center of Excellence" in Salzgitter with a capacity for 1200 tonnes per year (about 3000 LIBs) and the potential to expand the capacity once more batteries come back (late 2020s) followed by further decentralized recycling plants
Volvo Cars	No	Strategic priority according to a job posting: → Reuse: Reuse in car after remanufacturing → 2nd life: Utilise batteries in non-aggressive energy storage applications → Recycling: Recover battery materials to enable production of new batteries
Volvo Group	No	Life cycle strategy for LIBs under development: → Repair, refurbishing, and remanufacturing under investigation → Two second life pilot projects (small-scale energy storages for residential buildings) as verification projects → Recycling currently outsourced and pre-paid without closed-loop recycling, ongoing investigations for future setup

4.2.2 Operationalisation in circular business models

The operationalisation of the deployed CE strategies is covered in the following sections. The findings are presented and analysed along the CBM components as outlined in the analytical framework in section 3.6.2. First, the take-back system is discussed, as it is similar in most CBMs, before exploring the design of the other CBM components *(value proposition, customer relations, customer segments, channels, key activities, key partners, key resources, cost structure, revenue streams)* for the different CE strategies. A high-level summary of the general CBM designs is provided in Appendix F.

Take-back system

All end-of-use and end-of-life CBMs have in common that they rely on the return of LIBs, which is ensured by the take-back system organised by the OEM. Before a vehicle's end-of-life, the take-back system for LIBs has been found to be the same for all CE strategies: All interviewed companies organise the take-back through their dealer network, the primary point of contact with customers (Respondents 1, 4, 5, 6 & 14). In contrast, LIBs from end-of-life vehicles are usually collected and potentially returned to the OEMs by external recyclers and, for passenger vehicles, also by national producer responsibility organisations such as ARN in the Netherlands or BilRetur in Sweden. Most of these take-back systems are based on the voluntary returns from the customer and OEMs do not seem to put effort into actively retaining control of the LIBs. In the interviews it became clear that many OEMs are not concerned about

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[9] Most of this information applies to the brand of VW, particularly to their ID. models. Nevertheless, it was stated in the interview that the group intends to benefit from scale effects across the different brands and is closely collaborating to harmonise their strategies and activities for LIBs.

getting back their LIBs (Respondents 1, 4 & 5). One respondent specifically mentioned that, as long as LIBs are a cost for end-of-life, they will end up at the OEMs anyways (Respondent 5). However, a customer of Volvo Buses recently requested to keep the exchanged LIB (Respondent 14). This shows that once used LIBs hold a market value, OEMs might need to introduce other arrangements than a voluntary return to ensure their availability for potential CE activities. Renault's representative stressed that their battery leasing concept is very beneficial for their CE strategy as it clearly defines the ownership of the battery and ensures the return to the company (Respondent 6).

Within the take-back systems, there are differences in the LIB diagnostics set-up. Volkswagen transfers large competences to their own dealers: they are being trained to perform detailed diagnostic analyses on the battery using specially defined testing criteria even going down to cell level. Based on this, they are then able to decide on the optimal path of the LIB (i.e. repair, repurposing, or recycling) (Respondent 4). In comparison, dealers of most other companies only perform very limited diagnostics and simply classify the batteries for transport to central hubs of the OEMs. The LIBs are then diagnosed and processed in the central hub. Daimler, Renault, and VDL are working with such a central hub set-up and focus on optimising the logistics (Respondents 1, 5, 6 & 13). However, a growing volume of returning LIBs will likely lead to an increase in the number of central hubs per continent, thus lowering the logistics demand (Respondents 1 & 6).

Repair

Repair business models were not discussed extensively in the interviews and little information can be found in public sources. Nevertheless, many companies provide certain repair and maintenance services for LIBs to their customers. The *value proposition* of such a business model is to offer a service that restores and ensures the functionality of the bought LIB at an acceptable cost. The *customer segment* is, thus, defined as EV owners with a faulty LIB both within and outside of the warranty period. However, within the warranty period, an automotive OEM with an outsourced LIB production may transfer the responsibility to their battery suppliers via their own warranty with them (Respondent 7). The *customer relations* are managed via the well-known and trusted dealer network as well as contracted independent repair workshops, which benefit from existing close relationships and serve as the *channel* for value delivery as well.

The extent to which repair *activities* are performed varies between the companies. Several respondents argued that the design for repair (i.e. determining which components would most likely need to be repaired and making sure they are accessible) had to be considered early in the development phase (Respondents 1, 4, 6 & 13). At Volvo Group, the electronics in the newest LIB model have been placed together to allows quick access for the repair of faulty parts such as contactors or the fuse (Respondent 7). In comparison, Volkswagen's repair services encompass exchanges of modules too (Respondent 4). The respondent from Renault claimed that 99% of returning LIBs are repaired (without an indication of what that entails) but they do not necessarily go back to the original user because of their leasing model in which the service of a functional LIB is sold instead of one specific LIB (Respondent 6). Hence, despite the wording of the interviewee, this may rather be regarded as reuse since the LIB is then used as a replacement LIB for another leasing customer.

Depending on the level of repair needed, it is performed by local dealers where the LIB is returned or at specialised battery repair workshops of the automotive OEMs (Respondents 1, 4, 5, 6, 13 & 14). Volkswagen's dealers, for example, are being equipped to perform extensive diagnostics and change modules by themselves (Respondent 4), whereas Renault only has a few dealers that can handle LIBs and conducts repairs at a central repair centre (Respondent 6). At Volvo Group, it is currently being discussed to what extent dealers will be able to facilitate repairs. In any case, dealers are a *key partner* for the success of this business model together with potential spare part suppliers. Furthermore, it requires highly skilled technicians who can facilitate the repairs as a *key resource*.

The *revenue* of a repair business model is based on the sales of the one-time repair service or covered by a service contract sold with the battery which is based on a monthly fee (Respondents 6 & 14). Volvo Group is, for example, aiming to cover most of their EV sales with a so-called "Gold Service Contract", which includes a battery coverage and battery monitoring service (Respondents 10 & 14). The main *costs* for this business model include labour costs, costs for spare parts, and potential logistics costs if transport to a central hub is needed.

Refurbishing

Providing a refurbished LIB with a warranty that meets the demands of a second-hand customer at a lower cost than a new LIB has been identified as a *value proposition* for refurbishing CBMs amongst automotive OEMs. Interviewees mentioned that not every customer necessarily needs the maximum capacity of a LIB. Thus, a refurbished LIB can offer acceptable parameters to serve these customers' needs (Respondents 4 & 7). It can be provided as a replacement battery or potentially even be integrated into a new EV (Respondent 4). A cheaper refurbished battery solution is in high demand when the residual value of the vehicle does not justify purchasing an entirely new replacement battery for a high price (Respondent 14). The *customer segment* is, thus, similar to the automotive OEM's traditional EV customer segment but with a higher sensitivity to price when buying a new EV or replacing their LIB. The *customer relations* for this CBM are managed via the existing dealer network, which also serves as a *channel* for value delivery.

For the value creation, *key activities* can differ. Renault, for example, diagnoses down to module level and exchanges up to three faulty or defect modules (Respondent 6). In comparison, Nissan (in Japan) completely takes apart the battery packs, diagnoses the modules, and reassembles them based on their SOH (Nissan Motor Corporation, n.d.-a). Hence, *key resources* for such a refurbishing business model mainly include spare parts as a physical resource and human resources that execute the diagnosis and refurbishing of the product. Technical skills of the staff are either required at the OEM's local service organisations or at their central repair and refurbishing hubs. Storage and refurbishing facilities are needed in case of an organisation in central hubs. Alternatively, the refurbishing process may also be outsourced to a partner such as Spiers New Technologies, which is done by Nissan and Ford in the US (Kelleher Environmental, 2019). Battery module producers are a *key partner* as they provide replacement modules for the refurbishing activity. Furthermore, they may be even more important and involved if the automotive OEM is reliant on their knowledge transfer and support due to an outsourced LIB production. VDL, for example, agreed on a level of support provided by their battery manufacturer to cover gaps in their own capacities and capabilities (Respondent 5). Dealers are key partners as well because they serve as a direct connection to the customer.

The *costs* for a refurbishing business model mainly revolve around the spare parts (replacement modules) as well as labour costs for the diagnosis and module exchange by trained technicians. In case LIBs are refurbished in central hubs, additional logistics costs need to be accounted for. The *revenue* from selling the refurbished LIB must, thus, balance these costs. Nissan sells their refurbished battery packs in Japan for around $ 2850, which is half the price of a new battery pack (Karkaria, 2019). In the case of a leasing model, as it is deployed by Renault, the revenue is generated from the sale of leasing contracts and is part of the customer's monthly payment.

Remanufacturing

In comparison with other CBMs, remanufacturing was barely addressed in the interviews because it is not performed by many automotive OEMs. The only evidence of a remanufacturing CBM was found at Daimler for the LIBs from Smart. Here, the SOH of the cells is thoroughly analysed in a central remanufacturing hub and then single cells are exchanged as *key activities* (Respondent 1). However, it did not become clear whether this results in a performance that is as good as new or whether their activity should be classified as refurbishing by the definition used in this thesis. At Volvo Group, for instance, remanufacturing is understood as the exchange of all modules to ensure a capacity of 100% (Respondents 7 & 13).

Repurposing

Few full-scale repurposing CBMs exist amongst automotive OEMs yet. Most projects are still in the piloting and experimentation phase. Jan van Meijl, product planner at VDL Bus & Coach, even called the existing projects "window dressing". Nevertheless, Volkswagen's mobile charging stations (Drive Booster) and collaborations between automotive OEMs such as Renault or Nissan with companies such as Connected Energy and Eaton seem to have surpassed the piloting phase and could be seen as business models. These and other less mature projects of automotive OEMs serve as the basis for the analysis of the operationalisation in this section.

Value proposition

The *value propositions* of different second life applications are diverse. Most commonly, the offer consists of selling stationary energy storages with a specific warranty (ranging from 3 to 10 years) that can perform various services for the final customer. The use case and services of the energy storage vary depending on the specific application, its size, and the customer's modifications. Many energy storages have been found to perform multiple services and, thus, provide several value propositions. Most of the services are centred around providing grid stabilisation services[10] to utilities or back-up power to private customers, increasing renewable energy self-consumption usually combined with local solar power production and demand peak shaving (i.e. reducing the maximum power consumption of a household or building to avoid the installation of capacity or reduce the power contract), offering energy arbitrage[11], or providing fast-charging infrastructure for EVs. The latter is especially relevant for areas in which the grid would require an upgrade to support fast charging due to a lower voltage (Respondent 15) and is also found in mobile storage versions such as Volkswagen's Drive Booster. Few examples exist for other mobile and off-grid applications such as forklifts, streetlamps refrigerated vehicles, as well as energy storage for hybrid and electric propulsion ships. The increased resource efficiency through second life LIBs and the support of renewable energy integration in the grids in case of stationary energy storages are mentioned as additional environmental value propositions by most examples. Daimler, for instance, argues that utilising spare modules and packs in energy storages before the use in vehicles adds value at the beginning of the battery life by promoting Germany's energy transition which requires high-capacity energy storages to stabilise the power networks (Daimler AG, 2017a, p. 45).

Moreover, some OEMs such as Daimler, Renault, and Nissan also sell end-of-use batteries and modules to third parties. Daimler's subsidiary, Mercedes-Benz Energy, offers the procurement

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[10] Grid stabilisation services include a variety of different services such as load levelling, frequency regulation, capacity firming, peak shaving, and providing balancing power or an operating reserve (ABB, n.d.).

[11] Energy arbitrage with energy storage is based on purchasing electricity from the grid when it is cheap, storing it, and then selling or using it when the grid electricity is expensive, thus exploiting the price difference.

and sale of rated and certified second life batteries and modules, including certified components such as connections, interfaces, controls, and monitoring (Mercedes-Benz Energy, n.d.). Renault sells second life LIB packs to external producers such as Connected Energy and Powervault. Connected Energy markets large-scale, modular energy storage containers under the name E-STOR (Connected Energy, n.d.). Powervault builds small-scale energy storages for households and claims to reduce customers' electricity bills by up to 20% when using stored solar energy in the evenings and an additional 15% with energy arbitrage (Powervault, n.d.-b, 2019). Nissan follows a similar business model in which new and end-of-use LIBs are provided to Eaton who repurposes them and markets the product xStorage Home/Buildings/Compact/Container as a low-cost energy storage with excellent durability and reliability (Eaton, n.d., 2019). Figure 4-2 summarises the main repurposing set-ups from an OEM's perspective.

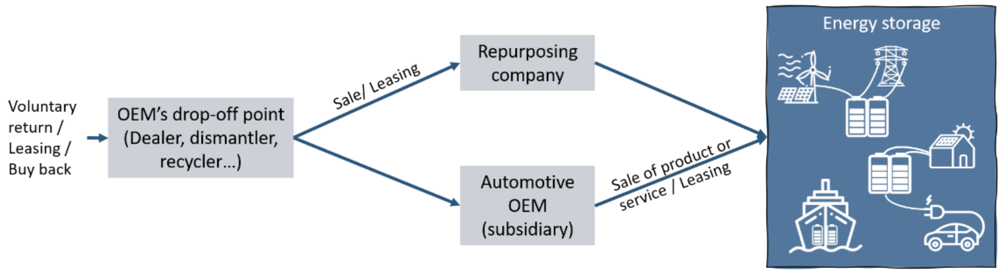

Figure 4-2. Observed repurposing set-up alternatives

The *customer segments* are dependent on the application and range from homeowners (with solar PV or EV) interested in saving money by storing and using their renewable energy to business customers including industries with large energy consumption, real estate companies, EV charging networks, and utility companies for grid stabilisation services. Furthermore, 'early birds' as well as environmentally minded people and businesses could be interested in second life applications even if they do not present a large cost saving in comparison to energy storages with new LIBs (Respondent 3).

For second life applications, close *customer relations* are very important. Several interviewees stressed customers' potential safety concerns when using an energy storage with second life LIBs (Respondents 3, 5, 7 & 12). Hence, close customer relationships need to be established to build trust. With business customers, this is mostly done through extensive direct contact between the customer and the manufacturer, which is already built up in the early stages of the project and collaboration. Private customer solutions are most often connected to a user-friendly app or online portal providing information about the performance of their product for monitoring purposes or to manage the energy consumption and storage (Eaton, 2019c; Powervault, n.d.-b, Respondent 3). A remote monitoring service by the manufacturing company that checks the customers' systems as well as a customer service that is accessible by phone or mail and visits their properties if necessary is part of all reviewed offers. This is meant to increase the trust and satisfaction amongst customers.

Value creation & delivery

The *key activities* for second life business models include the technology development, repurposing process, potential cooperation with energy utilities, monitoring, and customer services. Thorough testing and assessment of the battery packs, modules, or cells to ensure the functionality and safety of a second life application was mentioned as a requirement by many respondents (Respondents 2, 3, 4, 5, 9 & 12). These testing and assessment methods vary, and interviewees did not share detailed information. Nevertheless, a general difference was found between those who have access to the information on historical use from the BMS (e.g. Daimler, Volkswagen) who are, thus, able to predict the expected remaining life time of the battery much better and those that have to solely rely on practical tests of the physical battery at the time of return (e.g. as was the case for Box of Energy) (Respondents 1, 2, 3, 4, 5 & 9).

Another differentiation in activities regards the dis- and reassembly of LIBs. In some cases, second life systems are based on the original battery packs (e.g. Connected Energy and most other large-scale energy storage applications). Whereas in other cases, the original packs are dismantled and only modules (e.g. Volkswagen's mobile charging stations, Nissan's 4R business and xStorage products with Eaton, and Box of Energy's product) or even cells (e.g. Powervault) are repurposed and reassembled in a new casing together with other new components. At Nissan's 4R business in Japan, for example, battery packs are transported to the central processing plant, disassembled, modules checked for their SOH, and those with an SOH of <80% reassembled for second life applications (Nissan Motor Corporation, n.d.-a). In most cases, it is then required to add a superordinate BMS, power electronics, and control technology to the new system (Respondent 1, 3 & 12). Furthermore, software for control regulation of the complete system needs to be developed (Respondent 1 & 3). In case the original BMS is utilised for the individual LIBs, a special interface may need to be designed and added that enables a selected access to its data i.e. reading out necessary information on the batteries' health while protecting other proprietary data of the OEM (Respondents 2, 3, 9 & 12). Once the second life battery system is assembled, it needs to be installed for the respective customer. And lastly, a monitoring system needs to be put in place to ensure the product's/system's functionality and safety.

One aspect stressed by a few interviewees is the need for an agreement on the EPR for the repurposed LIB (Respondents 2, 3, 7 & 8). Since the current legislation is not providing a clear guidance and only few EU countries such as the Netherlands have introduced a special ruling for them, this needs to be arranged for every single case or collaboration. When the repurposing is not done by the automotive OEM, a respondent reported to have set up a civil contract by which the repurposing company agrees to take back the batteries at their end-of-life and also cover the accompanying recycling costs (H. Timmers, personal communication, 4 March 2020; Respondent 2). In this case, the automotive OEM remains legally responsible for the battery it put onto the market, but the converter agrees per a contract to take over the duties stemming from that responsibility.

A *key resource* mentioned by many interviewees to ensure the success of a repurposing business model is expertise on the batteries and their historic use (Respondents 2, 3, 4, 5, 6 & 9). This is crucial to ensure the safety of the second life application and to estimate the remaining useful life of the LIB. Next to these intellectual resources, it requires human resources such as knowledgeable engineers to develop prototypes and a software to control the second life application (Respondents 3, 9 & 12) as well as staff managing the customer relations. Financial capital is needed to cover the upfront costs especially early in the innovation process. Finally, a storage and repurposing facility as well as potentially new power electronics, BMS, and casings for the product are required as physical resources.

One important finding is that second life projects and businesses most often involve close collaboration with *key partners*. Depending on the product and size of the system, the installation and approval needs to be coordinated with the electricity grid operators and energy companies (Respondents 1 & 2). The development of small-scale applications requires a certain extent of cooperation to ensure the compatibility with energy tariffs and the grid access. Most of the large-scale applications involve either an energy utility or a company specialised on energy trading for the operational management of the system. All of Daimler's projects, for instance, include an energy services provider or utility company who is responsible for the sale of energy to the market such as The Mobility House, for which Daimler has acquired a minority holding in 2017 (Daimler AG, 2018a).

Moreover, the role and involvement of automotive OEMs in the second life ventures varies a lot. In some cases, the OEM is simply the provider of LIBs and is not involved in the analysis or execution of the repurposing or the subsequent sales of the product (e.g. Nissan and Eaton, Renault and Powervault, Honda and SNAM). In other cases, OEMs have created specific companies as subsidiaries or joint ventures who repurpose LIBs. Daimler founded Mercedes-Benz Energy in 2016, which deals with the efficient handling as well as the further development and second life of LIBs in scalable energy storage applications. They are now experts in superordinate BMS, power electronics, and control technology for energy storage systems (Respondent 1). Similarly, Nissan's joint venture company 4R is responsible for testing and repurposing in Japan, and Renault has a subsidiary Gaia (Respondent 6). Volkswagen's second life business model depends on partners such as E.On or Elli to manage the entire contact with final customers. Furthermore, local electrical installers are key partners for the success of the business with small-scale energy storages as well.

For private customers, the purchase of the currently existing second life products is, in all cases reviewed, facilitated via a direct contact request on the companies' websites (e.g. for xStorage and Powervault). Distribution *channels* for other customer segments include existing distribution networks of partner companies (e.g. with Wärtsila for Hyundai, or E.On for Volkswagen) and the direct contact with potential customers for specific pilot projects.

Value capture

The *revenue* of second life business models can be retrieved from the sales of the energy storage, a second life LIB, or a second life module to a customer, as well as by the sales of the services of an energy storage system to the grid operators, or by energy arbitrage. The ability to retrieve revenue from energy arbitrage, however, is dependent on the existence of variable electricity prices. Furthermore, several interviewees stressed that the customers' willingness to pay for a product with second life LIBs is much lower than for new LIBs (Respondents 3, 5, 6, 7, & 15). It was argued that second life LIBs could most likely only be sold 30-50% cheaper than a new LIB (Respondents 3 & 6). The main *costs*, mentioned by interviewees, are development and production costs which mainly refer to labour costs for testing packs/modules and potentially reassembling them. Furthermore, as for all other CBMs, logistics costs are high (Respondents 6, 7 & 12). In terms of the overall profitability, one respondent highlighted that the business case for energy storage services depends on highly fluctuating electricity prices based on the electricity generation from renewable energy (Respondent 3). And another interviewee argued that the commercial potential of energy storage systems that offer grid stabilisation services is uncertain and lacks profitability today (Respondent 4).

Closed-loop recycling

Common practice

The most applied recycling CBM is not necessarily a closed-loop recycling model. It is common practice to engage one or several recyclers who comply with the legal recycling target of at least 50% by weight and sell the reclaimed secondary materials on the market with no involvement or tracing by the automotive OEM (Respondents 1, 2, 4, 5, 6, 7 & 8). Accordingly, the materials may be recycled in an open- or closed loop in this model. The *value proposition* for OEMs is mainly to meet legal recycling requirements by receiving a certification from the recycler. OEMs are usually not involved in any *key activities* beyond the financing. Sometimes they arrange the transports themselves, but even this activity may be outsourced to the recycler or a third party who can transport waste LIBs (Respondent 1, 6 & 7). The actual recycling and sale of secondary raw materials on the market is realised by the recycler. The fee paid by an OEM to the recycler is based on the difference between the recycler's *revenue* from selling recycled raw materials and the *costs* for the treatment process (mainly for labour, especially if manual disassembly is required, and energy). The revenue is currently not high enough to cover the costs, not even for high-cobalt LIBs, which is why automotive OEMs pay recyclers for the treatment and finance the logistics (Respondents 1, 2, 5, 6 & 7). There is no indication of how closed-loop recycling of certain materials compares to open-loop recycling economically. It can, however, be assumed that recyclers are experts in optimising the revenue from the sales and opt for the most cost-efficient set-up.

This model appears to be the standard practice amongst OEMs. Renault currently only engages the recycler Veolia in France for the recycling of all end-of-life LIBs in Europe (Respondent 6). Hence their focus lies on the optimisation of logistics and the identification of markets where it may make sense to set up arrangements with a local recycler as well. The PSA Group has commissioned SNAM for the collection and recycling of LIBs (PSA Groupe, 2015). Similarly, Toyota partners with SNAM for nickel metal-hydride batteries used in most of their hybrid EVs as well as with Umicore for the recycling of LIBs from the Prius+ and Prius Plug-in models (Toyota Motor Corporation, n.d.-a). In contrast, Volkswagen engages different recyclers depending on the country (Respondent 4). With these models, it is not certain whether the materials are recycled in an open- or closed-loop because the recycler decides which and in what purity materials are recycled and who they are sold to. According to a recycler, however, most are downcycled to avoid additional expensive purification steps (Respondent 2). Nevertheless, several examples of closed-loop initiatives for LIBs exist independent from the automotive OEMs in the EU.

A cooperation between Fortum, BASF and Nornickel has recently been announced with the aim to create a closed-loop battery recycling cluster in Finland with a recycling rate of over 80% (BASF, 2020). BASF intends to use the recycled materials such as cobalt, nickel and other critical metals in its materials precursor plant. Another cooperation project between Eramet, BASF and SUEZ aims to develop an innovative closed-loop recycling process with a focus on nickel, cobalt, manganese and lithium to contribute to the raw material needs from the EV market in the future and enable battery production in Europe (BASF, 2019). SUEZ will be responsible for the collection and dismantling, Eramet for the recycling process and BASF for the manufacturing of cathode materials. Additionally, Umicore, one of the largest recyclers in Europe, announced multi-year strategic supply agreements with the battery producers Samsung SDI and LG Chem for secondary NMC cathode materials in autumn 2019 (Umicore N. V., 2019a, 2019b). And in 2016, the company Northvolt was founded with the aim to develop the world's greenest battery cell and establish one of Europe's largest battery factories. Key to Northvolt's concept is the vertical integration of the supply chain for cathode materials, which includes a recycling program to reintegrate battery materials for the new cells (Northvolt, 2019). A pilot plant to develop and validate the recycling process adjacent to their labs is expected to be opened in 2020 and a larger recycling plant will be built at their large production facility in 2022. By 2030, Northvolt aims to draw 50% of the material for battery cells from recycled materials (Northvolt, 2019).

Closed-loop initiatives involving OEMs

There are, however, also a few examples of closed-loop recycling initiatives involving automotive OEMs. For one, Umicore and Audi established a strategic research cooperation for closed-loop recycling. At the end of the test phase in December 2019, the partners confirmed that 90% of the cobalt and nickel from LIB modules of an Audi e-tron can be recycled through the pyro- and hydrometallurgical process of Umicore (Umicore N. V., 2019c). BMW is part of a joint technology consortium with Northvolt and Umicore aiming to establish a closed-loop life cycle (BMW AG, 2018). Furthermore, Volkswagen just recently opened a pilot line for LIB recycling with a closed-loop recycling process in Salzgitter next to their cell development pilot line (Volkswagen AG, 2019b). Here, LIBs from internal tests and the internal fleet as well as the limited number of LIBs coming back from the German market are recycled (Respondent 4). In comparison to the commonly practiced recycling model, the *value proposition* of these examples entails the OEM's retained control over the embedded raw materials of LIBs and the provision of high-grade secondary raw materials for the OEM's LIB cell production. Thus, environmental, social, and supply risks for some valuable materials such as cobalt and nickel are reduced for the OEM. Automotive OEMs, their cell producers, and active materials manufacturers interested in reducing these risks may be regarded as the main *customer segment* for such a closed-loop recycling model. The *customer relations* must be very close because several respondents mentioned existing concerns about the suitability and quality of recycled materials for new LIBs (Respondents 2, 6, 7 & 9). Hence, the recycler needs to engage very closely with the respective customers to build trust and overcome this uncertainty.

Key activities in these closed-loop collaborations are centred around design of LIBs, logistics, recycling processes that ensure the needed purity of the recycled materials, and active cathode material production. The design for recycling has mostly been described as enabling easy disassembly (either down to module or cell level), and the interviewed recycler added that the use of homogenous materials would be helpful as well, but that this seems to go against the trend of current technology development (Respondent 2). The recycling processes are slightly different for the different initiatives. For the Audi and Umicore partnership, first tests were carried out to determine the *"purity of the recovered materials, recycling rates and the economic feasibility of concepts such as a raw materials bank"* (Volkswagen AG, 2018a). As a result of these tests, the partnership includes the provision of end-of-life modules from Audi e-tron development vehicles from January 2020 onwards and in the future also from used vehicles to Umicore. At Umicore, cobalt and nickel are then recovered and used to produce precursor and cathode materials for new LIB cells (Umicore N. V., 2019c). Whether these materials are directly provided to Audi's cell manufacturer, LG Chem, who have a production facility in Poland, is not known. Similarly, Umicore's responsibility in the partnership with BMW and Northvolt is the recycling as well as active anode and cathode material development (BMW AG, 2018). The partnership covers activities around smart battery pack disassembly, screening for reuse of the battery cells, and closed-loop recycling of resources for cell production (BMW AG, 2018). In this regard, BMW claims that a reduced carbon footprint of cell suppliers, using recycled materials, and designing batteries for easy repair and recycling are of high priority already. In Volkswagen's case, most activities are internalised. In the design phase, recycling requirements were considered to the extent that the LIB was designed for disassembly down to module level (Respondent 4). The recycling process was developed specifically for Volkswagen's LIBs and includes a disassembly step, mechanical shredding, drying, sieving, and air classification at Volkswagen in Salzgitter. Then, recycling partners reclaim nickel, manganese, cobalt, and lithium from the black powder by hydrometallurgy (Volkswagen AG, 2019a). This model is based on the decentralised pre-treatment of LIBs followed by a centralised hydrometallurgical step, which is an approach the recycler Duesenfeld promotes as well to avoid costly transports of LIBs.

OEMs, recyclers, cell producers, and their active materials manufacturers are *key partners* for the success of closed-loop recycling models. This is represented in the three-party agreement between BMW, Umicore, and Northvolt. While Volkswagen has internalised many of the activities and may work as a cell producer in the future as well, it relies on recycling partners to facilitate the hydrometallurgy and uses its dealer network for the collection of LIBs. In terms of *key resources,* it requires knowledgeable engineers at OEMs for the design, while most other expertise is outsourced to the recyclers. However, if OEMs internalise parts of the recycling process, high financial resources are required upfront (e.g. in Volkswagen's case). *Channels* for the distribution of reclaimed materials to active materials manufacturers were not discussed in the interviews or in public documents but the sale is likely to be organised via direct contacts and contracts between companies or on a commodity market.

The general *costs* and *revenue* structure of a closed-loop recycling model is similar regardless of whether OEMs are involved. However, an optimised recycling process for the specific LIB could result in higher recycling rates and, thus, revenue from selling the secondary raw materials. If an OEM decides to integrate the recycled materials in their own cell production, this may lead to higher transportation costs if the active materials producer is based further away than the producer of another OEM that would have otherwise bought the materials for their production.

4.2.3 Influencing factors

In the following sections, the external and internal factors influencing the CE strategy selection and its operationalisation are discussed.

External factors

The *market developments* regarding prices for new LIBs, electricity, and raw materials as well as the demand for energy storage have been repeatedly highlighted by many respondents as highly influential for the decision of which CE strategies to deploy (Respondents 2, 3, 4, 5, 7, 8, 11, 12 & 15). In countries where the energy production fluctuates because of wind and solar utilisation and electricity prices are high, a second life energy storage solution is more likely to be economically viable. Furthermore, closed-loop recycling is mainly dependent on the raw material prices and supply risks regarding cobalt and other rare metals. Based on these influences, Honda for example claims that recent market developments may enable them to use LIBs in second life or recycle raw materials as feedstock for LIB production (Honda Motor Europe, 2020).

Furthermore, Volkswagen's representative mentioned that their strategic aim is to close the loop and retrieve materials for their cell production, but that it depends on the pricing and development of cell production in Europe (Respondent 4). With more facilities established in the EU, several interviewees expect closed-loop recycling to increase and recycling facilities being built close to these facilities (Respondents 1, 2, 4, 5 & 6). Hence, the *geographical proximity* of the recycling facility and the cell production was identified as another factor that stipulates closed-loop recycling practices amongst OEMs (Respondents 4, 5, 6 & 7). The same can be observed for second life projects: those in which automotive OEMs are more actively involved seem to be located close to where their headquarters are based e.g. Renault in France, VW, Daimler and BMW in Germany, Volvo Group in Sweden, and Nissan in Japan.

Several respondents mentioned *societal expectations* as a driving factor for the deployment of CE strategies (Respondents 4,5, 8 & 14). The transition to electromobility is based on environmental goals, which is why expectations from society are high that the entire vehicle is environmentally friendly. This includes handling LIBs without wasting resources and endangering the environment by ending up in landfills anywhere. Thus, CE strategies can be considered part of companies' risk management to avoid reputational damage.

Technological factors have been put forward by many respondents as well. Most importantly, the different *ageing patterns* of LIBs were discussed. Ideally, all LIB cells and modules should age at the same speed due to a controlled load sharing (Respondent 9). However, this cannot be guaranteed and, especially in older models, varying degrees of SOH have been observed in modules and cells. At Daimler, for example, the currently returning LIBs from Smart show heterogeneously ageing cells. Hence, it makes sense to exchange single cells to achieve the highest effect and reuse the LIB in a vehicle (Respondent 1). The same applies to the modules in the first generation of Nissan LEAF, which show high variations of SOH when returned. In this case, refurbishing by reassembling modules with higher SOH is a very promising CE strategy for this LIB (Respondent 6). The *speed* at which the module's SOH is *diagnosed* is crucial for the success of these business models. In 2018, Nissan announced the time for analysis of the 48 modules in a battery pack was cut down to 4 hours from the previously needed 16 days (Tajitsu & Doyle, 2018). This process can now potentially be shortened even further to about three minutes as was shown in a research project in 2020 (Clements & Ruf, 2020). In comparison, Renault also developed a specific tool to perform a module level grading from the pack level based on the BMS, but their analysis found that the modules in their batteries tend to age very homogenously (Respondent 6). Thus, a direct reuse in a second life application makes more sense in Renault's case.

Another technical aspect, which influences the design of LIBs and the CE focus of companies, is the *anticipation of defects and ageing* of single components of the LIB. Volvo Group, for example, expects the electronic equipment (e.g. contactors or fuse) to break before the battery cells and modules are at their end-of-life (Respondents 7 & 13). Hence, the design for repair has focused on making these components accessible. In comparison, some other companies expect the electronics to last longer than the modules, which is why higher attention is placed on enabling the exchange of modules as a repair option (Respondent 8).

Furthermore, the pre-1st life utilisation of LIBs in an energy storage was justified with technological factors as well. One respondent argued this has become common practice because replacement batteries must be charged and discharged regularly to keep them alive (Respondent 4). And Jean-Denis Curt, recycling and circular economy unit manager at Renault Groupe, supported this by elaborating that the alternative option for storing replacement batteries is an air-conditioned warehouse, which is very costly. Hence, the technological requirement of *conditioning the replacement batteries* offers a business opportunity to use them for non-aggressive energy storage services beforehand.

Internal factors

One deciding factor mentioned with regards to the maturity of CE strategies for end-of-use or end-of-life LIBs is the *volumes of returning batteries* (Respondents 5 & 6). Those with higher volumes today, such as Renault and Nissan, are further along in the process of implementing CE strategies because they had the opportunity to. Jan van Meijl argued that people find it difficult to be confronted with problems they do not yet have. Hence, if there is no or little return of batteries, it is harder to convince people of the need to develop repurposing business models, for example. The same was observed at Volvo Group, where the sudden return of about one hundred end-of-use LIBs created momentum for the discussion about repurposing (Respondent 10). In Jan van Meijl's opinion, it is easier not to spend time on convincing people but to put processes in place or have plans ready for when it becomes a more tangible issue. This may also explain why closed-loop recycling is not yet deployed by many automotive OEMs. Few batteries are available to recycling in the near future if they are utilised in a second life first. In an interview with Springer Professional, Jaguar Land Rover's technical design director, Dr. Wolfgang Ziebart, confirms that he does not expect recycling to become relevant before 2038 because of the long use of LIBs first in vehicles and then in second life applications (Ziegler, 2018).

Volkswagen, however, took another approach. Despite low returning numbers, they agreed on a very clear CE strategy for LIBs and are validating this with LIBs from internal tests and fleets (Respondent 4). The respondent mentioned the company's *sustainability ambitions* as a main driver for the early decision on a life cycle strategy for LIBs. The overall agenda for setting the strategy is to do everything they *"can to make e-mobility sustainable"* (Volkswagen AG, 2019a). Sustainability and the commitment to become a carbon-neutral company by 2050 in accordance with the Paris agreement have been described as a main driver for the company's transformation (Respondent 4). Based on this, the respondent mentioned that the environmental benefits of a life cycle option influence the decision making in such way that if the environmental benefits (especially with a perspective on CO_2 emissions) are higher for second life, it would potentially be prioritised even if another activity could be more profitable (Respondent 4). This reflects the influence of the sustainability impact as outlined in the conceptual framework in section 3.6.2.

Other companies have put their sustainability strategy forward as an influencing factor for the deployment of CE activities for LIBs as well. Volvo Buses mention their *"clear-cut sustainability strategy"*, ensuring that the *"entire value chain is sustainable"*, and using *"resources in a better way while at the same time reducing our climate impact"* (Volvo Buses, 2019) as motivations for repurposing projects. Environmental protection has been mentioned by the brand communication manager for BYD, Mia Gu, as the most important driving factor for their closed-loop recycling initiative in China (Daly, 2018). Audi argues that a closed-loop recycling contributes to the company's goals of a sustainable supply chain and achieving a carbon-neutral balance by 2050 (Umicore N. V., 2019c). And Renault's CE strategy is influenced by their environmental strategy and global partnership with the Ellen MacArthur Foundation. Thus, the sustainability ambitions and strategy of a company can directly steer their CE strategy for LIBs as well.

Moreover, repurposing activities can be supported or initiated by the overall *business strategy*. Renault and Daimler, for example, created subsidiaries (Mercedes-Benz Energy in 2016 and Renault Energy Services in 2017) to expand their companies to the energy business and incorporate second life applications (Daimler AG, 2016a; Groupe Renault, 2017c). This expansion is motivated by the fact that electricity is at the core of ensuring their future vehicles can drive. Similarly, Jan van Meijl, explained that VDL Bus & Coach's strategy is to design solutions that will enable them to continue selling buses. In the transition to electric mobility, energy is a crucial factor because a lack of electricity endangers the adoption of EVs. Thus, becoming involved in the energy sector and supporting its transition to renewable energy with stationary energy storages, potentially using second life LIBs, is a logical consequence of that strategy. Volkswagen's second life business with mobile charging stations is motivated by the business strategy of assuming responsibility of the charging infrastructure to support the uptake of EVs (Respondent 4). Hence, some automotive OEMs are trying to connect second life applications with their core business (providing vehicles) by addressing the new challenges of electric mobility, namely the availability of renewable electricity, charging infrastructure, and charging speed (Respondents 4, 5 & 15).

For the value network, two trends can be seen: the *vertical integration* of the LIB supply chain and the *outsourced LIB production*. Volkswagen and Daimler receive battery cells and have formed business units or subsidiaries (Volkswagen Group Components and Accumotive) that are responsible for the module and pack assembly. This increases their flexibility to deploy CE strategies such as refurbishing or repurposing which require in-depth knowledge about the battery's life and access to the BMS (Respondents 1 & 4). Thus, for activities that extend the life of LIBs, the vertical integration of LIB production may be advantageous because it allows knowledge creation and transfer within the company. Furthermore, respondents argued that an involvement in cell manufacturing can increase the likelihood of OEMs to establish closed-loop recycling practices, as is the case with Volkswagen (Respondents 5 & 6).

In comparison, those automotive OEMs with an outsourced LIB production must specify their technical requirements early on and collaborate with suppliers to enable the necessary knowledge transfer for the deployment of CE strategies related to the battery. VDL Bus & Coach receives LIBs from an external supplier, has defined clear interactions with the BMS to facilitate refurbishing of the battery by themselves and receive a certain extent of support from their supplier (Respondent 5). Renault has integrated the pack assembly in-house but does not build the BMS (Respondent 6). To ensure their ability to execute activities that slow the loop, they have included own specifications and communication protocol for the BMS. This relates to which parameters (e.g. voltage, temperature, resistance) the system is measuring, on which level (cell, module, or pack) and how these are accessed by the company. Renault's battery research and development team are deeply involved in these *design specifications*.

Design for disassembly, i.e. ability to easily access the battery in the vehicle and disassemble it, has been identified by several respondents as the most important design specification to enable all CE strategies (Respondents 1, 2, 3, 4, 6, 7, & 13). A recycler, who is also involved in the dismantling of LIBs, suggested this must include using screws instead of glue, and could further be advanced by putting screws in from the top, enabling the use of one tool for all screws, and deciding whether to weld cells together as this prohibits refurbishing or remanufacturing on cell level (Respondent 2). The respondent from Volkswagen explained they decided to repair and refurbish on module level, which has implications for the packing and accessibility of the cells (Respondent 4). At Renault, the disassembly design requirements were initially included for repair purposes but now they are much more relevant for refurbishing and repurposing (Respondent 6). Hence, the differences amongst OEMs in the design for disassembly influence their ability to utilise CE strategies.

Different *organisational capabilities* were also highlighted as influencing factors supporting the adoption of CE activities. Volkswagen's approach to internalise both the production of second life applications as well as the recycling process was explained as a predominantly top-down strategic decision and process enabled by *strong leadership* (Respondent 4). A good internal communication and a clear strategy are expected to help employees navigate this transformation process within the company and build up *team commitment*. In contrast, the respondent from VDL highlighted the benefits of their learning by doing *company culture*, which can enable faster change and innovation due to less reliance on central decision making which could slow down the innovation process. Intrapreneurship may be encouraged by establishing a specific programme or by promoting a learning by doing culture as it is the case at VDL (Respondent 5). Additionally, *devoting resources* to the CE innovation process and the implementation has been described as an enabling factor (Respondents 11 & 15). A financial commitment is especially relevant in the early phases of the innovation process where experiments and pilot projects need to be paid for. Accordingly, if a company is financially well-off, chances are higher it may be willing to experiment and devote resources to innovation (Respondent 5). Furthermore, it was mentioned that the management would need to assign human resources such as engineers for the development of technical processes for CE strategies as well (Respondent 11).

In terms of the organisational set-up, Jan van Meijl argued that VDL's ability to innovate and react upon trends is supported by the decision-making structure in the company because it is family-owned (Respondent 5). Moreover, having a *dedicated environmental or CE team* can help put the topic on the agenda and be included in the minds of people. Jean-Denis Curt stressed the importance of a strong environmental team to ensure that for example the requirements for disassembly remain in the design specifications (Respondent 6). The technological progress towards thinner and lighter batteries sometimes makes gluing more compelling than screws, which is why active engagement is needed to avoid this and protect the ability to establish CE activities. Moreover, the organisational alignment with a CE strategy has been found to support the operationalisation and success. Based on the example of a repurposing CBM, one interviewee highlighted the need for inter-organisational cooperation (Respondent 1). This can be supported by the formation of a dedicated team or even a specific subsidiary that is closer to the new customer segment and market of the second life application of the LIB (e.g. the energy market). Examples of this are the subsidiaries Mercedes-Benz Energy, Renault Energy Services, and 4R Energy Corporation as well as the business unit Volkswagen Group Components.

Another aspect that was highlighted as an enabling factor is a well-organised *knowledge transfer and management* within the company or from suppliers to the OEM to ensure the internalisation of necessary expertise for CE activities (Respondents 1, 5, 7 & 13). One respondent mentioned that their R&D team bundles all knowledge but makes sure it is passed on to specialised departments or subsidiaries responsible for specific tasks (e.g. process integration or remanufacturing). Furthermore, access to information about a specific battery needs to be secured by, for example, using a comprehensive data base (Respondent 1). This could store and provide data on the *usage patterns during its first life*. Most often, interviewees stressed the importance of knowledge on the use patterns during its first life, which is needed to assess whether a battery can be used in a second life application (Respondents 2, 3, 4, 5 & 9). Johan Stjernberg, former CEO of the now bankrupt start up Box of Energy, mentioned this as the one thing he would insist on if he started a second life business again. Similarly, Jan van Meijl argued that there is *"no second life without a first life"*.

The availability of information on the LIBs' usage history and data sets for the determination of its SOH was highlighted as crucial for those aiming to use it in a second life application (Respondents 2, 3, 4, 5 & 9). The safety of a second life application and the estimation of the remaining lifetime of the LIB are dependent on prior use patterns as well as projected *use patterns in second life application* and their impact on the battery. The latter are tested in simulations and pilot projects by the OEMs to anticipate and learn about the battery ageing behaviour in second life applications. This information is then used to estimate the remaining lifetime and to set the warranty for repurposed LIBs (Respondent 4, 9 & 12). The internalisation of this knowledge is especially given when the automotive OEM is also the producer and designer of the second life application (e.g. Volkswagen Group Components). Volkswagen's respondent argued that the company was able to incorporate the development and system competence for their EV LIBs over the past 15 years, know the characteristics of them very well across the entire life cycle, and are skilled in evaluating what is possible outside of the use in a vehicle (Respondent 4).

Figure 4-3 provides a summary of all influencing factors that were identified in the interviews as well as in the literature, whereby those only mentioned in the literature are shown in italics.

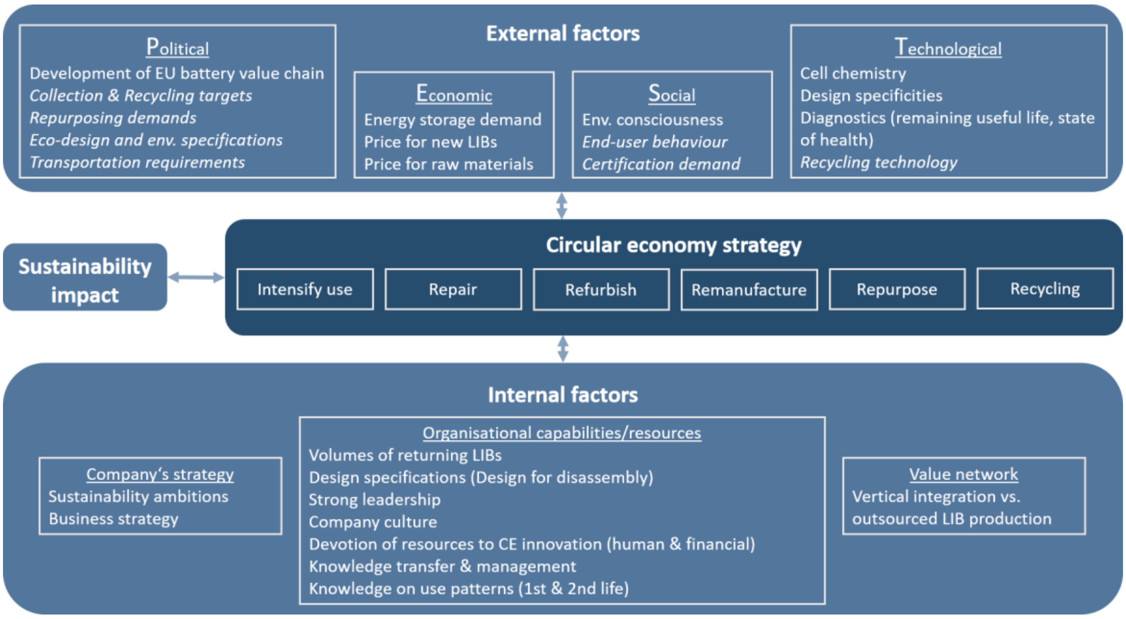

Figure 4-3. Summary of influencing factors

4.3 Potential circular business models at Volvo Group

In this section results for *RQ3* are presented. First the Volvo Group case is introduced. Then, the current LIBs business model and situation are described and opportunities for improvement identified. Finally, potential CE strategies and CBM ideas identified by interviewees and generated by the author based on the findings from *RQ2* are presented.

4.3.1 Case description

Volvo Group is a publicly traded Swedish multinational manufacturing company with a focus on trucks, buses as well as construction equipment and comprises ten business areas: Volvo Trucks, Volvo Buses, Renault Trucks, UD Trucks & JVs, Mack Trucks, Volvo Construction Equipment, Volvo Penta (marine and industrial drive systems supplier), Arquus (military vehicles), Volvo Financial Services, and Volvo Autonomous Solutions. Currently, Volvo Group focuses on three strategic areas: connectivity, automation, and electrification. The aspect of electrification is especially encouraged in the EU because of the CO_2 emission performance standards for 2025 (Art. 1 Regulation (EU) 2019/1242).

On the journey towards electrification, Volvo Group launched different products. The first hybrid electric buses and trucks were put on the market in 2009 using high-power LIBs, followed by a plug-in hybrid electric bus in 2016. The first fully electric buses were released in 2018 using LIBs with a relatively balanced power and energy density. In November 2019, Volvo Trucks started selling fully electric medium-duty trucks for urban transport in selected European markets. Traditionally, the main markets for trucks have been Sweden and France, while buses have been mostly sold in Sweden and Poland. For Volvo Group's EVs, it is estimated that more than 4500 vehicles have been put on the market so far. The majority of these (90%) have been sold in the EU, with the United Kingdom being an important market.

Volvo Group currently uses three different battery types for hybrid, plug-in hybrid, and full EVs because of the different requirements in terms of power and energy density. The number of battery packs per vehicle can differ. Depending on the range required by the customer, the number of LIBs integrated in the vehicle is determined, which allows both flexibility and cost savings for their customers. This leads to customised energy capacity variations of fully electric vehicles, for example, from 147 to 396 kWh. The modularity adds complexity to the technical and control set-up. Not only a BMS controlling the modules of a single battery pack is needed, but an energy storage control module controlling the different battery packs in a vehicle as well. This energy storage control module is produced by Volvo Group in-house, while the LIBs are currently sourced from different suppliers. In 2019, Volvo Group entered a strategic alliance with Samsung SDI to develop battery packs for Volvo Trucks and strengthen Volvo Group's *"long-term capabilities and assets within electromobility"* (Volvo Group, 2020, p. 22). This deal includes the provision of battery cells and modules by Samsung SDI to Volvo Group and the use of Samsung's battery pack technology to assemble battery packs within Volvo Group's manufacturing operations. It also demonstrates Volvo Group's ambition to increase its know-how and to integrate an increasing amount of the battery production in-house.

Today, aftermarket services and recycling solutions for LIBs are solved on a project to project basis because of the different battery chemistries and suppliers. However, Volvo Group sees a trend to harmonise their battery technology solution in the future, which is why they aim to develop a more global and proactive approach. Traditionally, the repair, refurbishment, and remanufacturing of components in a conventional truck or bus has been a part of Volvo Group's business model. With the LIB production currently being outsourced, Volvo Group highly relies on the knowledge exchange with suppliers for aftermarket activities and needs to determine the feasibility of those.

No official and uniform LIB life cycle strategy currently exists, but a program for developing this strategy has been initiated in early 2020. An overarching strategy is also needed because, as a heavy-duty vehicle manufacturer, Volvo Group will most likely receive LIBs earlier than other passenger vehicle OEMs. While LIBs could potentially last 15-20 years in a car (Harper et al., 2019), the lifetime of LIBs in heavy-duty vehicles is currently estimated to be less than 10 years because of the heavier average daily usage of the vehicle. Thus, the time lag between the sale of an electric bus or truck and the return of end-of-use or end-of-life LIBs will be much shorter than for passenger car OEMs. While Volvo Group's numbers of returning LIBs currently remain in the lower hundreds, they will increase by the mid- and late-2020s.

4.3.2 Current lithium-ion battery life cycle management

Today, Volvo Buses is the only brand within the group that experiences return flows of LIBs. The take-back of LIBs is currently based on the voluntary return of LIBs at Volvo Group's dealers. This is ensured by only providing replacement LIBs to Volvo Group dealers and not to independent operators (Respondent 14). A LIB can end up at the dealer by several paths: (1) the vehicle is still good for use, but a fault code indicates the LIB needs to be checked and potentially repaired or exchanged, (2) the vehicle is still good for use, but the LIB's capacity has declined so that it cannot provide the desired range to the user anymore, (3) the battery breaks down completely and the vehicle must be towed to the dealer, or (4) the vehicle is at its end-of-life because of other components than the LIB (e.g. because of an accident) (Respondent 14).

While the theoretical end-of-life of a LIB in a vehicle has been defined in collaboration with the battery producer, there is currently not fault code or message informing the user once this end-of-life capacity is reached (Respondents 9 & 14). Hence, even lower capacities could be observed once the LIB or vehicle is returned by the user. The experience with the high-power LIBs in hybrid buses has shown that LIBs lasted almost twice as long than anticipated by the battery producer and reached very low SOH as well as capacity levels (Respondent 14). VDL's representative confirmed the same experience for their LIBs (Respondent 5). It is uncertain whether it will be similar for LIBs in fully electric vehicles.

When a LIB is returned to a Volvo dealer with a problem outside of the warranty period today, fault codes are retrieved from the vehicle's onboard computer and transmitted to a data base. Technical experts at Volvo Buses then decide about the repair needed or a potential replacement of the LIB (Respondent 14). The diagnosis is currently performed on pack level (Respondent 9). Hence, a replacement can also only be done on pack and not on module or cell level. Volvo's dealers can facilitate functional repairs of the control unit and electronic components for hybrid LIBs and it is to be decided whether they will also be qualified to do so for the fully electric vehicles (Respondents 10 & 14). The recycling of the first LIBs used in hybrid buses was agreed when purchasing the LIB from the supplier. This agreement entails that the logistics are organised (and currently outsourced) by Volvo Group, but the recycling itself is arranged and administered by the LIB supplier (Respondent 7). For the other LIBs, Volvo Group aims to bundle and optimise the end-of-use and end-of-life activities by analysing the applicability of repair, refurbishing, remanufacturing, repurposing, and closed-loop recycling.

Currently, two pilot projects for second life applications exist ("Viva project" and "Stena project"). They were initiated by external partners and Volvo Group agreed to participate (Respondent 12). Volvo Group was very involved in the activities of the Viva project, serving as a project partner for the development of the system, specifying the necessary control and cooling interfaces, safety requirements, and transportation. In comparison, Volvo Group's involvement in the Stena project was limited to the provision of LIB modules. The responsibility for all other activities completely shifted to Stena. Hence, these two projects serve as proof of two different concepts: the leasing of repurposed LIBs with a close collaboration and the sale of end-of-use LIBs (Respondent 12). No decision regarding the deployment or in-depth investigation of a second life business model has been taken so far because the Group intends to wait for the results from the existing pilot projects. Nevertheless, several of Volvo Group's companies are likely to be impacted by the energy transition in the mobility sector, which is why they are looking to diversify their product portfolio (Respondent 11). Accordingly, an internal company within Volvo Group is already investigating the sale of products and solutions using first and second life LIBs.

Based on the analysis of Volvo Group's current situation and the learnings from *RQ2*, Table 4-3 summarises several opportunities for improvement identified during the interviews that would help the future deployment of different CBMs. Determining how the LIBs used in Volvo Group's buses and trucks age under real life conditions and whether the modules and cells age homogenously or heterogeneously is crucial to identify the best suitable CE strategy. It was indicated that the modules of newer LIBs most likely age rather homogenously (Respondent 9), which favours repurposing instead of refurbishing. Moreover, this ageing behaviour impacts the decision on which level Volvo Group intends to facilitate potential CE activities (pack, module, or cell level) and how detailed the diagnostics need to be. The current limitation of not being able to assess the SOH of single modules from the BMS without manual testing was one of the most frequently mentioned aspects Volvo Group would need to improve. This would enable any of the CE activities that slow the loop and involve a module exchange such as refurbishing and potentially repurposing (Respondents 9 & 13). Furthermore, the need for clear and decisive leadership and a top-down directive to provide guidance and commit resources was highlighted by a few respondents (Respondents 7, 11 & 12).

Table 4-3. Internal factors and opportunities for improvement at Volvo Group

Area	Opportunities for improvement
Diagnostics	• Determine ageing behaviour of own LIBs (heterogenous or homogenous) • Diagnostics on module level through BMS (negotiation with battery supplier to share data for earlier generations of LIBs and to measure and share parameters for future LIBs) • Automated, predictive monitoring of SOH and usage patterns via cloud connectivity for future LIBs
LIB design	• Design for disassembly needs to be a central premise as it is an enabler for all CE activities • Determine on which level life extending activities should be deployed (pack, module, cell level) to take it into consideration in the design of future LIBs
Organisational capabilities	• Commitment from higher management for CE activities • Commitment of resources (financial and human) for the CBM innovation process
Closed-loop supply chain	• Optimise logistics to reduce costs (decide what capabilities will be transferred to dealers) • Ensure a retained control of LIBs (e.g. leasing, deposit-refund, service contract, buy-back) • Active materials and cell supplier producing in EU for closed-loop recycling • Close collaboration and partnerships within the closed-loop supply chain

4.3.3 Ideation of potential circular business models

In theory, all CE activities could be deployed by Volvo Group and operationalised in CBMs. However, several Volvo Trucks employees mentioned that the company may need to focus on a few activities first because of limited resources. The historic involvement in refurbishing and remanufacturing as a key business area for the OEMs, as well as the strong customer demand for refurbished batteries as replacement batteries for buses[12] lead to the prioritised investigation of these CE activities (Respondents 10 & 14). However, with a sole focus on activities that are geared towards the already existing customer segment, Volvo Group risks missing out on a business opportunity with repurposing.

Slowing the loop

High potential is seen in both, repair and refurbishing, by exchanging a few faulty modules or those with a low SOH in case of a heterogeneous ageing behaviour (Respondents 7, 10, 13 & 14). This is because the overall SOH of a LIB is determined by its weakest module (Respondent 9). Currently, only manual testing of the modules can provide the necessary information for the estimation of a module's SOH. This has been found to be very time consuming and labour intensive. Partnering with a company that is specialised in diagnosing and refurbishing LIBs of different producers has been discussed as a potentially more suitable option for the short-term (Respondent 13).

Regardless of who carries out the repair and refurbishing activities, these models are reliant on the supply of spare parts. There is a discussion at Volvo Group as to whether modules from an older generation of LIBs can be replaced with modules designed for a newer generation LIBs from the same producer. While it is mechanically possible, it is said to require updates of the BMS and electric connections (Respondent 9). Alternatively, the supply of modules for older generations of LIBs could be secured by purchasing them before they are needed by a customer

[12] For trucks this is unclear because it is expected that most owners will decide to scrap their truck due to a low residual value.

and utilising them in an energy storage prior to their use in a vehicle (pre-1st life utilisation). The same could be done for replacement battery packs. Renault's respondent mentioned their tests have shown that the capacity loss in stationary energy storages is very low due to the very balanced conditions regarding temperature, charging cycles, and power demand. In a pilot project with second life LIBs for residential energy storage they even experienced that the SOH remained almost stable over several years (Respondent 6). While grid services may be more aggressive in use, the system can be managed with the priority to preserve the batteries by, for example, limiting the output of the system. Moreover, this pre-1st life utilisation has been discussed as an opportunity to assess the business case of second life applications and to build a potential customer base for such as well. Because of the limited returns of used LIBs, an upscaled second life CBM is currently not realistic. By using repurposing replacement LIBs prior to their first use in a vehicle, Volvo Group could build up in-house expertise on stationary energy storage solutions and integrate second life LIBs in the future (Respondent 15).

Volvo Group is faced with different options regarding the specific design of a repurposing CBM and its role in it. The industry overview (in section 4.2) has shown that there are different possibilities and ways to do it. For one, the packs or modules could be sold to a third party which repurposes them, markets the product and assumes full responsibility for the recycling at the final end-of-life. This model would potentially involve the provision of certain information about the LIB to the repurposing company, ideally through access to BMS data (Respondents 2 & 3). This information relates to technical parameters such as original and current battery values (such as capacity, internal resistance, cell voltage), charge and discharge history, as well as a list of errors. It would have to be determined whether sharing this data from the BMS is possible without violating data protection rights and intellectual property rights of manufacturers. Furthermore, it is crucial to clearly define liabilities and responsibilities in a contract and to identify potential risks in close collaboration with the respective LIB supplier of Volvo Group (Respondent 7). It was found that some recyclers are investigating repurposing CBMs such as Stena with their subsidiary BatteryLoop. Hence, Volvo Group could also partner with a recycler and allow them to use the LIBs and their modules for these investigations. In this case, the sales price is potentially offsetting recycling treatment costs that would otherwise be paid to the recycler and a responsible recycling is guaranteed.[13] Volvo Group could also partner with a third party by leasing the packs or modules to them for repurposing. This way, Volvo Group would retain ownership of the LIBs and leave the doors open for a subsequent closed-loop recycling business opportunity.

Alternatively, Volvo Group could become a producer of second life energy storage systems and sell or lease a storage solution to a customer. In the industry overview, this has mostly been observed with the creation of a separate entity. However, an already existing company withing Volvo Group could potentially take upon such a role. In this case, all repurposing activities would be integrated and necessary components supplied by other companies. Several respondents mentioned that small-scale energy storages for home applications have not shown to be profitable yet especially due to the reassembly of modules (Respondents 2, 3, 12) and that in countries with higher labour costs, medium- to large-scale storage systems based on LIB packs would be a more realistic business case (Respondent 2).

Furthermore, linking the second life application with the original business of the company has been shown to increase the acceptance and motivation within automotive OEMs to get

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13 One respondent was concerned that other start-ups may not be able to guarantee a responsible recycling in case of bankruptcy (Respondent 8).

involved. A few employees voiced concerns about committing to a new business area such as stationary energy storages. The customer segment for second life applications differs from the usual customer of Volvo Trucks and Buses. An application that connects to and enables the continuation of the core business by supporting the energy transition or charging infrastructure for EVs could, thus, be a motivator for Volvo Group to get involved despite the new customer segment. If Volvo Group does get involved and partners with other companies to develop a stationary energy storage product, learnings from the Viva project should be integrated into the design of the business model. These included that one company should take clear ownership of the final product, the maintenance responsibility needs to be defined, and a safety standard should be developed to minimise the work for the customer (Respondent 12).

Overall, repurposing is an especially interesting business model for LIBs that do not contain cobalt or nickel because they are not likely to ever achieve a positive economic value from a closed-loop recycling process due to high treatment costs and the abundance of cheap virgin materials.

Closing the loop

Because of the high potential for CE activities that extend the life of LIBs, closed-loop recycling will only become relevant in the long-term and most likely be limited to a few valuable materials such as cobalt and nickel. For many other materials, costs for the recycling and purification processes are too high to reintegrate them at a competitive price in comparison to virgin materials (Respondent 2). The most advanced set-up was observed at Volkswagen, where secondary cobalt, nickel, manganese, and lithium are supposedly reintegrated into the cell production. In contrast, Audi and BMW focus on cobalt and nickel only. However, price estimates for the future are very uncertain and subject to change as discussed in section 3.4.2, which is why it is not possible to provide a final assessment of the profitability for recycling certain materials.

In the short-term, Volvo Group will have to select a recycler who is well located, accepts small volumes of LIB packs or modules, and can offer logistics and treatment of severely damaged LIBs. While the selection of more than one recycler for the different markets is a possibility too, this was rarely observed in the industry overview (only for Volkswagen) and may only be economically beneficial in case of high volumes in specific countries. Moreover, the recycling of modules only can potentially lead to cost reductions for mechanical and hydrometallurgical recycling because the recycler then does not have to disassemble the LIB in a pre-treatment step. Instead, the module can immediately be crushed and recycled without additional human labour. However, this would mean Volvo Group internalises the disassembly of the LIB pack before sending modules to a recycler. This could be applicable in the short-term while Volvo Group is still investigating refurbishing and repurposing possibilities and, thus, handling all LIBs internally anyways. However, a storage facility may need to be installed as a physical resource to gather larger volumes of waste LIBs before passing them on to recyclers to make the logistics and recycling process more efficient.

In the long-term, closed-loop recycling for certain materials from high-cobalt LIBs could be operationalised by collaborating and partnering with Volvo Group's cell producer and their respective cathode material producers, who are the actual customer of such a CBM. The customer relations need to be very close to address the uncertainty about the suitability and quality of recycled materials for new LIBs. A research collaboration involving a recycler could be set up to determine the economic potential of closed-loop recycling, to identify cost-saving potentials through, for example, design specifications and to address quality concerns of the cell producer. Samsung SDI, Volvo Group's strategic alliance partner for LIBs, has a supply agreement with Umicore for secondary NMC cathode materials mostly from plants in Korea already. However, Umicore deploys a pyrometallurgical process which has higher environmental impacts than other recycling processes (see results for *RQ1* in section 4.1). Thus, a collaboration with the cell producer could potentially include the selection of a recycler that is able to provide high-quality secondary materials as well as a more beneficial environmental recycling process.

The decentralised disassembly to module level and even further pre-treatment (as envisioned by Duesenfeld with the provision of a containerised shredding and sorting solution) to allow for local recycling of base materials (steel, aluminium) in conventional recycling facilities has been identified as a potentially promising solution for high-cobalt LIBs (Respondents 1, 2, 4 & 6). Since logistics are one of the key cost drivers, a regional pre-treatment solution could significantly lower the overall costs once larger volumes occur. This pre-treatment could potentially be carried out by Volvo Group in those countries with the highest sales volume or outsourced to the recycling company to benefit from a higher occupancy rate if Volvo Group's volumes are not high enough. If dealers are qualified to disassemble LIBs for repair or refurbishing in the long-term, it would seem obvious to utilise them for the disassembly of end-of-life LIBs if they or single modules have been diagnosed as unsuitable for any other CE activities. Next to logistics, manual disassembly is a second cost driver for recycling, which is why these two aspects need to be weighed up in the decision making.

Another alternative that was, however, not observed in practice or much touched upon in interviews and conversations is to partner with or set up national producer responsibility organisations with other OEMs to organise recycling of LIBs locally. This could be a feasible strategy to benefit from larger combined numbers while there is not much volume to recycle. However, the differentiation in the pack and cell design as well as cell chemistry could hinder the effectiveness of such a combined system, especially if its process includes the disassembly to module or cell level for hydrometallurgy. Nevertheless, the potential to reduce costs for both transport and recycling due to larger volumes may be reason enough to investigate this option.

Figure 4-4 summarises the identified CE strategy and CBM options at Volvo Group.

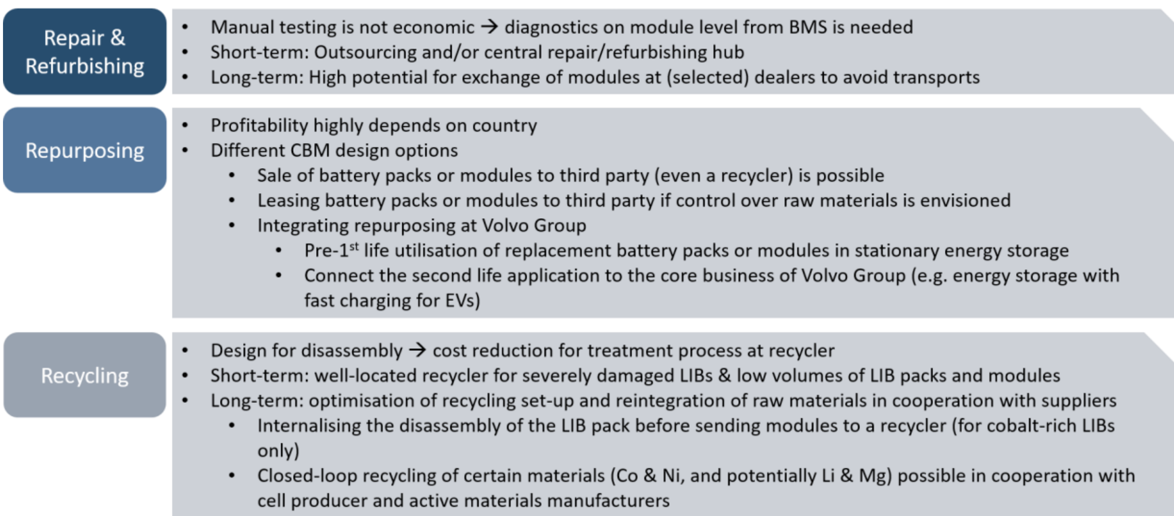

Figure 4-4. Identified CE strategy and CBM options at Volvo Group

5 Discussion

This thesis aimed to explore how automotive OEMs could innovate their business model for LIBs to ensure the lowest environmental impacts from EVs through the utilisation of CBMs. This aim was approached by identifying an ideal life cycle management for LIBs from an environmental perspective (*RQ1*), analysing current strategies amongst OEMs, their operationalisation and underlying influencing factors (*RQ2*), as well as exploring the potential for CBM innovation and implementation at Volvo Group (*RQ3*).

The following sections discuss the main findings along the three research questions and relate them to the existing literature, highlighting this research's contribution to the state of knowledge. Finally, methodological reflections are provided.

5.1 Overview of the findings and their significance

5.1.1 A circular economy hierarchy for lithium-ion batteries

While the existing environmental assessments have mainly focused on the use of LIBs in second life applications, a general trend can be deduced. According to this trend, CE activities that enable a maximised use of the existing product or components and reduce the need to produce new batteries could significantly lower and avoid many environmental impacts. Even though only one assessment integrated refurbishing, it was found to be an environmentally beneficial strategy, especially if the replaced modules are then repurposed in a second life application. Therefore, the ideal CE strategy prefers slowing the loop of LIBs before closing it and opting for activities that preserve the integrity of the product or component for as long as possible. This research's contribution lies in the proposal of a CE hierarchy for LIBs that includes all potential CE activities by interpreting existing life cycle assessments. The proposed CE hierarchy for LIBs is in line with the waste management hierarchy as set out in the EU Waste Directive 2008/98/EC and adopted by the CE theory in the technical cycle by the Ellen MacArthur Foundation (2015) presented in section 3.1. It also confirms the frequently stated presumption that LIBs are a promising product for CE strategies because of its low energy consumption during the use phase.

The proposed CE hierarchy must be interpreted with regards to the studies' limitations outlined in section 4.1 because some uncertainties with the assumptions made prevail. The assessments offer an indication of general correlations such as a positive effect of the extension of life of LIBs. This positive effect is reliant on that the repaired, refurbished, or repurposed LIB replaces the need to produce a new LIB or to use fossil fuels to provide the desired function. While a more advanced and dynamic assessment could slightly change the results, their general trend is expected to remain similar. Thus, the existing studies can still provide guidance for decision making despite their limitations.

Moreover, a potential short-term trade-off between material depletion and other environmental impact categories was observed when using LIBs for a second life. However, in the long-term LIBs will end up in recycling anyway, making the raw materials available for battery production with a time lag and highlighting the importance of both strategies. Another potential positive side-effect of postponing recycling is that its technical processes may advance, thus increasing recovery rates and the profitability (Sun et al., 2018). Even though there are uncertainties about the technological developments of batteries and their raw material needs in the future, the cobalt demand is projected to increase further at least until 2030 (Dias et al., 2018). With the potential introduction of stricter legislation regarding recycled content in LIBs, it is very likely that there will be a customer for recycled materials. Therefore, the immediate recycling of a LIB would not be justified from an environmental perspective. It also highlights that the ideal life cycle management of LIBs from an environmental perspective deals with competing objectives and contextual factors. The feasibility of different CE activities is further influenced by safety standards and concerns, OEMs' capacities, standards, and processes, as well as the economic business case. Meeting regulatory requirements could likely take precedence over environmental benefits of life extension activities, which is why policy needs to be designed carefully with regards to incentives created by it.

Overall, it is more of a strategic decision of an OEM to recycle straight away and integrate a few recycled materials in its own cell production today. The European Battery Alliance, for example, primarily focuses on recycling to secure access to secondary raw materials in Europe (European Commission, n.d.-a), which may indicate the priority of the battery production industry. The results of this study, however, reveal it may not necessarily reflect automotive OEMs' positions as was shown with the results for *RQ2* in section 4.2.1.

5.1.2 Common themes in the industry

The circular economy strategies for lithium-ion batteries

The findings demonstrate that the few companies with an official strategy for LIBs are generally front-runners in terms of EV development and deployment. Hence, it is expected that they are the first to have been confronted with the challenge of what to do with LIBs their first use. At the same time, it shows that the life cycle strategy development amongst most manufacturers is rather reactive than proactive. This may be explained by the high uncertainties regarding the technological developments, regulation, and economic feasibility of different CE strategies. It could also indicate that the automotive OEMs mainly focus on improving and launching the initial product with little consideration of the end-of-life of LIBs in the design stages because the aim is to accelerate the transition towards electrification.

While repurposing is in focus of both academic literature and the public communication of OEMs, the interviews revealed that repair and refurbishing CBMs are also widely deployed by OEMs as they relate directly to their core business. Hence, it could be construed as a standard practice which does not need to be communicated to the public. This coincides with Melin's (2020) experience according to which most OEMs are deploying these activities themselves or through service providers. Little evidence of remanufacturing CBMs was found, which may indicate a rather homogenous ageing behaviour of most LIBs in which case remanufacturing is unsuitable. The findings revealed that many OEMs are utilising replacement LIBs in pre-1st life energy storages. Using new LIBs in energy storages can be a way to condition the replacement batteries and to ensure the availability of replacement LIBs or modules. It was also recognised as a means to build relationships with potential end customers for second life applications to gain insight into their capacity expansion plans and as a basis to intelligently select the end-of-use management pathway. This repurposing option has not been discussed in the reviewed literature as a potential repurposing and business case. Therefore, this research contributed to the state of knowledge by highlighting that repurposing may not only be a CE activity for end-of-use LIBs but *prior* to intended use as well.

Furthermore, only a small number of closed-loop recycling initiatives for high-cobalt LIBs with the involvement of automotive OEMs were found. The results showed that the OEMs in these initiatives are invested in the battery and cell production. Furthermore, only a few materials are considered for which raw material prices are high or very volatile, or other social and environmental risks are high. This is in line with the existing literature, which indicates that price developments for raw materials are the main factor influencing the deployment of closed-loop recycling (Kurdve et al., 2019; Pagliaro & Meneguzzo, 2019). The results further demonstrate that closed-loop recycling occurs without the OEMs' involvement as well because recyclers directly cooperate with cell producers. The close collaboration between parties was found to be crucial, regardless of the set-up, to overcome uncertainties regarding the suitability and quality of recycled materials for new LIBs. Furthermore, the few existing closed-loop initiatives show a trend to regional recycling solutions, close to where battery cells are being produced to avoid transports, which indicates that the supply chains for recycled materials are likely to become more local.

Operationalisation

The specific operationalisation has been found to vary amongst OEMs. No generic or ideal operationalisation applicable to all OEMs was identified in this research for any of the CBMs. This confirms the findings of Wells & Seitz (2005) and Kringelum & Gjerding (2018) according to which CBMs, closed-loop supply chains, and business model innovation are highly dependent on contextual factors. The involvement of OEMs in repurposing CBMs has been observed at varying degrees. OEMs may sell their LIBs to a third party or expand in the second life and energy storage business by setting up a specific subsidiary or joint ventures for the repurposing of their LIBs. The same was found for closed-loop recycling which may take place with or without the involvement of OEMs. Instead, the collaboration between the cell producer or the active materials manufacturer and the recycler was identified as more important for a closed-loop recycling CBM as previously suggested by Gaines et al. (2018). Hence, automotive OEMs must design their CBMs based on their context and needs.

When comparing the findings from the operationalisation with the generic CBM patterns proposed by Lüdeke-Freund et al. (2019), the following can be observed: For repair, refurbishing and recycling most of the findings confirm their identified CBM patterns. The repurposing CBM pattern, however, falls short in reflecting the repurposing CBM of a LIB. While second life applications generally appeal to a green customer, the environmental value proposition was identified as insufficient to convince other customer segments. Instead, the functional and economic value propositions must be competitive too. This either means that the product must be cheaper or provide a similar function and warranty as a new product. Repurposing was shown to be a much more complex and diverse value creation process than proposed by the authors. It may include the reassembly of modules and the addition of other components and requires manufacturers and potentially service providers as well as suppliers as key partners. Suppliers have also been found to be additional key partners for refurbishing and closed-loop recycling CBMs if the battery production is not vertically integrated at OEMs. In line with the findings of Lüdeke-Freund et al. (2019), transportation and logistics were identified as a cost driver for all CBMs, including repair if it organised centrally and not at the dealers.

Influencing factors

Regarding the influencing factors, many of the external factors presented in the literature were confirmed during the interviews. Surprisingly, few respondents mentioned the regulatory framework as a prohibiting factor for repurposing. In the literature review this factor was quite prominent (e.g. Bobba, Cusenza, et al., 2018; Kurdve et al., 2019; Olsson et al., 2018). One possible explanation for this may be that the interviewed companies were successful in overcoming difficulties with the legislation and, thus, did not view it as a major barrier. Instead, the respondents mainly referred to economic and technological factors. While in the long-term, the integration and dominance of fluctuating renewable energy in the grid is expected to lead to an increase in energy storage demand in all EU countries, today this only applies to a few countries. Hence, repurposing CBMs may currently only be profitable and applicable in countries with vulnerable energy grids who already have a higher demand for energy storage (e.g. Germany). For closed-loop recycling, the development of a European value chain (i.e. cell and battery production in the EU), commodity prices, and future cell technology were found as main influencing factors. Even though it is difficult to foresee or influence the development of the last two, both practitioners and politicians may assist in promoting the development of a European cell production as it is done by the European Battery Alliance (European Commission, n.d.-a). Overall, the results show that there are market disparities between new LIB materials, components, or products, which often do not incorporate negative externalities, and CE strategies, whose positive externalities are not necessarily reflected in the economic valuation. Hence, it remains a challenge to internalise externalities (environmental costs and benefits) in the economic valuation to ensure the economic competitiveness of environmentally beneficial business models and products.

The results further highlight that design for disassembly and efficient diagnostics through the BMS are key enablers for any CBM, but especially for those that are slowing the loop. These relate to external technological factors as well as the knowledge and expertise within the organisation as an internal factor. By exploring the internal influencing factors, which are insufficiently covered in previous literature, this research was able to expand the current state of knowledge. It was shown that especially organisational capabilities and resources influence the CE strategy and its success in implementation. While the integration of battery production was found to be a driver for CBMs, it is not a necessity as Renault's case shows. More importantly, the knowledge on diagnostics and clear interactions with the BMS have been identified as internal factors enabling slowing the loop activities. This coincides with existing literature (e.g. Klör et al., 2015; Olsson et al., 2018), but this thesis stressed the importance of it and highlighted the fact that the automotive OEM may be dependent on knowledge transfer from the battery supplier too. This was reflected in the case of Volvo Group.

5.1.3 Volvo Group's potential

Within the context of Volvo Group, several opportunities for improvement to support the adoption of CBMs were identified based on the enabling factors discovered in *RQ2*. On an organisational level, CBM innovation within Volvo Group could be supported with strong leadership, a clear vision and strategy, and a commitment to incorporate more responsibilities at Volvo Group to navigate the uncertainties. Otherwise, Volvo Group might outsource the CE activities to external partners, which could mean potentially losing control of the LIBs. Several technical aspects have been found to need clarification and improvement too. This relates to the determination of the ageing behaviour of Volvo Group's LIBs (heterogenous or homogenous), the implementation of diagnostics on module level through the BMS, and the decision on the level at which CE activities shall be executed (pack, module, or cell). Furthermore, resources must be allocated to the CBM innovation process, especially if involvement of the OEM in repurposing CBMs is envisioned.

The LIBs life cycle innovation process at Volvo Group seems to not have been guided by a clear vision or strategy thus far. Instead, the repurposing pilot projects were initiated and brought to Volvo Group by external companies and the refurbishing activities are a result of the historic engagement of the company with refurbishing and remanufacturing. This diverts from the ideal and steered business model innovation process as it is proposed and outlined by authors such as Wirtz & Daiser (2018) and further developed for CBM innovation by Kraaijenhagen et al. (2016), in which leadership, vision and purpose, as well as the analysis and ideation of potential business models are steps to be considered before prototyping. Volvo Group would be well advised to incorporate these steps into the newly set up life cycle program and to facilitate a strategic CBM innovation process.

Based on the anticipated ageing behaviour of Volvo Group's LIBs, repurposing seems like a promising CE strategy. Especially the pre-1st life utilisation of replacement LIBs was identified as a potential business case for the company to maximise the use of LIBs and secure the accessibility of spare parts. For an organisation like Volvo Group, which will not produce battery cells in the near future, it is crucial to highlight that a closed-loop recycling CBM may only be successful if the cell producers and their active materials manufacturers are included in a collaboration. It is a strategic decision whether Volvo Group intends to stay in control of the materials within their high-cobalt LIBs by setting up a three-party agreement and ensuring the recycled raw materials are directly used as input for cell production for LIBs for Volvo Group. This, however, may only make sense if their cell production is in the EU because geographical proximity was found as an important factor influencing the success of closed-loop recycling models. Alternatively, Volvo Group may simply leave it up to the market/the recycler how much of the recycled material is reintegrated for LIB production. Then the focus would only lie on the optimisation of reverse logistics, design for disassembly, and potentially dismantling the packs in-house to avoid costs at the recycler by only providing modules (relevant for mechanical and hydrometallurgical processes).

5.2 Methodological reflections

By design, this thesis focused on CBMs deployed by automotive OEMs. The reason was the assumption that they will be the ones driving the change and implementing CBMs or actively task other companies to do so, and the collaboration with Volvo Group. With this, however, certain gap exploiter business models in which an independent third party offers a product or service to EV LIB owners were systematically excluded. Mapping all existing CBMs where EV LIBs are used, regardless of the OEM's involvement, may have provided a more comprehensive picture of the currently existing practices. However, this thesis aimed to explore the role and opportunities of automotive OEMs with regards to the LIB life cycle management, which was achieved by the research design. By assessing the deployed CBMs amongst automotive OEMs, this research provided a snapshot of their current practices in the EU. It is important to note that these are subject to change. As an alternative, the research could have focused on the innovation process and progress within automotive OEMs. This would have required a closer collaboration with the different OEMs and was not considered feasible within the scope of this thesis.

Furthermore, the author had to accept a trade-off between the breadth of the chosen research design by examining all potential CE strategies and the detailed exploration and explanation of their operationalisation as well as the strategy-specific influencing factors. This could impact the usefulness of findings for certain actors that are more interested in the practical operationalisation of specific strategies. Interestingly, one respondent remarked that the OEMs are all watching each other, and no one knows whether anyone has found *"the holy grail"* (especially with second life projects) or if they are close to *"falling off a cliff"* (Respondent 5). Examining one mature example of a successful CBM may provide more detail and insights into the specific success factors of that case than the mapping of all activities. The respondent's comment also relates to the fact that it is difficult to gather data on failure. Companies tend to not report or talk about their failures, which means others may repeat the same mistakes. In this thesis, the former CEO of a bankrupt repurposing start-up was interviewed in the attempt to understand factors that contributed to their failure. This could, however, be expanded and the focus of another study.

The third part of this research (i.e. the application and ideation of CBMs for LIBs) is limited by design to the investigation of a single case company, namely Volvo Group. Single case study approaches have been criticised to only produce context-dependent knowledge, thus, limiting the generalisability and transferability of the findings to other cases (Walliman, 2006). However, the choice of the single case study was justified in section 2.1.1 and the author does not make a claim for generalisability of results for *RQ3*. In contrast, an analytical generalisation of results from *RQ2* is possible with regards to influencing factors. These were derived from patterns and themes identified amongst the multiple cases based on the theoretical concepts and the analytical framework presented in chapter 3. Furthermore, this study provides practical examples of CE strategies amongst OEMs and their operationalisation, which may be of additional value by the *"force of example"* (Flyvbjerg, 2006, p. 228) for both practitioners as well as academia and policymakers.

Different analytical frameworks could have been used in this thesis. The author decided to create a conceptual framework based on several existing ones to cover the complexity of the topic. The business model canvas was used to analyse the operationalisation instead of for example the ReSOLVE framework (Ellen MacArthur Foundation, 2015) or the business model classification by Bocken et al. (2016). The rationale for this was that, while most of these frameworks depict how the CE can be strategically addressed by business actions, they do not discuss the specific business model components and design process (Lewandowski, 2016). These, however, were regarded as important to answer the research questions. Hence, the business model canvas was selected as most appropriate for the purpose of this thesis. Overall, the analytical framework proved valuable for providing an overview of the different influencing and enabling factors for the definition of a CE strategy and the operationalisation of it.

Another reflection relates to the analysis of documents and media reports of automotive OEMs to identify the adoption of CE strategies in practice. The information and data provided by these sources is limited to the perspective and potential bias and agenda of the respective authors (Sovacool et al., 2018). For this thesis, the author assumed that the companies' reports on their activities reflect reality. This was considered an acceptable assumption given that the objective was to gain a general overview of the current adoption of CE practices. However, the public communication does not necessarily correspond to what is really happening. Examples of this are the repair and refurbishing practices that were described in the interviews but rarely represented in the public communication. For more accuracy, a survey could have been created and sent out to all OEMs to give them a chance to describe what they are doing without requiring as much time as for an interview.

6 Conclusions

Sales of EVs are expected to increase substantially and with it, the number of LIBs. High costs, resource, and energy demands to produce LIBs as well as environmental concerns and supply risks motivate stakeholders to investigate and implement CBMs that slow and close the loops of LIBs. This research intended to explore how an automotive OEM could innovate its business model to incorporate an environmentally responsible life cycle management of LIBs. To do so, three research questions were posed and answered as follows:

RQ1: What is an ideal CE strategy for a LIB life cycle from an environmental perspective?
The findings indicate an ideal CE strategy for LIBs follows the EU's waste hierarchy as it is translated into the technical cycle of the CE. Accordingly, slowing the loop of LIBs is preferred before closing it. Within slowing the loop, it is recommended to opt for activities that preserve the integrity of the product or component for as long as possible because this reduces the need to produce new batteries and enables a longer and more efficient use of resources. The existing life cycle assessments especially pointed out the environmental benefits of second life applications that are combined with renewable energy production, and where little changes are made to the original product.

RQ2: Which CE strategies for LIBs are deployed by automotive OEMs in the EU, how and why?
The industry overview has shown that OEMs focus mostly on repair, refurbishing, and repurposing to slow the loop, while remanufacturing is rarely deployed. Some OEMs are involved in all these activities, including a utilisation of replacement LIBs in stationary energy storages before the first use in a vehicle. Nevertheless, very few full-scale repurposing CBMs exist as of today because most projects are still in their piloting phase. Furthermore, only a small number of closed-loop recycling initiatives with involvement of automotive OEMs were found and they were mostly limited to valuable materials such as cobalt and nickel. The results highlight that the different CE activities are not mutually exclusive, but complementary. Different CBM designs were observed especially for repurposing and closed-loop recycling with varying involvement of OEMs. Most often, repurposing models were characterised by close collaborations with partners such as energy utilities or repurposing companies. The findings suggest that the environmental value proposition of a repurposing CBM is not sufficient to compensate for the product's lower functionality and warranty. It needs to offer a competitive economic value to the customer as well. For closed-loop recycling, the cooperation between cell producers or their active materials manufacturers and recyclers is crucial to build trust regarding the quality of secondary raw materials. Design for disassembly and efficient diagnostics through the BMS were identified as key enablers for any CBM. Closed-loop recycling is expected to increase with the development of a cell production industry in the EU and rising raw material prices. While they can be supported by OEMs, currently existing closed-loop recycling initiatives only involve OEMs if they are (starting to get) involved in cell production as well.

RQ3: Which CBMs could Volvo Group implement for LIBs in the EU?
Several opportunities for improvement were identified to support and enable the adoption of CBMs at Volvo Group. For the operationalisation of CE strategies, the importance of close customer relations was highlighted as crucial to reduce uncertainties and concerns. Moreover, the necessity to design for disassembly and to build expertise to thoroughly diagnose the SOH of LIBs was identified. The potential for repair, refurbishing, and repurposing was found to be high. Especially the utilisation of replacement LIBs before the first use in a vehicle was identified as a potential business case for the company to maximise the use of LIBs and secure the accessibility of spare parts. For high-cobalt LIBs, a closed-loop recycling model may also be applicable for a few metals such as cobalt and nickel.

6.1 Recommendations for practitioners

This thesis has shown that automotive OEMs are well-advised to engage in an innovation process to incorporate CBMs for LIBs because they offer much potential from a CE perspective and are one of the most valuable parts of EVs. Hence, it is recommended to facilitate a strategic CBM innovation process for LIBs and making this a strategic priority instead of reacting upon short-term opportunities. An OEM's CE strategy should be guided by the proposed CE hierarchy for LIBs if the aim is to develop an environmentally friendly life cycle management. Additionally, environmental criteria such as the GHG emissions should be regarded when selecting a recycler. Overall, automotive OEMs must design CBMs based on their context and needs. Assessing whether LIB modules and cells used in the specific OEM's LIB age homogenously or heterogeneously could help the overall strategy selection. Moreover, the operational decision which CE activity to deploy for a specific LIB requires a thorough diagnosis of its SOH. Practitioners would highly benefit from developing a (standardised) method to estimate the SOH and remaining useful life of LIBs to support CE strategies that slow the loop and that rely on these metrics. Lastly, practitioners could aim to accelerate the CE transition in the automotive industry by influencing policymakers via industry associations such as ACEA to remove legislative barriers for repurposing CBMs and to support the economic viability of CBMs in the EU in general.

6.2 Recommendations for policymakers

Policymakers in the EU would be advised to develop a clear regulatory framework that supports environmentally favourable CE strategies and improves the economic viability of respective CBMs. This is important because this research has shown there is a misalignment between environmental and economic value. In particular, measures that promote the adoption of repurposing CBMs, which do not seem to have a clear business case despite the environmental value and being the most promising CE activity, should be a focus of a future CE framework for LIBs. Moreover, it is recommended to continue and intensify the support for the development of a European LIBs value chain to ensure geographical proximity between recyclers and producers, which is an enabler for closed-loop recycling. Measures such as demands on local content could support this. Additionally, policymakers are advised to support initiatives and research for a standardised method to estimate the SOH of LIBs. This standardisation could enable CBMs on a larger scale beyond the OEMs.

6.3 Recommendations for future research

Further research is needed to thoroughly assess and compare the different life cycle management options for LIBs. A more dynamic assessment, taking the technological developments and advancements into account when comparing the life cycle impacts, would be useful. Moreover, future research should analyse and develop an ideal CE strategy based on all three dimensions of sustainability, including the economic and social value provided by different options. Additionally, there is a need to determine the optimal recycling rate for LIBs from an overall environmental perspective, balancing the material gains and energy needs. To further support companies in the design of their CBMs, a more in-depth analysis of the operationalisations of a specific CBM for refurbishing, repurposing, or closed-loop recycling should be the subject of future research. Further studies should also explore the entire spectrum of CBMs deployed for LIBs, regardless of the involvement of OEMs, to determine the role of for example gap exploiter business models in the system as well. In this regard, it would be important to explore how standardised access to BMS data, which allows the fast assessment of the SOH by independent entities, could be compatible without violating the intellectual property rights of manufacturers.

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Appendix A: List of search terms for literature review

	Search terms used	Platforms
Academic and grey literature	- Circular economy - Circular business models - Circular supply chains - Closed-loop supply chains - Reverse logistics - (Circular) business model innovation - Reuse - Repair - Refurbishment - Remanufacturing - Second life/use - Recycling - Environmental assessment - Life Cycle Assessment - Batteries Directive Combined with: - Electric vehicles - Lithium-ion batteries Combined with: - Names of automotive OEMs	Web of Science Google scholar Scopus Ecosia.org Electrive.com

Appendix B: List of interviewees

No.	Company	Representative	Position	Type of company	Date	Time (h)	Mean
1	**Daimler AG**	Respondent 1	Employee for Circular Economy Concepts for LIBs	Automotive OEM	06.02.20	0:41	Online
2	**Company 2**	Respondent 2	Business developer	2nd life actor, Recycler	19.02.20	1:55	In person
3	**Box of Energy**	Johan Stjernberg	Founder and former CEO	Failed 2nd life company	27.02.20	0:40	In person
4	**Volkswagen Group**	Respondent 4	Technical planner	Automotive OEM	10.03.20	1:05	Online
5	**VDL Bus & Coach**	Jan van Meijl	Product planner charging infrastructure, energy storage and autonomous driving	Commercial vehicles OEM	20.03.20	1:10	Online
6	**Renault Group**	Jean-Denis Curt	Recycling & Circular Economy Unit Manager	Automotive OEM	25.03.20	1:00	Online
	Volvo Group			Commercial vehicles OEM			
7	Trucks Purchasing	Mélanie Girardot	Project Manager Purchasing Early Phase		Several dates	>4	In person
8	Trucks Purchasing	Respondent 8	Buyer		11.02.20	1:10	In person
9	Trucks Technology	Respondent 9	Principal System Design Engineer		24.02.20 18.03.20	1:30	In person
10	Volvo Trucks	Respondent 10	Product Manager Trucks aftermarket		27.02.20	1:10	In person
11	Volvo Penta	Respondent 11	Director Electromobility		02.03.20	1:00	In person
12	Trucks Technology	Respondent 12	System Design Engineer		09.03.20	1:20	In person
13	Trucks Operations	Respondent 13	Senior Global Reman Engineer		11.03.20	1:05	In person
14	Volvo Bus	Respondent 14	Parts Product Manager Aftermarket		12.03.20	1:40	In person
15	Trucks Technology	Respondent 15	Senior Innovation Manager		16.03.20	0:45	In person

Appendix C: Interview guide for automotive OEMs

Topic area 1 – Introduction and context	1. Could you please present the core business activities of your organisation and your role in this organisation? 2. How engaged is your organisation in the production of LIBs? (Cell, Module, Pack design and production?)
Topic area 2 – LIBs life cycle activities and strategy	3. Could you please describe the current life cycle of LIBs within your organisation? 4. Does your organisation envision or follow a circular economy strategy (extending the lifetime and closed-loop recycling) for LIBs? And if yes, how?
Topic area 3 – Reverse logistics	5. How does your organisation retain ownership of the batteries? 6. How does your organisation organise its reverse logistics of LIBs? 6.1 Please describe the logistics flow of your organisation's LIBs within the EU. 6.1.1 How does a customer return a LIB? 6.1.2 Are LIBs always transported in packs or does it go down to module/cell level? 6.2 At which point and by whom is the state of health of the battery diagnosed? 7. What factors contribute to the success of your organisation's reverse logistics set-up? 7.1 Which strengths does your organisation build on to successfully set up a reverse logistics system for LIBs? 8. What are the main challenges that remain for your organisation to set up a reverse logistics system for LIBs?
Topic area 4 – Slowing the loop	*If activities or aspirations to extend the life of LIBs exist, otherwise jump to TA 4 straight away.* 9. Could you please describe your organisation's activities to extend the life of LIBs (repair, refurbishing, remanufacturing, repurposing)? 10. Supplier involvement 10.1 What is the involvement of your battery suppliers in repair/remanufacturing/ repurposing activities? 10.2 Is design for repair/remanufacturing/repurposing an aspect in your organisation's battery procurement? And if yes, how (e.g. selection criteria or early collaboration in design)? 11. What factors contribute to the success of your organisation's activities to extend the life of LIBs? 11.1 Which strengths does your organisation build on to successfully extend the life of the LIBs? 12. What are the main challenges that remain for your organisation to extend the life for LIBs?
Topic area 5 – Closing the loop	13. How does your organisation make sure it is compliant with the Batteries Directive 2006/66/EC recycling targets (50% recycling by weight)? 13.1 What are the criteria by which you choose your recycling suppliers? 14. Supplier involvement 14.1 What is the involvement of your suppliers in battery recycling activities? 14.2 Does your organisation collaborate with your cell/battery suppliers to have a closed-loop recycling? And if yes, how? 14.3 Is design for recycling an aspect in your organisation's battery procurement? And if yes, how (e.g. selection criteria or early collaboration in design)? 15. Is recycling LIBs a cost or a potential business case for your organisation? 16. What factors contribute to the success of your organisation's LIBs recycling activities? 16.1 Which strengths does your company build on to successfully recycle LIBs? 17. What are the main challenges that remain regarding recycling within your organisation?

Appendix D: Overview of environmental assessments

Author	Cell chemistry	Environmental impact categories	Second life application	Comparison	Recycling	System boundary
Ahmadi et al. (2017)	LFP	climate change, fossil depletion freshwater eutrophication, metal depletion, particulate matter, photochemical oxidant formation	Stationary energy storage with Ontario electricity grid mix for 10 years	Conventional system (internal combustion engine and natural gas)	Pyro- and hydrometallurgy (Ecoinvent process for laptop LIBs recycling)	Entire life cycle system comparison
Bobba et al. (2018)	NMC	abiotic depletion, acidification, climate change, cumulative energy demand, freshwater ecotoxicity, freshwater eutrophication, human toxicity cancer effects, human toxicity non-cancer effects, ionizing radiation, marine eutrophication, ozone depletion, particulate matter, photochemical ozone formation, terrestrial eutrophication	Stationary energy storage for 4 years for - peak shaving in a grid-connected office building or - increasing the photovoltaic self-consumption of a residential dwelling	New battery (lithium-ion or lead-acid) or diesel generator backup	Pyrometallurgy	Allocation of manufacturing and recycling impacts, first use in EV excluded
Casals et al. (2017)	NMC	climate change	Stationary energy storage with second life range from 8 to 20 years	Lead-acid batteries	-	Exclusively second life phase
Cusenza et al. (2019)	NMC	abiotic depletion, acidification, climate change, cumulative energy demand, freshwater ecotoxicity, freshwater eutrophication,	Stationary energy storage system in residential buildings combined with renewable electricity generation lasting for 12 years	New LIBs (2x as many to fulfil first and second life functions)	Pyrometallurgy followed by Hydrometallurgy	Entire life cycle system comparison

		human toxicity cancer effects, human toxicity non-cancer effects, ionizing radiation, marine eutrophication, ozone depletion, particulate matter, photochemical ozone formation, terrestrial eutrophication				
Genikomsakis et al. (2013)	LFP	acidification/eutrophication, carcinogens, climate change, ecotoxicity, fossil fuels, land use, minerals, ozone depletion, radiation, respiratory organics, respiratory inorganics	Small-scale energy storage unit in a smart building with solar photovoltaic panels in Spain	New LIBs	unclear	
Ioakmidis et al. (2019)	LFP	acidification, carcinogens, climate change, ecotoxicity, fossil fuels, land use, minerals, ozone depletion, radiation, respiratory organics, respiratory inorganics	Small-scale energy storage unit in a building with Spanish electricity mix or solar photovoltaic for 1500 cycles (roughly 4 years)	newly manufactured, smaller LFP battery for storage	-	Including first use, Recycling excluded

Richa et al. (2017)	Lithium manganese oxide (checked sensitivity of results to NMC and LFP)	Cumulative energy demand, eco-toxicity, metal input	Reuse in EVs for 4.5 years and/or second life in stationary energy storage for 5 years	Lead-acid batteries	50% Pyrometallurgy, 50% Hydrometallurgy	Excluding manufacturing and first use
Yang et al. (2020)	LFP	climate change, fossil depletion, freshwater eutrophication, metal depletion, particulate matter, photochemical oxidant formation	Stationary energy storage for a communication base station for 5 years	Lead-acid batteries	Hydrometallurgy	Allocation of manufacturing and recycling impacts, first use in EV excluded

Appendix E: Full overview of OEM's life cycle initiatives in the EU

Company/ Group	First use (Intensifying use & repair)	Refurbishing & Reman-ufacturing	Repurposing	(Closed-loop) Recycling	Sources
ADL	*No info*	*No info*	*No info*	*No info*	-
BAIC	*No info*	*No info*	*No info on EU, but China:* - Partnership with **Mercedes-Benz Energy** for a second life energy storage system at BAIC Beijing location - Tests and simulations to demonstrate the potential for evening out fluctuation in Chinese grid system and supporting power-failure management	*No info on EU* **China**: - Set up a subsidiary focusing on the recycling of precious metals in Hebei Province	(Daimler AG, 2019a; Ying & Liangheng, 2017)
BMW	*No info*	*No info*	Several pilot projects: **09.2014**: Small-scale second life storages in Hamburg (running for 5 years) in cooperation with **Vattenfall** for two applications: - Interim storage and power buffering for fast-charge stations - Storage of solar energy, maximising self-consumption of solar energy by interim storage of energy in batteries during sunny periods with low electricity demand (solar PV of Vattenfall's Hafen City district heating station) **Autumn 2016**: Large-scale energy storage pilot project scheduled for 10-year period in Hamburg in cooperation with **Bosch** and **Vattenfall:** - 2.8 MWh from 2.600 second life modules from 100 BMW i3 and Active E - Grid balancing services **10.2017:** Large-scale second life energy storage system in Leipzig production plant - 15 MWh from up to 700 second life and replacement battery packs from/for BMW i3 - Combined with wind energy from four wind turbines - Increase renewable self-consumption, grid balancing services	No closed-loop recycling yet but envisioned with the **Umicore/Northvolt** partnership (Umicore is building a cathode material manufacturing facility in EU). Aim to reach a recycling rate >90% in collaboration with partners and constantly trial recycling concepts in recycling and dismantling centre. Battery Cell Competence Centre to increase expertise and work even more intensely on recycling techniques that could be applied on an industrial scale.	(BMW AG, 2014, 2017, 2018, 2019; Bosch, 2016; Hustadt, 2019; Umicore N. V., 2018)

BYD	*No info*	*No info*	*No info on EU, but China:* Repurposing on pack and module level (disassembly of battery pack, assembly to repurposed application). Different pilot projects for energy storage: Utility scale (pack level): - 30 MWh Baolong, Shenzhen - 22.6 MWh Changsha Energy storage station (under construction in 2018) Communication Base Station (pack level): - 2018: Agreement to supply second-life LIBs for back-up power for **China Tower**'s telecom base stations (currently running on lead-acid batteries) Streetlamps (module level) Low Speed Vehicles (module level) **25.10.2019**: Joint venture with **Itochu** to set up a global business for container-type (40-foot) 1MWh second life energy storage systems based on second life batteries: - Target market: factories and stores in Australia and Southeast Asia, then US & Japan, places with undeveloped electricity infrastructure (e.g. mining sites) combined with solar power as an interim power plant - Revenue model: pay according to volume of electricity used - Itochu will remain the owner of the batteries	*No info on EU* **China**: Automatic mechanical battery disassembly (to cell level) → Physical Separation → Hydrometallurgy (full ability of battery recycling technologies) Recycling rates in presentation for NMC (assuming it is for their own recycling process): 85% for lithium 95% for manganese, nickel, aluminium, copper, and cobalt 98% for graphite Trial battery recycling at a site close to its manufacturing facilities in Shenzhen.	(Ando, 2019; Daly, 2018; Jiao, 2018; Stringer & Ma, 2018; Zhao, 2018)
DAF	*No info*	*No info*	*No info*	*No info*	-
Daimler AG	*No info*	Reman considered in early stages of the development process → collaboration between reman	Several pilot projects for stationary energy storage administered by **Accumotive** (internal battery producer), **Mercedes Benz-Energy** (subsidiary founded in 2016, responsible for efficient handling, further development and reuse in scalable applications; initially manufactured photovoltaic home storages, but now is concentrating on second life batteries):	Partner in AutoBatRec2020 project aiming *"to develop an industrialized recycling process in Europe that provides a sustainable raw materials source for its high-tech industry"* with **Umicore** and **Samsung SDI**;	(Daimler AG, 2015, 2016b, 2017b, 2018b, 2019b; EIT RawMaterials, 2018)

		experts and battery system engineers → requirements for series development specifications → relevant for negotiations with suppliers	- All projects provide grid balancing services (primary balancing power) - Estimated lifespan extension of at least 10 years **13.9.2016:** Second life energy storage in Lünen in collaboration with **The Mobility House** - 13 MWh from roughly 1.000 second life Smart ED2 battery packs **23.10.2017:** Active spare parts warehouse in Herrenhausen in collaboration with **enercity** - 17.4 MWh from 3.000 Smart ED3 replacement modules **1.6.2018**: Active spare parts warehouse in Everlingsen in collaboration with **The Mobility House** and **GETEC ENERGIE** - 9.8 MWh from 1.920 Smart ED3 replacement modules	Further partnerships with **Remondis SE** for the recycling from second life projects and **Farasis Energy** to increase the integration of recycled materials in battery cells	
Ford	*No info on EU* **US**: Exclusive repair contract via Battery M.D.	*No info on EU* **US**: Refurbishing by Spiers New Technologies	*No info*	*No info*	(Kelleher Environmental, 2019)
Honda	*No info*	*No info*	Recycling partnership with **SNAM** expanded April 16th, 2020 to also include a potential preparation for second life for renewable energy storage: - Collection of LIBs from Honda's dealer network, Authorised Treatment Facilities, or centralised storage hubs in 22 EU countries - Analysis of suitability for second life or recycling - Suitable LIBs are repurposed and made available by SNAM for domestic and industrial applications	**SNAM** contracted for recycling since 2013 - Hydrometallurgy to extract materials such as cobalt and lithium to be reused in LIB production, colour pigments, or additives for mortar - Closed-loop unclear	(Honda Motor Europe, 2020)
Hyundai	*No info*	*No info*	**26.06.2018**: Partnership with **Wärtsilä** to use second life EV batteries for stationary energy storages using the existing channels and customers of Wärtsilä	*No info*	(Herh, 2019; Hyundai Motor Group, 2018; Kongae, 2019)

			South Korea: - Develop a 1 MWh second life stationary energy storage - Demonstration project in Hyundai Steel's factory **27.09.2019**: Partnership for second life energy storage systems with state-run renewable energy developer **Korea Hydro & Nuclear Power Co. (KHNP)** - 2 MWh pilot with a feasibility study combined with solar power project at Hyundai's Ulsan plant - Commercial 10 MWh storage project		
Irizar	*No info*	Modular design for easy isolation and replacement of modules in case of an error in one of the modules	- Envision second life utilisation until 50% capacity - Use for other types of applications being evaluated - Collaboration with **Cidetex Technology Centre** for projects related to the analysis of second life batteries **31.10.2019**: Collaboration agreement signed with **Ibil** for second-life batteries to be integrated at Repsol service stations - Reduce the power needed from the grid - Deploy high power charging infrastructures, even in places where connecting to the electrical grid is more costly and complex	*No info on closed-loop, but* claim their LIBs are 99% recyclable, and recycling being addressed in collaborations with several European companies	(Irizar, n.d., 2017, 2019)
Jaguar Land Rover	*No info*	*No info*	**2018**: Collaborate with **Connected Energy** for second life stationary energy storage application (based on battery packs) **2019**: Supplied batteries and components from the Jaguar I-PACE to a research project for off-grid energy storage at University of Warwick	*No info*	(Harrup, 2018; The Engineer, 2019)
LEVC	*No info*	*No info*	*No info*	*No info*	-
Mitsubishi	*No info*	*No info*	**2015**: Studying the possibility of energy storage business using second life LIBs in collaboration with **EDF**, **Forsee Power**, and **PSA Peugeot Citroën** - Demonstration project at Forsee Power's headquarter near Paris	*No info on closed-loop, but* development of recycling technology for valuable metals from LIBs	(Forsee Power, 2015; Mitsubishi Materials Corporation, 2018)

			- Envision second life utilisation until <50% capacity - Service: optimised smart grid and energy management		
Nissan	**Nissan Energy Share**: Sharing energy via bidirectional charging with homes, buildings or the grid; currently pilot programs in e.g. in Hagen (Germany) in cooperation with **The Mobility House** and grid operator **Amprion**	*No info on EU* **Japan**: joint venture **4R Energy Corp.** formed in 2010 (51% Nissan, 49% **Sumitomo Corp**) and started operations in March 2018 to produce refurbished battery replacement packs for first Nissan Leaf generation selling at half price of new replacement batteries (¥300,000 = $2850) **US**: Spiers New Technologies contracted for refurbishing	**EU**: Several small- to large-scale applications **2015-2019**: Partner in Energy Local Storage Advanced system (ELSA) research project (based on battery packs) - 192 kWh containerised second life storage with 12 second life Nissan LEAF battery packs at Nissan Europe office near Paris - Testing for services of energy arbitrage and peak shaving **05.2018:** Second life energy storage business (based on modules) with **Eaton Industries** - xStorage Home: 4.2 kWh to 10.08 kWh - xStorage Buildings: 20 kWh to 10 MWh - Warranty 5-10 years - Different services depending on product (energy arbitrage, increasing self-consumption of renewable electricity produced by customers' own solar PV, lowering electricity bills by demand peak shaving, back-up supply of energy, grid stabilisation services) - Selling B2C in UK, but B2B projects also in Norway, France, South Africa **29.6.2018**: 2.8 MWh stationary energy storage application in Johan Cruyff Arena (Amsterdam) in cooperation with **Eaton Industries** and **The Mobility House** - Equivalent to 148 LIB packs, but made of second life and new LIB modules - Self-consumption of electricity from stadium's own solar PV and back-up **18.02.2019**: Nissan x **OPUS** concept: Small-scale 700 Wh power pack ("Nissan Energy ROAM power pack) integrated in an OPUS camper (based on cells) - Providing off-grid remote power	*No info*	(Clements & Ruf, 2020; Eaton, n.d., 2019, 2020; ELSA consortium, n.d.; Nissan Motor Corporation, n.d.-a, n.d.-b, 2015, 2018a, 2018b, 2018c, 2019; Sumitomo Corporation, 2014, 2015; Tajitsu & Doyle, 2018)

			21.01.2020: Partner in **UK Energy Storage Lab** (UKESL) project providing 50 second life LIBs - Created a demonstration facility for grading and sorting of LIBs (prove technical and commercial viability) - Delivered 1 MWh second life energy storage to market Supplies LIBs to **Connected Energy Ltd** (UK) for large-scale second life application in their *E-STOR* products (based on battery packs) **Japan**: All pilot projects led by joint venture **4R Energy Corp**. **02.2014**: Testing a large-capacity energy storage system for a 10 MW solar plant in Osaka - 600 kW/400 kWh with 16 second life battery packs - "verification project" **07.2015**: Energy management system for Nissan Advanced Technology Center - 24 second life battery packs **11.2015**: Large-capacity energy storage pilot in Satsumasendai (city on a remote island) - Grid balancing services - 800 kW based on 36 second life battery packs **26.03.2018**: - Operations start at 4R plant - "The reborn light" project's first prototype: solar-powered LED streetlight operating completely off the main power grid with repurposed second life modules in Namie, Fukushima → full-scale installation planned for late 2018		
PSA Group	*No info*	Opel claims they aim to refurbish batteries	**2015**: Studying the possibility of energy storage business using second life LIBs in collaboration with **EDF**, **Forsee Power**, and **Mitsubishi Motor Corporation**	*No info on closed-loop, but* collection and recycling outsourced with SNAM, who	(Forsee Power, 2015; Opel, n.d.; PSA Groupe, 2015)

		whenever they can	- Demonstration project at Forsee Power's headquarter near Paris - Envision second life utilisation until <50% capacity Opel claims *"batteries are refurbished so they can be used for secondary electrical storage"*, but no projects are public yet	recycle up to 80% of the weight Opel claims to recycle any previous materials	
Renault Group	Energy sharing: - Four Zoe prototypes with bidirectional charging to test real conditions (user gets paid from operator for the service) EV battery diagnosis & repair centres: - Monitoring of LIB condition over the air - 99% of all returned LIBs are repaired	EV battery diagnosis & repair centres: - Diagnose the modules state of health on pack level with info from the BMS - Refurbishing batteries by replacing up to 3 faulty or defect modules	- Estimate the residual capacity after the first life at 60-75% - Lifespan extension of up to 10 years through second life with stationary energy storage as most compelling scenario - Envision second life utilisation until 40% capacity Stationary energy storages: **2015-2019**: Partner in Energy Local Storage Advanced system (ELSA) research project (based on battery packs) - Five small-scale (22-95 kWh) energy storage pilot projects with second life battery packs (Ampere building, Gateshead College, E.On Energy Research Center, City of Kempten, City of Terni) - Testing for various services: peak shaving, energy arbitrage, automated demand response services (cost minimisation, power flexibility, increase of local sources self-consumption) **04.02.2016**: Supplies LIBs to **Connected Energy Ltd** (UK) for large-scale second life application in their *E-STOR* products (based on battery packs) - Grid balancing services, EV charging - Existing projects in UK, Belgium, Germany, Netherlands **06.2017**: Supplies LIBs to **Powervault Ltd** (UK) for small-scale second life stationary energy storage system *Powervault 3eco* (based on cells) mainly intended for households with solar PV - 3.9 kWh to 7.9 kWh - Warranty 3 years	No closed-loop yet as materials are sold on the market by current recycling partner **Veolia**, but ongoing investigation. Current process at Veolia: Disassembly to cell level (other components are reused or recycled through conventional recycling processes) → mechanical crushing → hydrometallurgy Recycling rates: 60% overall 80% for cobalt and nickel	(Brunet, 2019; ELSA consortium, n.d.; Groupe Renault, 2016, 2017a, 2017b, 2018a, 2018b; Laurent, 2018, 2019a, 2019b; Powervault, n.d.-a)

	Intelligent charging to maximise the performance and lifespan		- Increasing renewable self-consumption, energy arbitrage, grid balancing services **25.08.2018**: Launch of "Advanced Battery Storage project" in collaboration with **The Mobility House** (operational management) - Large-scale containerised stationary energy storage system - Combining second life and new replacement LIB packs for aftermarket services - Grid balancing services **2018/2019**: Smart island projects with second life stationary energy storages to store renewable energy - prolonging the life of LIBs by at least 5 years - 132 kWh storage, Porto Santo (2018) - Belle-Île-en-Mer (2019) Mobile applications: - Tested refrigerated vehicles (based on modules) - Electric or hybrid propulsion ships: 3-year partnership signed in 2018 with **Neoline** start-up to provide second life LIB packs for energy storage on two wind-powered cargo ships		
Solaris Bus & Coach	*No info*	*No info*	Producer of battery cells supposedly works on a second life programme	Unclear: *"elements used in the batteries undergo recycling processes implemented by producers of battery cells, and can thus be reused"*	(Solaris Bus & Coach, 2019)
Streetscooter	*No info*	*No info*	*No info*	*No info*	-
Tazzari	*No info*	*No info*	*No info*	*No info*	-
Tesla	Over the air updates and monitoring	*No info*	Decision to not get actively involved	*No info on EU, but* in the US aim to incorporate a closed-loop recycling process at their Gigafactory 1 to recover valuable materials and	(Tesla, 2019)

				dispose of others “responsibly”; currently use third-party recyclers	
Toyota	*No info*	*No info*	No existing projects but investigate the possibilities of second life stationary energy storage systems in Europe (number of batteries available is limited due to their reliability in their first life). **Japan**: - “Smart Green Batteries” at Toyota dealers with 10 second life hybrid battery packs to store locally produced renewable energy - **2018**: partnership with **Chubu Electric Power** for verification project for large-scale second life energy storage system, based on results proceeding with 10 MWh storage system with 10.000 LIBs in 2020 - **05.02.2020**: Announce new ultracompact EV: Leasing cars for several years with scheduled battery checks, then intend to sell used LIBs to **Panasonic** and utilities such as **Chubu Electric Power** to be used in homes (based on a standardised battery that can easily be repurposed for use in homes) **US**: - 208 second life hybrid battery packs forming an 85 kWh off-grid energy storage in combination with solar park	**Umicore** recycling partner for LIBs. Collect >90% through retailer networks, aim to achieve 100% take-back rate. Investigate closed-loop recycling of rare-earth metals in collaboration with **Chubu Electric Power** in Japan	(Fujioka, 2020; Toyota Motor Corporation, n.d.-b, n.d.-a, 2018)
VDL Bus & Coach	Functional repair at customers	Refurbishing in specialised VDL workshop with module exchanges; support from battery producer	VDL Charging Test Center integrated two second life battery packs from an electric bus in charging infrastructure in collaboration with **Siemens**. Preparations for potential future second life application in energy storages: joint venture company "V-storage" with **Scholt Energy Control** (system's energy trading and monitoring).	No closed-loop recycling yet. Actively explore options to recycle internally or with third-party recyclers.	(VDL Bus & Coach, 2019; VDL ETG, 2016; VDL Groep, 2017)

		through local service organisations.	**24.4.2017**: First V-Storage battery system at VDL ETG site in Eindhoven serving as operating reserve for **TenneT** - New batteries used in this case		
Volkswagen Group	Volkswagen dealers perform detailed analysis of the battery's status down to cell level and replace modules.	Refurbish for reuse in a car and sell for a lower price (interesting for those that do not need the highest capacities).	**Second life business:** **27.12.2018**: **Volkswagen Group Components** (independent business unit since January 2019) announces second life application in mobile charging stations with up to 360 kWh capacity to serve temporary needs (start of series production planned before of 2020). - Based on modules from the VW Modular Electric Toolkit (used in VW passenger cars) - Production in Hanover replacing production for parts of the conventional motor **Feb. 2020**: Drive Booster introduced at E-World in Essen with 194kWh capacity (3-10 EV per day) in collaboration with **E.On** **Several other pilot projects:** **2016**: **Porsche** provided dismantled modules from Panamera G1 II to start-up **Box of Energy** for the assembly in a small-scale stationary energy storage system. - Residential storage unit with 18 kWh **Audi**: - Envision second life utilisation until 10% capacity **17.07.2018**: Containerised second life energy storage in collaboration with **Wendelstein Bürgerkraftwerk GmbH** and **N-ERGIE Regenerativ GmbH** close to Nuremberg - 1 MWh from 84 second life battery packs - Expected lifespan extension of 20 years - Grid balancing services	Clear focus on closed-loop recycling. **Audi** partnered with **Umicore** for an investigation of closed-loop recycling of cobalt and nickel. Confirmed that 90% of materials can be recycled from Audi e-tron LIB modules. **Volkswagen** envisions an internal closed-loop recycling in newly built "Center of Excellence" in Salzgitter with pilot line for battery cell production. - Pilot recycling facility for 1.200 tonnes per year (≈ 3.000 LIBs), potential to expand capacity when more batteries come back (late 2020s). - Disassembly → mechanical shredding, drying and sieving → hydrometallurgy (nickel, manganese, cobalt, lithium recovery for cell production)	(Audi AG, 2018, 2019; MAN Truck & Bus, 2019; Manthey, 2018; Quartier, 2020; Stringer & Ma, 2018; Umicore N. V., 2019c; Volkswagen AG, n.d., 2018b, 2019a, 2019b)

			24.05.2019: Stationary energy storage unit on Berlin EUREF campus opened in collaboration with **Belectric** and **The Mobility House** - 1.9 MWh from 20 LIB packs used in Audi test vehicles - Demand peak shaving, grid balancing services **20.12.2019**: **MAN** containerised second life energy storage in collaboration with **Verkehrsbetriebe Hamburg-Holstein** at depot charging hub for buses - 495 kWh - 50 second life VW Passat GTE plug-in hybrid LIB packs - Testing of different scenarios e.g. peak shaving (reduce up to 600 kW of peak load)	- Outlook: further decentralized recycling plants. Recycling rates: Currently 53% Salzgitter: 73% long-term plan 97%	
Volvo Cars	*No info*	*No info*	**2016**: Provided LIB packs from test vehicles to start-up **Box of Energy** for the assembly in a small-scale stationary energy storage system. - Residential storage unit with 18 kWh	*No info*	(Stringer & Ma, 2018)
Volvo Group	Functional repair of electrical equipment at dealers	Refurbishing investigated and outsourced.	Two pilot projects for residential storage units: **5.12.2018**: Viva research project in collaboration with **Göteborg Energi**, **Riksbyggen** and **Johanneberg Science Park** - 200 kWh from 14 second life hybrid bus LIB packs - Combined with local electricity production from solar PV - Increase renewable self-consumption, demand peak shaving, energy arbitrage **11.12.2019**: Announcement of collaboration with **Stena Property** and Stena Recycling's subsidiary **BatteryLoop** - Second life energy storage based on modules - Combined with local electricity production from solar PV	No closed-loop, but ongoing investigations.	(Volvo Buses, 2018, 2019)

Appendix F: CBM designs across automotive OEMs

	First sale with prolonged use	Refurbishing	Repurposing	(Closed-loop) Recycling
Offer	(Hybrid-) electric passenger car, bus, or truck with extensive repair services	Refurbished LIB (lower capacity and price than a new one)	Stationary energy storage system / energy storage services / second life pack or modules	Conventional recycling option compliant with legislation / closed-loop recycling to retain control over materials
Customer segments	Professionals or private customers, interested in minimised downtime and reliable performance	Price sensitive customers when residual value would not justify a new LIB	Environmentally conscious B2B or B2C customers, utility companies, real estate companies, industries with large energy consumption, EV charging networks / repurposing companies	OEMs and cell producers aiming to reduce environmental impacts and supply chain risks
Customer relationship	Close relationship			
			Transactional (if LIB is sold to repurposing company)	Transactional (for conventional recycling)
Key partners	Dealers, spare parts supplier	Dealers, refurbishing partner, spare parts supplier	Energy utilities, energy trading company, repurposing partner, local electrical installers	Recyclers, cell producers
Key resources	Highly skilled technicians, mechanics, replacement modules		Expertise on the LIBs and their historic use, engineers, staff for customer relations, financial capital, storage and repurposing facility, new parts (power electronics, BMS, casings)	Engineers, most skills outsourced to recycler, storage facility
Key activities	Design for disassembly, diagnostics, logistics			
	Design for repair, repair	Refurbishing (potentially outsourced)	Technology development, repurposing process (potentially dis- and reassembly), cooperation with energy utilities, monitoring, customer services, EPR transfer	Recycling process (outsourced)

Channels	Dealers		Distribution networks of partner companies, direct contact for specific pilot projects	Recyclers organise reintegration through direct contacts and contracts between companies or on a commodity market / direct return to cell producers
Take-Back System	Voluntary return via dealer network		Voluntary return or retained ownership through leasing / Transfer of recycling responsibility to repurposing company	Voluntary return via dealer network, external recyclers, producer responsibility organisations
Costs	LIB, development, spare parts, human labour, logistics	Spare parts, human labour, logistics	Development, human labour, logistics	Logistics, treatment process (human labour, energy)
Revenue flows	Sale of bus or truck / monthly service fee / sale of one-time repair service	Sale of refurbished product / included in monthly payment (leasing contracts)	Sale of storage solution, revenue from services provided and energy arbitrage / sale or leasing of LIB packs or modules	Sale of recycled raw materials / avoided purchasing costs for virgin materials if integrated in own production