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FINDING NEW PURPOSE

ELECTRIC VEHICLE BATTERY REPURPOSING AS A CASE FOR IMPLEMENTING A CIRCULAR ECONOMY IN AUTOMOTIVE INDUSTRY

BY
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The cover photo is the Five Circles Pedestrian Bridge ("Cirkelbroen") in Copenhagen, Denmark. The bridge is designed by Olafur Eliasson and invites bicycles and pedestrians to reduce their speed and take a small break. At the same time, it opens gracefully for boats to pass through. The bridge in many ways embodies the principles of a Circular Economy for me and reminds me of my precious time in this wonderful and inspiring city.

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CV

Magnus started his academic career in 2010 as part of an integrated bachelor-program to obtain a B.Sc. Industrial Engineering at the FH Nordakademie in Elmshorn in collaboration with Philips Medical Systems in Hamburg, Germany. After completion in 2014, he quickly put his industry knowledge into practice by working as a project manager for cost-optimization of x-ray tubes. Implementing refurbishment and re-use of x-ray tube components were already among his responsibilities back then.

In order to be able to continue his academic education and pursue his interest in the technical aspects of product life cycle management, Magnus enrolled temporarily at the University of Hamburg between 2014 and 2015 to collect additional courses for admission to higher universities. While in parallel making his first experiences in consultancy, he was finally accepted into the M.Sc. Industrial Engineering & Management at the Technical University of Denmark (DTU) in 2016.

During his studies in Denmark, Magnus followed his enthusiasm for sustainability and started experimenting with his newly acquired skills in the field of entrepreneurship and facilitating co-creation. Among other projects, he organized sustainability-related events and workshops at DTU Skylab Innovation hub, founded a start-up in the realm of a sharing economy and became a co-founder of the SDG student ambassadors Copenhagen, a student initiative to promote sustainability-oriented career planning among engineering students.

After obtaining his M.Sc. degree from DTU in 2018, his path then lead Magnus back to Germany where he started his PhD project at the production planning department of Mercedes-Benz in Stuttgart. As part of his research on sustainable battery life cycles, Magnus engaged with different departments of the company, including strategic sustainability, smart city services and product design and innovation. Through his affiliation with Aalborg University throughout his PhD, his personal and professional link to Copenhagen and the Danish sustainability research community has prevailed until today.

ENGLISH SUMMARY

The PhD project is motivated out of the circumstance that the need for a deep decarbonization of personal mobility and increasingly growing electric vehicle (EV) markets force automotive manufacturers to develop strategies to manage the resource consumption and environmental impacts associated with lithium-ion batteries (LIB). As a result, political entities on both national and international level emphasize the need for an adoption of a Circular Economy (CE) in industry in general and for the case of LIB in order to both reach the climate targets stated in the Paris Agreement and drive the implementation of the Sustainable Development Goals (SDG) in society. With e-mobility being a public focus area, respective regulations for addressing value preservation and recovery at the battery End-of-Life (EoL) are expected to intensify in the next decade, requiring manufacturers to adopt new practices for resource preservation today. Meanwhile, NGOs and independent researchers find that most large industrial companies still struggle to decarbonize entire value chains and decouple their economic growth from resource consumption.

In this context, one option of a circular business model (CBM) for LIB is to repurpose EV batteries in second life stationary Battery Energy Storage Systems (SLBESS) after their use in the EV. In this way, the useful life of LIB can be extended in order to balance electricity grids and support the transition towards renewable energy systems. However, implementing EV battery repurposing – also called Battery Second Use (B2U) – imposes several challenges, which are not resolved in scientific literature today. These include uncertainties regarding the contribution of B2U to environmental and economic sustainability of battery life cycles, as well as a lack of methods to support the implementation of a CE within organizations. To address these gaps, the following overall research question and three sub-research questions are formulated and further investigated as part of this thesis:

Overall research question: How can automotive manufacturers implement electric vehicle battery repurposing in order to achieve economic and environmental sustainability of battery life cycles in a circular economy?

- **Sub-research question 1:** How can automotive manufacturers apply life cycle assessment (LCA) to assess the environmental impacts of EV battery repurposing?

- **Sub-research question 2:** What are the key tasks for implementing EV battery repurposing as a circular business model in automotive industry?

- **Sub-research question 3:** Which methods can support automotive manufacturers in implementing a circular economy in decision-making for EV batteries in the organization?

In order to address these questions, this thesis uses real-world industry data to explore methods for assessing benefits of EV battery repurposing in a CE, taking into account both the perspective of the automotive manufacturer and the B2U customers, i.e. the energy consumers in energy systems.

Based on the defined sub-research questions, the project provides a number of key contributions to the corresponding research fields. Firstly, key contributions in relation to sub-research question 1 and to the research field of LCA include a classification of approaches for assessing B2U in LCA in the context of a CE. Furthermore, the results include a two-step framework based on energy flow modelling, which is applied to a case study in Germany. Key findings are the differentiation of SLBESS applications in multi-use cases based on the energy-related environmental benefits, as well as the comparison of EV battery repurposing to alternative CBM options for LIB.

Secondly, the results regarding sub-research question 2 contribute to the research field of implementing CBM by providing quantitative evidence of profitability for the case of B2U, thereby confirming the potential to support the deployment of storage technologies for the energy transition. Additionally, the study provides theoretical contributions regarding different forms of value capture from B2U while formulating seven practical key tasks for implementing B2U as a CBM.

Thirdly, the project contributes to the research field of CE indicators based on the findings in relation to sub-research question 3. This includes the identification of key decision-contexts for managing a CE for LIB in automotive industry. Furthermore, it provides practical tools for estimating future material circularity for LIB based on different CE indicator methods. Additionally, results suggest a number of characteristic ways in which certain CE decision-makers in an organization can contribute to reaching company-level CE targets.

In summary, the findings lead to the following response to the overall research question: To ensure an environmentally and economically sustainable implementation of electric vehicle battery repurposing in a CE, automotive manufacturers should:

i) apply <u>dedicated assessment methods</u> such as energy flow simulation and planning processes for stationary battery storage systems to fully understand the role of repurposed batteries in future energy systems,
ii) ensure <u>sustainable value creation</u> of repurposing as a CBM by focusing on the targeted customers, and
iii) enable decision-makers to align repurposing with <u>alternative CBM options for batteries</u> towards a joint material circularity target.

The thesis focuses exclusively on the case of EV battery repurposing in automotive industry based on a real-world case of implementing a SLBESS in Germany. Future studies could build on the methodological guidance provided in this thesis and carry out multi-case studies on B2U across regions, or assess the degree to which the findings are applicable to LIB from consumer electronics, such as e-bikes and e-scooters. Furthermore, findings on the need for cross-stakeholder collaboration for CE decision-making calls for advanced research in the realm of co-design for CE and sustainability in general. Rather than focusing exclusively on providing more sophisticated assessment methods, the findings suggest that investigating the interplay of internal and external stakeholders, innovation in organizational structures and ways of creating an entrepreneurial culture for CE seems to be a promising avenue in research.

DANSK RESUME

Ph.d.-projektet er motiveret ud fra den omstændighed, at behovet for en dyb dekarbonisering af personlig mobilitet og stadigt voksende markeder for elektriske køretøjer tvinger bilproducenter til at udvikle strategier til at styre ressourceforbruget og miljøpåvirkningerne forbundet med lithium-ion-batterier (LIB).). Som følge heraf understreger politiske enheder på både nationalt og internationalt plan behovet for en vedtagelse af en cirkulær økonomi (CE) i industrien generelt og for LIB's tilfælde for både at nå de klimamål, der er angivet i Paris-aftalen og drive implementeringen af Sustainable Development Goals (SDG) i samfundet. Da e-mobilitet er et offentligt fokusområde, forventes de respektive regler for håndtering af værdibevarelse og -gendannelse ved batteriets end-of-Life (EoL) at intensiveres i det næste årti, hvilket kræver, at producenterne vedtager ny praksis for ressourcebevarelse i dag. I mellemtiden finder ngo'er og uafhængige forskere, at de fleste store industrivirksomheder stadig kæmper for at dekarbonisere hele værdikæder og afkoble deres økonomiske vækst fra ressourceforbrug.

I denne sammenhæng er en mulighed for en cirkulær forretningsmodel (CBM) for LIB at genanvendelse EV-batterier i andet liv stationære batterienergilagringssystemer (SLBESS) efter deres brug i EV. På denne måde kan levetiden for LIB forlænges for at balancere elnettene og understøtte overgangen til vedvarende energisystemer. Implementering af EV-batterier – også kaldet Battery Second Use (B2U) – pålægger dog adskillige udfordringer, som ikke er løst i videnskabelig litteratur i dag. Disse omfatter usikkerheder vedrørende B2U's bidrag til miljømæssig og økonomisk bæredygtighed af batterilivscyklusser, samt mangel på metoder til at understøtte implementeringen af et CE i organisationer. For for at adressere disse udfordringer, formuleres og undersøges følgende overordnede forskningsspørgsmål og tre delforskningsspørgsmål som en del af dette speciale:

Overordnet forskningsspørgsmål: Hvordan kan bilproducenter implementere genanvendelse af batterier fra elektriske køretøjer for at opnå økonomisk og miljømæssig bæredygtighed af batterilivscyklusser i en cirkulær økonomi?

- **Delforskningsspørgsmål 1**: Hvordan kan bilproducenter anvende livscyklusvurdering (LCA) til at vurdere miljøpåvirkningerne af genbrug af el-batterier?

- **Delforskningsspørgsmål 2**: Hvad er nøgleopgaverne for at implementere genanvendelse af EV-batterier som en cirkulær forretningsmodel i bilindustrien?

- **Delforskningsspørgsmål 3**: Hvilke metoder kan støtte bilproducenter i at implementere en cirkulær økonomi i beslutningstagningen for EV-batterier i organisationen?

For at løse disse spørgsmål bruger denne afhandling industridata fra den virkelige verden til at udforske metoder til at vurdere fordelene ved genanvendelse af EV-batterier i en CE, idet der tages hensyn til både bilproducentens og B2U-kundernes perspektiv, dvs. energiforbrugerne inden for energi. systemer.

På baggrund af de definerede delforskningsspørgsmål giver projektet et antal centrale bidrag til de tilsvarende forskningsfelter. For det første omfatter centrale bidrag i relation til delforskningsspørgsmål 1 og til forskningsfeltet LCA en klassifikation af tilgange til vurdering af B2U i LCA i sammenhæng med en CE. Ydermere omfatter resultaterne en totrinsramme baseret på energiflowmodellering, som anvendes på et casestudie i Tyskland. Nøgleresultater er differentieringen af SLBESS-applikationer i flerbrugssager baseret på de energirelaterede miljømæssige fordele, samt sammenligningen af EV-batteriets genanvendelse med alternative CBM-muligheder for LIB.

For det andet bidrager resultaterne vedrørende delforskningsspørgsmål 2 til forskningsområdet for implementering af CBM ved at levere kvantitative beviser for rentabiliteten for B2U-tilfældet, hvilket bekræfter potentialet til at understøtte udbredelsen af lagringsteknologier til energiomstillingen. Derudover giver undersøgelsen teoretiske bidrag vedrørende forskellige former for værdifangst fra B2U og formulerer samtidig syv praktiske nøgleopgaver til implementering af B2U som en CBM.

For det tredje bidrager projektet til forskningsfeltet for CE-indikatorer baseret på resultaterne i forhold til delforskningsspørgsmål 3. Dette omfatter identifikation af centrale beslutningskontekster for styring af en CE for LIB i bilindustrien. Desuden giver det praktiske værktøjer til at estimere fremtidig materialecirkularitet for LIB baseret på forskellige CE-indikatormetoder. Derudover tyder resultaterne på en række karakteristiske måder, hvorpå visse CE-beslutningstagere i en organisation kan bidrage til at nå CE-mål på virksomhedsniveau.

Sammenfattende fører resultaterne til følgende svar på det overordnede forskningsspørgsmål: For at sikre en miljømæssigt og økonomisk bæredygtig implementering af genanvendelse af elektriske køretøjers batterier i et CE, bør bilproducenter:

i) anvende dedikerede vurderingsmetoder såsom simulering af energiflow og planlægningsprocesser for stationære batterilagringssystemer for fuldt ud at forstå den rolle, genbrugte batterier spiller i fremtidige energisystemer,
ii) sikre bæredygtig værdiskabelse af genbrug som en CBM ved at fokusere på de målrettede kunder, og
iii) gøre det muligt for beslutningstagere at tilpasse genanvendelse med alternative CBM-muligheder for batterier mod et fælles materialecirkularitetsmål.

Afhandlingen fokuserer udelukkende på tilfældet med genanvendelse af EV-batterier i bilindustrien baseret på et realistisk tilfælde af implementering af en SLBESS i Tyskland. Fremtidige undersøgelser kunne bygge på den metodiske vejledning i dette speciale og udføre multi-case studier af B2U på tværs af regioner, eller vurdere i hvilken grad resultaterne er anvendelige på LIB fra forbrugerelektronik, såsom e-cykler og e-scootere. Endvidere kræver resultaterne af behovet for samarbejde på tværs af interessenter for CE-beslutningstagning avanceret forskning inden for co-design for CE og bæredygtighed generelt. I stedet for udelukkende at fokusere på at levere mere sofistikerede vurderingsmetoder, tyder resultaterne på, at undersøgelse af samspillet mellem interne og eksterne interessenter, innovation i organisationsstrukturer og måder at skabe en iværksætterkultur for CE synes at være lovende vej inden for forskning.

ACKNOWLEDGEMENTS

Firstly, I’m extremely grateful to have had Monia Niero and Niki Bey as my supervisors and want to thank them for their heartwarming kindness and support in becoming a researcher – something I had not imagined when starting at University. In times when achieving sustainability can sometimes seem like a mammoth task, your personal enthusiasm and focus on practical achievements were always a source of motivation for me, both professionally and personally.

Similarly, I owe special thanks to Michael Lebrecht, whose unconventional and yet humble way of making things happen at Mercedes-Benz that nobody else believes in is still fascinating to me every day. His unconditional support of my work was never a given, but always much appreciated.

Furthermore, I want to thank Susse Georg for being such an exceptionally sharp mind and for supporting me when Covid-19 happened. Your calm and thoughtful way of responding to my plans and ideas (even the bad ones) was the most precious thing one can rely on during those times.

Additionally, I want to thank the people I have worked with over the last 4 years: My colleagues at Mercedes, especially Davis Meike for his pragmatic inputs and technical expertise. Katrin Bauer and Michael Schnell for the sometimes long but always fruitful reflections on what a Circular Economy is - or should be. Steve Evans for inviting me to the University of Cambridge and making this stay as much of an enriching experience as it was. Patrick, Mohamed, Leonie and Lucas for being such bright and brave students to supervise in writing their thesis. Roy Vercoulen and Rolf Gelpke from Circular IQ for their fantastic work in the field and their good spirit as project partners. And lastly, special thanks to Tilmann Vahle from SystemIQ for being such a brilliant advocate for sustainability in real life and on the social networks – we need to be loud and clear on what sustainability means if we want to get it right.

Lastly, I must thank everyone who encouraged and supported me personally to continue my academic path. This first and foremost includes my beloved wife Lea, but also my family and friends. Nothing works without you, ever.

Finally, I want to dedicate this last sentence to the head of the Economics faculty at the University of Hamburg, who in 2015 tried to convince me that my previous education was not suitable for an academic career and that I should come to terms with this fact. The gratification of hereby proving you wrong shall be my inspiration in the future to always encourage people around me and to never accept somebody else’s view on what I myself or somebody else is capable of for a fact.

Magnus, August 2022

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ABBREVIATIONS

B2U	Battery Second Use
CBM	Circular Business Model
CE	Circular Economy
Co	Cobalt
DC	Direct Current
EoL	End-of-Life
EV	Electric Vehicle
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
Li	Lithium
MFA	Material Flow Analysis
Mn	Manganese
NPV	Net present value
Ni	Nickel
NMC	Nickel Manganese Cobalt
PaaS	Product-as-a-Service
PEF	Product Environmental Footprint
PV	Photovoltaic
RE	Renewable Energy
SBTi	Science Based Targets initiative
SLBESS	Second Life Battery Energy Storage System
S-RQ	Sub-Research Question
WBCSD	World Business Council for Sustainable Development

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LIST OF PAPERS

This thesis is based on the following journal papers (referred to as paper J1-4) and peer-reviewed conference papers (referred to as paper C1-2) in the following course of this summary:

Schulz, M., Bey, N., Niero, M. & Hauschild, M., (2020): Circular Economy considerations in choices of LCA methodology: How to handle EV battery repurposing? *Procedia CIRP 90, 182–186.* https://doi.org/https://doi.org/10.1016/j.procir.2020.01.134 *(conference paper, C1, **published**)*

Schulz-Mönninghoff, M., Bey, N., Nørregaard, P.U. & Niero, M., (2021): Integration of energy flow modelling in life cycle assessment of electric vehicle battery repurposing: Evaluation of multi-use cases and comparison of circular business models. *Resources, Conservation and Recycling.* 174. https://doi.org/10.1016/j.resconrec.2021.105773 *(journal paper, J1, **published**)*

Schulz, M., Michel, M., & Hintennach, A. (2020). Nachhaltigkeit bei Daimler - Mehr als eine technologische Herausforderung. (Engl.: "Sustainability at Daimler – More than a technological challenge") *Nachhaltige Industrie*, *1*(1), 40–47. https://doi.org/10.1007/s43462-020-0004-1 *(journal paper, J2, **published**)*

Schulz, M., Niero, M., Rehmann, L. M., & Georg, S. (2021). Exploration of decision-contexts for circular economy in automotive industry. *Procedia CIRP*, *98*, 19–24. https://doi.org/10.1016/j.procir.2020.11.005 *(conference paper, C2, **published**)*

Schulz-Mönninghoff, Neidhardt, M. & Niero, M., (202X): What is the role of company-level circular economy indicators in an organization? A case study for electric vehicle batteries. *Journal of Cleaner Production. (journal paper, J3, **under review**)*

Schulz-Mönninghoff, M., Evans, S. (202X): Key tasks for capturing economic value from circular projects: A case study on electric vehicle battery repurposing from a customer perspective. *Sustainable Production and Consumption. (journal paper, J4, **submitted**)*

CHAPTER 1. INTRODUCTION

For decades now, scientific research points out that a significant shift towards providing products and services in a sustainable manner is needed in order to maintain the global ecosystem earth in a healthy state. It is during the writing of this thesis that the 50-year anniversary of the „Limits to growth“ report published in 1972 reminds us how little we as a society have responded to their early warnings, stating that the former - and current - way of consumption is not sustainable (Meadows, Meadows, Randers, & Behrens III, 1972). In fact, signs of the predictions in the report, concluding that resource consumption and population growth of humanity will cause a global collapse of environmental and economic eco-systems in the first half of the 21st century, are already tangible and visible today. Meanwhile, „Limits and beyond“, which is a re-issue of the first report by the Club of Rome published in May 2022, finds that the world is off even worse than predicted, with climate change and loss of biodiversity having become some of the most pressing issues of our generation (Bardi & Alvarez Pereira, 2022).

So how come both policy makers and industry have failed to respond to the proclaimed urgency over the last 50 years? Why is it that scientific knowledge still today does not lead to the required action regarding climate protection and preservation of natural eco-systems? How can we re-define the concept of value - or „purpose“, as stated in the title of this thesis - in order to achieve the urgently needed decoupling of resource consumption and economic activity (UNEP, 2011)? Or in other words: What do we need to do differently in order to not make the same mistakes again and face an even deeper crisis in the next 50 years?

Today, the pathways to prevent this are well defined and internationally agreed upon. The planetary boundaries have been developed in 2009 to define absolute budgets for environmentally safe operating space in 9 dimensions (Steffen et al., 2015). The United Nations Sustainable Development Goals (SDG) provide a global agenda for sustainable development by 2030, which is made actionable through 17 goals and 169 specific targets (United Nations, 2015). The Paris Agreement signed in 2015 states to “[keep] global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius” (UN & FCCC, 2015). The International Panel on Climate Change (IPCC) clearly states that in order to comply with the Paris Agreement, global CO2 emissions need to decline by 45% by 2030 from the levels of 2010 and reach net-zero by 2050 (IPCC, 2018). Frankly, one could say we know exactly what to do.

Meanwhile, a recent study by the New Climate Institute and Carbon Market Watch released in 2022 finds that out of 25 multi-national companies assessed, which together are responsible for around 5% of the global GHG emissions, only 3 companies commit to the decarbonisation of over 90% of their full value chain emissions (Day et al., 2022). Furthermore, although more than half of those companies are certified to be on a 1.5°C pathway according to the Science Based Targets initiative (SBTi), 18 out of the 25 companies – among them two German automotive manufacturers - are stated to show low or very low integrity in their carbon reduction strategy through low quality or misleading targets (ibid).

Based on these observations, it becomes clear that despite significant scientific progress, large industrial companies still struggle to fully address environmental targets and to define clear strategies for decarbonizing entire product life cycles, including supply chain, production, use stage and end of life (EoL)[1]. It is in this context that this thesis, through research in an industrial setting of a German automotive manufacturer, aims to investigate how the concept of a circular economy (CE) can be a vehicle for implementing sustainable resource consumption patterns and support companies in finally overcoming this struggle today and in the future.

1.1. FROM A LINEAR TO A CIRCULAR ECONOMY

The concept of a CE is stated to aim at decoupling resource consumption from economic growth (UNEP, 2011). While originating from other research fields like industrial ecology (Lifset & Graedel, 2002), cradle-to-cradle (McDonough W.; Braungart M., 2013) or looped and performance economy (Walter R. Stahel, 2010), the official coining of the term of a circular economic system is found to date back to the late 1980s (Ghisellini, Cialani, & Ulgiati, 2016).

Overall, the term CE describes an alternative to the linear consumption model, in which products are produced, bought and discarded and which has lead to a steady increase in global resource consumption per capita over the last 70 years (UNEP, 2011). In contrast, the CE is based on closed-loop product systems in which products are reused, repaired, remanufactured or recycled in order to minimize waste and thereby reduce resource consumption (Kirchherr, Reike, & Hekkert, 2017). The concept has gained increasing popularity through the work of public actors, such as the EllenMcarthur Foundation, who published the famous butterfly diagram and introduce the concept of inter-connected biological and technical cycles of resource flows (EM Foundation, 2015).

Meanwhile, research emphasizes that the concept of a CE entails the use of renewable and overall less material in products, to design products for an extended lifetime, and to enable refurbishment, repair and re-use as much as possible. Other trends that align with the concept of a CE include products-as-a-service (PaaS), e.g. through sharing services or pay-per-use models (Murray, Skene, & Haynes, 2015; Tukker, 2015), which besides slowing, closing and narrowing also aim at intensifying and dematerializing resource use at consumption level (Ferasso, Beliaeva, Kraus, Clauss,

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[1] Also referred to as GHG Scope 3 emissions as defined by the GHG protocol (WBCSD & WRI, 2012).

& Ribeiro-Soriano, 2020; Geissdoerfer, Savaget, Bocken, & Hultink, 2017). In this sense, the transition from a linear to a circular economy is stated to require a systems change approach, which needs to involve an intensified and efficient use of resources and must involve new use patterns on the demand-side to reduce the consumption of resources in the first place (Grabbe, Potočnik, & Dixson-Declève, 2022):

> *"Greening the supply side will not be enough to meet European Green Deal targets. Europe must address the inherent wastefulness of our production and consumption. [It's] pointless to decarbonize steel production if it is used to produce under-used cars and houses. Demand-side measures get closer to addressing responsibility and equity"*
>
> *Heather Grabbe*
> *Senior Adviser at the Open Society European Policy Institute* [2]

Despite the emphasis in research on the wide scope of a CE, the most common interpretation of a CE is focused on improving waste treatment (European Environment Agency, 2019). While the notion of a CE keeps evolving in research and legislation, the adoption in industry is still slow and linear practices remain the dominant paradigm. Based on a report published since 2019, the world is still only 8,6% circular for several years in a row (Circle Economy, 2021).

Consequently, the promising effects of implementing a CE for economic prosperity and the severity of damages in case of failure to act will presumably lead to a fully circular global economy at some point in the future. The urgent question at hand is thus how to stir this transition and enable companies to embrace the full potential of a CE quick enough to prevent further damage to global ecosystems.

1.2. PROBLEM DEFINITION AND KNOWLEDGE GAPS

Similar to the overall resource consumption per capita, the number of vehicles owned per person globally has increased steadily over time and is projected to continue growing in the future (European Environment Agency, 2010). Transportation contributes with appr. 23% of total energy-related CO2 emissions worldwide and 37% of carbon emissions from end users (IPCC, 2018). Hence, the provision of sustainable mobility by 2030 is one of the main challenges to staying within the safe operating space of climate change. In this regard, the electrification of the transport sector in

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[2] Quote retrieved from presentation held at the online event "*Small Changes Won't Do: Why We Must Change the System to Solve the Climate Crisis*", hosted by The Club of Rome and SystemIQ on July 5th 2022.

combination with an ongoing decarbonization of the electricity grids provides a pathway to reduce the emissions associated with the use of vehicles.

Meanwhile, the required electric vehicle (EV) batteries impose new challenges in terms of decarbonization of supply chains, additional consumption of resources with limited availability and significant impacts on local eco-systems, as well as changes in vehicle cost structures and concentration of value creation in manufacturing (World Economic Forum, 2019). Implementing a Circular Economy (CE) for batteries is thus seen as one solution to these challenges as it introduces a new way of creating sustainable production and consumption patterns, which lead to environmental, social and economic benefits for automotive manufacturers and mobility in general (European Commission, 2020b). Particularly for materials like Nickel (Ni), Manganese (Mn), Cobalt (Co) and Lithium (Li), which are required for commonly used battery technologies, a CE represents a way to reduce the associated economic, social and environmental issues (European Commission, 2020a).

For automotive manufacturers, this means that implementing a CE for EV batteries is an essential part of ensuring a sustainable transition towards low-carbon mobility. At Mercedes-Benz, different strategies are applied for implementing a CE for batteries (Daimler, 2019). Among those, repurposing EV batteries in so-called second life battery (SL) battery energy storage systems (BESS) is one option. It describes the further use of batteries for grid balancing in energy systems (Cready et al., 2003; E. Martinez-Laserna et al., 2018). For implementing EV battery repurposing as part of a CE for EV batteries, a number of knowledge gaps can be identified in scientific literature today.

Firstly, the contribution of EV battery repurposing to the reduction of environmental impacts of battery life cycles is not clear today. Among the existing studies, a number of different assessment approaches can be observed, however without establishing a common standard (Bobba et al., 2018; Faria et al., 2014; Richa, Babbitt, Nenadic, & Gaustad, 2015). Particularly, few studies address the variety of SLBESS applications in energy systems and corresponding implications for environmental benefits, with no reference to current trends such as multi-use cases for BESS (Tepe, Collath, Hesse, & Rosenthal, 2021). Furthermore, there is a gap in the literature on comparing EV battery repurposing to other options of CBM for batteries in LCA (Richa, Babbitt, & Gaustad, 2017).

Secondly, few case studies exists on which factors determine the economic feasibility of EV battery repurposing for energy customers. Despite a large body of literature on economic assessments of BESS, the implications of using repurposed batteries are not clearly defined. Furthermore, existing studies provide a basis for characterizing EV battery repurposing as a CBM (Jiao & Evans, 2017; Madlener & Kirmas, 2017; Reinhardt, Christodoulou, Gassó-Domingo, & Amante García, 2019), but lack empirical data on the required tasks for manufacturers for implementation. Especially given the cost pressure on EVs in general, the contribution of battery repurposing to the economic performance of battery life cycles for manufacturers is not addressed in scientific literature today.

Thirdly, the lack of common frameworks for implementing a CE in an organization causes issues in supporting CE decision-makers in managing EV battery life cycles holistically. To the knowledge of the author, there is only one study, which addresses the full CE hierarchy for batteries (Richa et al., 2017), and no case study on assessing the material circularity at the company-level for the case. As a consequence, there is a knowledge gap on how methods for assessing material circularity can support decision-makers in managing EV battery repurposing in relation to alternative CBMs (Olsson, Fallahi, Schnurr, Diener, & van Loon, 2018).

1.3. RESEARCH OBJECTIVES AND RESEARCH QUESTIONS

An overview of the research question, research fields and overall objective of the project is presented in Figure 1. Following the identified knowledge gaps presented in section 1.2, the overall research question is formulated as follows:

Overall research question (RQ): How can automotive manufacturers implement electric vehicle battery repurposing in order to achieve environmental and economic sustainability of battery life cycles in a circular economy?

The overall RQ thereby reflects the notion of the CE as an interdisciplinary task and thus requires researchers to engage with a combination of research fields. This firstly includes the application of Life Cycle Assessment (LCA) in the context of a CE in order to assess the contribution to the environmental sustainability of battery life cycles (Lonca, Muggéo, Imbeault-Tétreault, Bernard, & Margni, 2018; Niero & Rivera, 2018; Rosenbaum et al., 2015; Sassanelli, Rosa, Rocca, & Terzi, 2019). Secondly, it involves the field on CBM, which is considered a common framework for investigating the commercialization of CE strategies and thereby enables the research project to analyze if and how EV battery repurposing can be an economically sustainable business model (Bocken, de Pauw, Bakker, & van der Grinten, 2016; Urbinati, Chiaroni, & Chiesa, 2017). Thirdly, the research field of CE indicators is identified as relevant in order to investigate requirements for implementing EV battery repurposing within the decision-making for CE in the organization of an automotive manufacturer (British Standard Institution, 2017; Elia, Gnoni, & Tornese, 2017; Franco, Almeida, & Calili, 2021).

The joint summary and interpretation of results enables this research to provide guidelines for automotive manufacturers on how to assess and implement EV battery repurposing in a CE, including recommendations on respective methods and tools developed for the case at Mercedes-Benz AG. In this way, the project pursues the overall objective to bridge the gap between theoretical knowledge in the field of CE and to advance and combine relevant research fields towards implementing a CE under current conditions in automotive industry.

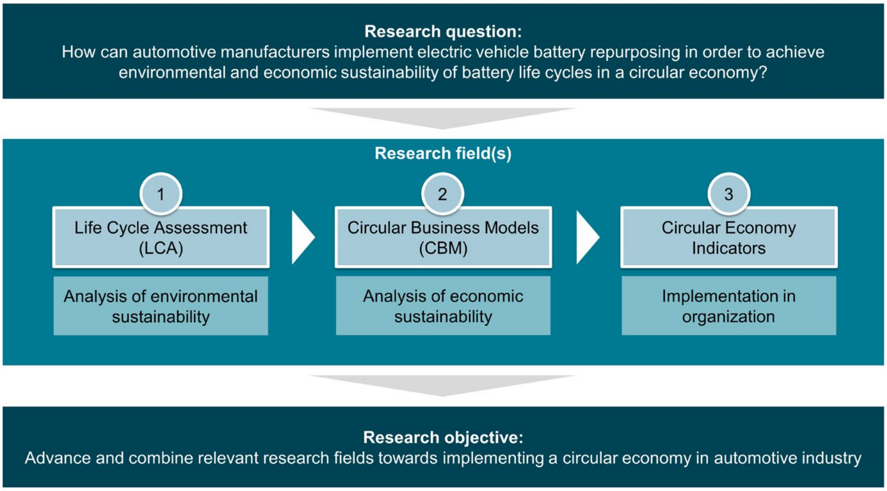


Figure 1. Overview of the research question, research fields and overall objective

In order to structure the research process, three sub-research questions (S-RQ) are formulated, each addressing the challenge within a respective research field.

Firstly and within the research field of LCA, an analysis of the contribution of EV battery repurposing to the decarbonization of the EV battery life cycle is conducted. This takes into account the respective methods provided in literature for addressing the case in LCA in order to provide guidance on both the modelling approach and the corresponding results for the case at Mercedes-Benz. This aims to answer the following sub-research questions (S-RQ):

S-RQ1: How can automotive manufacturers apply life cycle assessment (LCA) to assess the environmental impacts of EV battery repurposing?

Secondly and for the research field of CBM, a combination of qualitative and quantitative research methods is used to understand the value creation of EV battery repurposing. Here, a particular focus lies on the value creation of EV battery repurposing for CBM customers, i.e. the energy consumers, and the associated key tasks for implementation for automotive manufacturers. This task is guided by the following S-RQ:

S-RQ2: What are the key tasks for capturing economic value from EV battery repurposing as a circular business model?

Thirdly, an exploratory approach is used to study the requirements of company-internal stakeholders for making decisions for CE. Afterwards, company-level CE indicators are tested regarding the benefits for addressing those specific requirements, considering not only EV battery repurposing but also other CBM options for EV batteries. In this way, the analysis aims to shed light on how to implement EV battery repurposing in the larger context of implementing a CE in an organization. Correspondingly, the following S-RQ is formulated more broadly in order to guide the analysis:

S-RQ3: Which methods can support automotive manufacturers in implementing a circular economy in decision-making for EV batteries in the organization?

The following section outlines how each individual paper contributes to answering the S-RQs described above.

1.4. OVERVIEW OF PAPERS

Throughout this thesis, the implementation of EV battery repurposing is studied in seven papers (see Table 1), which address the three S-RQs using different methods. The summary of the individual findings is then used to formulate a response to the overall RQ.

Table 1. Overview of papers

Paper	Title	Research approach	S-RQ	Year of publication
C1	Circular Economy considerations in choices of LCA methodology: How to handle EV battery repurposing?	Qualitative	S-RQ1	2020
J1	Integration of energy flow modelling in life cycle assessment of electric vehicle battery repurposing: Evaluation of multi-use cases and comparison of circular business models	Quantitative	S-RQ1	2021
J2	Nachhaltigkeit bei Daimler - Mehr als eine technologische Herausforderung (Engl.: “Sustainability at Daimler – More than a technological challenge”)	Qualitative	S-RQ3	2020
C2	Exploration of decision-contexts for circular economy in automotive industry	Qualitative	S-RQ3	2021

J3	What is the role of company-level circular economy indicators in an organization? A case study for electric vehicle batteries	Quantitative	S-RQ3	202X
J4	Key tasks for capturing economic value from circular projects: A case study on electric vehicle battery repurposing from a customer perspective	Qualitative, quantitative	S-RQ2	202X

1.5. SCOPE AND LIMITATIONS

This thesis focuses on repurposing of EV batteries exclusively, which is investigated as a case for implementing a CE in automotive industry. This implies that considerations for implementing a CE in other sectors is not part of the scope of this work, e.g. for batteries in consumer electronics or in other modes of transport such as electric scooters. Similarly, the research focuses on the interface between automotive- and energy sector as a characteristic feature of repurposing (Bowler, 2014). While this means that the energy sector is to a certain extent included in the scope of this thesis, other sectors such as material recycling or waste treatment, as well as the underlying technologies, trends and regulations, are not included. Table 2 provides an overview of the scope of the research project in different domains.

Regarding the unit of analysis, most studies conducted as part of this research focus on a specific, real-world case for implementing a SLBESS at Mercedes in Sindelfingen, Germany. Details about the corresponding benefits in terms of access to in-depth primary data are provided in section 3.4. This means that other cases of battery repurposing at different companies or geographical regions other than Germany are not included in the scope. From that, it follows that the unit of analysis is either the SLBESS and the energy system under investigation in Germany, or when taking the perspective of the automotive manufacturer, the unit of analysis is repurposing as a CBM option for batteries. Other units of analysis such as CE policies are not taken into account.

Another limitation is given by the scope of life cycle stages of the battery. The present research focuses mainly on the assessment of repurposing in comparison to other CBM options at the battery EoL. Although other life cycle stages are modelled as part of the environmental impact assessment and the material circularity assessment, the specific challenges in battery design, e.g. design for re-use or disassembly, as well as challenges and trends in battery manufacturing, are not in focus in the project. Similarly, and although generally relevant for any CBM, the market recovery and rebound logistics of batteries from EV markets are only considered when estimating the amounts of batteries available for different CBM options after use in the EV (see *paper J3*). No detailed investigations on how to improve access to EoL batteries are included in this thesis.

Most importantly, the evolution of battery technologies across cell chemistries and the specific technology in focus is known to affect the analysis of environmental impacts and battery performance characteristics (Ali, Khan, & Pecht, 2021; Ellingsen, Hung, & Strømman, 2017; Fischhaber, Schuster, Regett, & Hesse, 2015). However, due to the wide scope of research fields included in the project, it was not feasible to include battery technologies in the scope of the study other than the evolution from NMC111 to NMC622 and NMC811 by 2030 (see *paper J3*). Similarly, it is assumed that direct electrification of mobility is to be preferred over other supposedly sustainable solutions for mobility, e.g. hydrogen and e-fuels. Both are excluded from the scope of the project, given their drawbacks in terms of energy efficiency and due to their inherent risk of technology lock-in of internal combustion engines (Ueckerdt et al., 2021).

Lastly, the analysis of sustainability is limited to environmental and economic aspects of battery life cycles. This is on the one hand due to the complexity and sensitive character of the social aspects inherent to EV battery technology (Ali et al., 2021; Betz, Buchert, Dolega, & Bulach, 2021), which requires thorough and dedicated research. Given the other practical challenges, this was not feasible within this project. On the other hand, the missing knowledge base and data availability, e.g. to conduct a social LCA for batteries, requires exploratory methods of data collection, mostly in the battery supply chain (Egbue, 2012). As mentioned above, the raw material supply chain is not within the focus of this project, thus the exclusion of social aspects from this thesis.

Table 2. Scope of the research project in different domains

Domain	**In scope/ focus**	**Not in scope/ focus**
Sector	Automotive sector, Energy sector	Batteries from consumer electronics; Specific waste treatment/ recycling technologies;
Unit of analysis	Real-world second life battery energy storage project (single case) Repurposing as one out of three Circular Business Model options	Comparison of different cases or companies; Policy-making for circular economy;
Geography	Germany/ Europe	Rest of world

Battery life cycle stages	Battery end-of-life	Product design/ development Battery manufacturing, Electric vehicle use stage (incl. market recovery and logistics)
Battery/ storage technology	Lithium Nickel-Manganese-Cobalt (NMC)	Lithium Iron Phosphate (LFP) Lithium Nickel Cobalt-Aluminium oxid (NCA) Lead Acid (PbA) New battery technologies potentially available beyond 2030 Fuel-cell technology
Sustainability dimensions	Environmental, economic	Social

A reflection of the limitations outlined above, as well as the implications for the results of this thesis in relation to the methodological approach is provided in the discussion in sections 4.5 and 4.6.

1.6. THESIS STRUCTURE

This thesis continues with an introduction to the theoretical foundations (chapter 2), followed by the methodology (chapter 3). Afterwards, the presentation and discussion of results is carried out in relation to the three S-RQ as well as the overall research question. This includes reflections on the methodology and the analytical framework (chapter 4). Finally, the conclusions are presented based on the key contributions to practice and theory before closing with directions for future research (chapter 5).

CHAPTER 2. THEORETICAL FOUNDATIONS

This chapter lays the theoretical foundations for this thesis by presenting relevant aspects from the body of literature on CE, key concepts for CE implementation and backgrounds on the case of EV battery life cycles. For detailed information on the specific literature used for addressing the individual S-RQs, please refer to the individual papers presented in section 1.4.

2.1. CIRCULAR ECONOMY

In order to provide an overview of the recent developments in the field of CE, Figure 2 presents a timeline of selected publications in the field. The selection is non-exhaustive and serves the purpose of conveying a picture of the current state of knowledge and adoption in policy-making and industry. Given the urgency for a transition towards a full commitment to the scope of a CE, the objective is to provide the reader with an impression of the recent discourse.

Within the last decade, the year 2015 was an important date for the adoption of a CE as it marks the launch of the first CE action plan by the European Commission (European Commission, 2015). The underlying ambitions of the plan are manifold and reach across economic, environmental and social benefits for Europe. This is supported by an article published around the same time by Walter Stahel, who can be considered one of the early thought leaders on the CE concept. He points out that a CE has the potential to create new job opportunities, reduces waste and costs, reduces resource consumption and risks, resource scarcity and harnesses environmental benefits (Stahel, 2016).

Interestingly, a study by (Kirchherr et al., 2017) just two years later analyzes 114 available definitions of a CE in literature and emphasizes the need for a harmonization of understandings of what a CE entails in order to prevent a collapse of the concept. A comparison of three definitions of a CE shall illustrate the variety in the scope and focus:

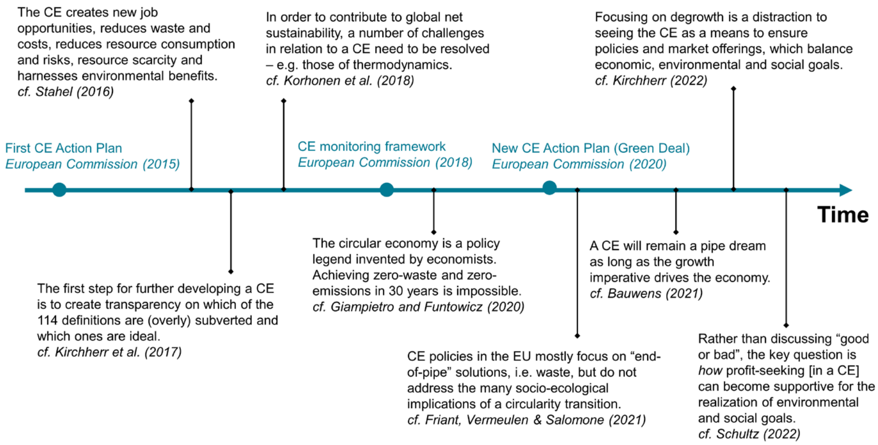
- “A Circular Economy […] aims at keeping products, components, and materials at **their highest value** at all times” (EM Foundation, 2015)
- “A CE is about **decoupling economic growth from resource consumption** […]” (Ghisellini et al., 2016)

- “A Circular Economy [is] a regenerative system **in which resource input and waste, emission, and energy leakage are minimised** by slowing, closing, and narrowing material and energy loops” (Geissdoerfer et al., 2017)

These definitions show how the concept of a CE simultaneously entails considerations of value preservation, i.e. a matter of individual usefulness of resources, a link to economic growth, i.e. a matter of socio-economic prosperity, as well as a minimization of material- and energy consumption, i.e. a matter of physical flows. This use of the CE concept as a carrier for a wide range of political aspirations is further manifested in the CE monitoring framework, which was launched in 2018. It introduces a measuring framework for tracking progress on CE deployment and includes measures on waste treatment, secondary material supply but also progress on financing innovation in terms of investments and numbers of patents in the realm of recycling technologies (European Commission, 2018).

Meanwhile, scholars continue to question the CE concept and emphasize unresolved scientific grounds. In a holistic assessment of what a CE can and cannot be, (Korhonen, Honkasalo, & Seppälä, 2018) formulate a number of challenges to CE adoption, which include thermodynamical limits as well as aspects regarding technology lock-in and organizational barriers. At the same time, (Giampietro & Funtowicz, 2020) state that a CE is a policy legend invented by economists, which ignores physical limits to achieving “zero waste” and prevents policy makers from facing uncomfortable demand-side measures to achieve holistic sustainability.

Nevertheless, the launch of the New CE action plan in 2020 as part of the European Green Deal again marked a further increase in the pace of policy action for CE and sharpened its scope, now clearly stating key action areas for implementing a CE such as electronics, batteries, packaging and plastics (European Commission, 2020a). However again, others find that CE policy in the EU still mostly focuses on “end-of-pipe” solutions [...] but “does not address the many socio-ecological implications of a circularity transition” (Calisto Friant, Vermeulen, & Salomone, 2021, p. 337).



Note: The statements reflect only selected arguments presented in the referenced articles.

Figure 2. Selection of publications on circular economy between 2015-2022[3]

Finally, a most recent and rather lively debate around whether or not a CE is compatible with economic growth further illustrates the ambiguity around the concept between policymaking and research, but also among researchers. While some criticized the concept of a CE to maintain the unsustainable growth paradigm and called for true de-growth to achieve reductions in resource consumption (Bauwens, 2021), others argued that a call for de-growth (or "post-growth") for the economy represents a distraction from achieving sustainable forms of growth (Kirchherr, 2022). Finally, others recently attempted to moderate the discussion, stating that both positions are indeed compatible if combined in a constructive manner (Schultz, 2022).

Overall, this short and non-exhaustive review of recent CE-related activities in research and policy-making on the one hand illustrates how scientific research has neither come to a uniform and agreed definition of what a CE entails, nor has it provided clear guidance on which of the many goals a CE should be pursued by whom and how. On the other hand, political action towards adopting a CE increases in pace and scope and slowly but steadily moves away from the limited focus on waste ("closing"), but instead progresses towards higher forms of value preservation ("slowing") and reduction of consumption in the first place ("narrowing") (Bocken et al., 2016).

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[3] Selection of publications is non-exhaustive and based on personal preferences of the author; no systematic approach to literature review applied and thus no claim to completeness.

2.2. IMPLEMENTING A CIRCULAR ECONOMY

The following sections describe the main frameworks for implementing a CE existing in literature.

2.2.1. FRAMEWORKS FOR INDUSTRY

Generally, a CE is linked to achieving sustainable practices in industry (Geissdoerfer et al., 2017). More specifically, a CE is mentioned as one way of implementing sustainable production and consumption patterns, e.g. for achieving SDG target 12.5 to "substantially reduce waste generation through prevention, reduction, recycling and reuse" as stated in SDG (United Nations, 2015). As stated previously, the underlying goal is to decouple resource consumption from economic growth (Ghisellini et al., 2016). This suggests that a CE framework at company level should first and foremost address the degree to which a company can reduce its resource consumption while taking into account the link to social and economic implications of their business (Kristensen & Mosgaard, 2020; Pauliuk, 2018).

Meanwhile, research finds that the implementation of a CE is not incorporated explicitly in common, sustainability-related reporting frameworks existing today (Opferkuch, Caeiro, Salomone, & Ramos, 2021). Instead, the search for suitable standards for assessment- and management frameworks for a CE is still ongoing (ISO, 2018; Walzberg et al., 2021). Existing studies state that the goal of implementing a CE for companies is to be both environmentally and economically regenerative, i.e. sustainable (Lieder & Rashid, 2016). Achieving this goal is stated as a combined effort of regulation and policy initiatives (top-down) and of manufacturing industries to increase competitiveness and profitability (bottom up) (Lieder & Rashid, 2016). The latter is supported by other studies, finding that "circular champions" are performing better in terms of economic results, suggesting that economic drivers are most effective at encouraging the adoption of CBM (Gusmerotti, Testa, Corsini, Pretner, & Iraldo, 2019).

Elsewhere, studies dealing with practices of companies on CE and sustainable business models in general emphasize the need for collaboration among firms and pro-active stakeholder management in order to achieve an adoption at scale (Geissdoerfer, Vladimirova, & Evans, 2018; Korhonen et al., 2018; Rizos et al., 2016). This implies that different stakeholders of a company need to participate in CE initiatives. Such a multi-disciplinary approach is also addressed in one of the few standardized frameworks available for CE implementation, which defines five levels for organizational circularity maturity (British Standard Institution, 2017). These include innovation for CE at process- , product- and ultimately at business-model level of a company (see Table 3). To achieve this, companies are advised engage different business fields in CE activities while following eight steps: *i) framing, ii) scoping, iii) idea generation, iv) feasibility, v) business case, vi) piloting and prototyping, vii)* *delivery and implementation and viii) monitoring, review and reporting* (British Standard Institution, 2017). Regarding the latter, a critical review of the framework emphasizes the lack of integration with existing sustainability assessment methods, which inhibits measuring and reporting progress on CE implementation (Pauliuk, 2018).

Table 3. Levels of organizational circularity maturity, adapted from (British Standard Institution, 2017)

Level	**Name**	**Description**
0	Unformed	Characterized by limited and/or ad-hoc actions (e.g. waste legal compliance)
1	Basic	Initial framing and scoping, actively exploring opportunities
2	Improving	Process improvement: Characterized by way of working that align with Circular Economy principles
3	Engaged	Product/ service/ process innovation: To align value proposition to circular economy principles
4	Optimizing	Business model innovation: Organizational ways of doing business and creating value fully aligned with circular economy principles

From this it follows that for companies, there is currently no clear standard or framework for implementing a CE. However, the final objective should be to adopt a business model approach for CE implementation, which achieves both economic and environmental sustainability.

2.2.2. CIRCULAR BUSINESS MODELS

Business models have emerged as a concept to describe how companies create, deliver and capture value (Osterwalder, Pigneur, Smith, & Movement, 2010). Given the potential value for companies that results from implementing a CE, the business model lense is a particularly useful tool of analysis and design (Lewandowski, 2016).

The research field of CBM has evolved substantially since 2016 (Ferasso et al., 2020). Several studies provide classifications of CBM. A general categorization in four strategies, namely cycling, extending, intensifying and dematerializing, is provided by (Geissdoerfer, Pieroni, Pigosso, & Soufani, 2020) (see Figure 3). Elsewhere, (Lüdeke-Freund, Gold, & Bocken, 2019) propose six CBM patterns based on a morphological analysis. Additionally, (Rosa, Sassanelli, & Terzi, 2019) review numerous CBM classification methods and identify five CBM archetypes.

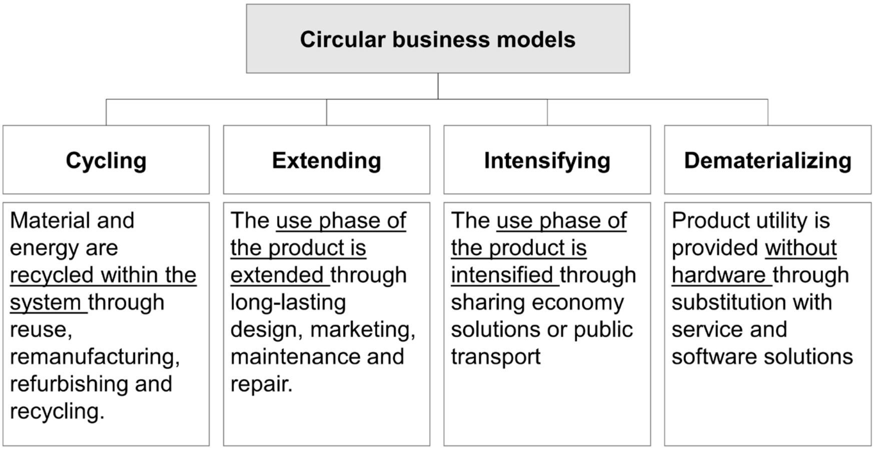

Figure 3. Overview of circular business model strategies based on (Geissdoerfer et al., 2020)

In terms of CBM implementation, different studies investigate drivers and barriers in manufacturing firms (Lieder & Rashid, 2016), in SMEs (Rizos et al., 2016), in relation to decision support in industry in general (Puglieri et al., 2022) and in terms of internal- or external factors of a company (Hina, Chauhan, Kaur, Kraus, & Dhir, 2022). As a common element, one challenge is to extend the view of CBM from the individual firm level to an eco-system or network level (Antikainen, Valkokari, & Mcclelland, 2016; Rizos et al., 2016). In this regard, some authors point towards the need to increasingly focus on CBM customers and their characteristics (Lüdeke-Freund et al., 2019).

2.2.3. ASSESSING A CIRCULAR ECONOMY

A review of assessment methods identifies a number of methods applied in research (Sassanelli et al., 2019). Among those, LCA and material flow analysis (MFA), Input-output analysis and other simulation tools are identified as the methods which aim at analyzing the entire life cycle of a product (ibid).

In this regard, research has confirmed the role of LCA to measure the environmental benefits of implementing CE strategies (Niero & Rivera, 2018). Some guidance exists on how to address the benefits of CBM in LCA (Wolf, Hofstra, Vroege, De Schrijver, & Zampori, 2019), however without having reached a standard in practice.

For MFA-based assessments, the research field of CE indicators has emerged in scientific literature, providing numerous methods. Several reviews find that CE indicators can be classified based on the assessment level, which can be a*) nano (product)-level, b) micro (company)-level, c) meso (industry/sector)-level or d) macro (country)-level* (Blomsma et al., 2019; De Oliveira, Dantas, & Soares, 2021; Parchomenko, Nelen, Gillabel, & Rechberger, 2019; Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019).

At the same time, guidance on the benefits of using certain CE indicators is lacking behind. Several authors investigate how CE indicators can be interpreted in relation to LCA (Niero & Kalbar, 2019; Roos Lindgreen, Mondello, Salomone, Lanuzza, & Saija, 2021; Roos Lindgreen, Salomone, & Reyes, 2020). Others focus on the selection process for CE indicators based on the individual context (Kravchenko, Pigosso, & McAloone, 2020b). Despite reviews on mapping methods with specific CE strategies (Franco et al., 2021; Nika et al., 2021), others state that existing frameworks for implementing a CE provide little guidance on the required assessment methods to be used, which implies that “guidance on monitoring CE strategy implementation remains vague” (Pauliuk, 2018, p.81).

2.3. ELECTRIC VEHICLE BATTERY LIFE CYCLES

2.3.1. BATTERY TECHNOLOGIES AND TRENDS

With the uptake of e-mobility, automotive manufacturers explore different battery technologies for their strategic use for EVs and PHEVs. Table 4 provides an overview of the most common lithium-ion based-battery technologies used today.

Table 4. Overview of lithium-ion battery technologies based on (Engel et al., 2018)

Cell chemistry	**Chemical formula**	**Properties**
Lithium-Cobalt-Oxid (LCO)	$LiCoO_2$	High share of Co causes high cost
Nickel-Mangan-Cobalt-Oxid (NMC)	$LiNi_xMn_yCo_zO_2$	Ni increases the specific energy density of the cell and Mn increases the specific power; Share of Co is lower than for LCO
Nickel-Cobalt-Aluminium-Oxid (NCA)	$LiNiCoAlO_2$	High specific energy density, stability and performance. Safety issues and relatively high cost;
Lithium-Iron-Phosphate (LFP)	$LiFePO_2$	High stability causes long lifetime; lower cost compared to Co-based technologies; lower performance due to lower cell voltage level

Generally, research and innovation in the field of LIB causes constant shifts in the use of technologies. An overview provided in (Neidhardt et al., 2022) reviews different forecasts on which LIB technology will be dominant in the future. In the most realistic scenarios, NMC-based technologies will represent the largest share until 2030 (ibid). Thus, as described in section 1.5, the present thesis therefore focuses on NMC-based technologies exclusively, albeit taking into account shifts towards lower shares of Co and, in return, increasing shares of Ni by 2030 (Zhao et al., 2021).

Overall, the battery demand for mobility is estimated to increase from appr. 0,16 GWh per year in 2020 to 1,6-3,2 TWh per year by 2030 depending on the forecast, thereby putting pressure on battery supply chains to ensure resource availability (IEA, 2021).

2.3.2. CIRCULAR BUSINESS MODELS FOR BATTERIES

In a comprehensive review of a CE for batteries, (Bonsu, 2020) describes how a CE is the best suited instrument to jointly address environmental, economic and social sustainability issues. In accordance with this finding, different political initiatives analyze drivers, barriers and potentials for implementing a CE for batteries (Circular Economy Initiative Deutschland (Ed.), 2020; Lebedeva, Di Persio, & Boon-Brett, 2016; World Economic Forum, 2019).

Figure 4 provides an illustration of the options for a LIB in a CE. The life cycle starts from the production stage, which here summarizes all processes related to the mining of materials such as Co, Ni, Mn and Li, taking into account the associated risks in terms of environmental and social impacts and supply security (European Commission, 2020b; Lebedeva et al., 2016). The vehicle production is then followed by the use phase, which according to evidence exceeds the stated warranty period of manufacturers of 8 years by far and can be expected to reach between 10-15 or even 20 years (Hoekstra & Steinbuch, 2020). Due to degradation, which largely depends on the driving pattern and the thermal conditions during the use phase, the battery will reach the EoL in the vehicle at around 70% of it’s original capacity (Casals, Amante García, & Canal, 2019; Egoitz Martinez-Laserna et al., 2018). From a technical perspective, literature identifies three CBM options for EV batteries (Bonsu, 2020; Daimler, 2019; Olsson et al., 2018; Richa et al., 2017):

- **Remanufacturing** (i.e. refurbishment and reuse in the electric vehicle)
- **Repurposing** (i.e. reuse in stationary battery energy storage systems)
- **Recycling** (secondary material recovery)

In practice, economic incentives need to be taken into account for LIB remanufacturing (Kampker et al., 2016), repurposing (Neubauer et al., 2015) and recycling (Lander et al., 2021). However, with growing EoL battery quantities returning from markets by the mid-end of the century, the allocation of LIB to CBM options can be expected to become a strategic decision, requiring manufacturers to implement corresponding tools and methods (Bobba, Mathieux, & Blengini, 2019; Richa et al., 2017).

Additionally, regulatory requirements for handling battery EoL are being tightened towards minimum recycling rates and towards creating additional incentives for repurposing and reuse of batteries (European Commission, 2020c). In this regard, the regulation also intends to set targets for minimum shares of recycled content, which again incentivizes LIB recycling in order to recover valuable battery materials and comply with regulatory targets in the future (Neidhardt et al., 2022).

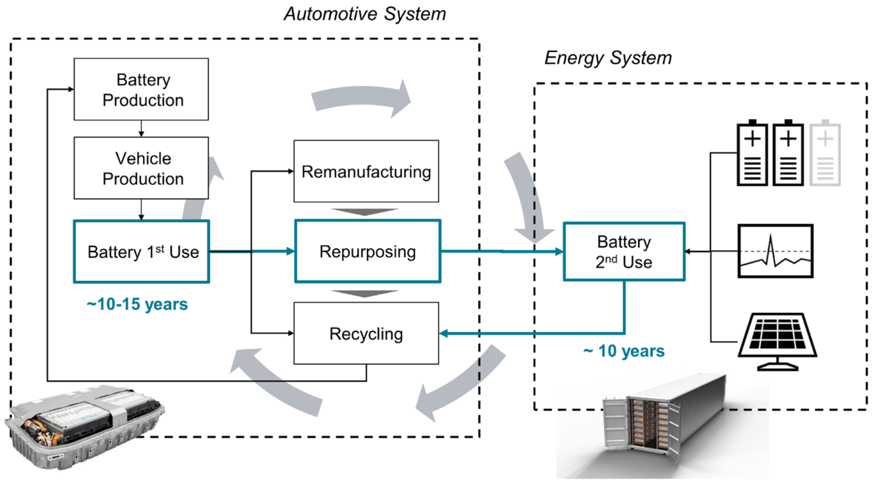

Figure 4. Visualization of electric vehicle battery life cycle (own illustration)

In summary, automotive manufacturers are facing numerous dimensions when managing a CE for batteries in the future. With the growth in volumes, strategic decision-making will me a mandatory task, taking into account environmental and economic parameters alike. The following section describes in detail the case of EV battery repurposing and gives an overview of the current state of research.

2.3.3. REPURPOSING ELECTRIC VEHICLE BATTERIES

As presented in section 1.2 and in the previous section, repurposing in the context of the present project means enabling further use of EV batteries in so-called SLBESS for the sake of supporting future energy systems in their transition towards decarbonization (Jiao & Evans, 2017). Based on this premise, the development and uptake of battery repurposing, which as a CBM is also referred to as “battery second use" (B2U)[4], is linked to the energy transition towards fully renewable electricity grids. Given the ongoing energy crisis in Europe[5], the recently proposed plan called "REPowerEU" suggests a RE target of 45% by 2030 across all member states (Europian Commision, 2022). In this context, the need for short-, medium- and long-term storage technology deployment at scale stands at the core of the energy transition (IRENA, 2017).

Battery storage can here play an essential role to provide short- and medium-term storage and thereby match RE supply and demand or provide grid-stability services at different levels of the energy supply chain (Balducci, Alam, Hardy, & Wu, 2018; Müller, 2018). A review of recent projections concludes that the cumulative installed capacity of stationary BESS worldwide could grow from 3.5 GWh in 2017 to appr. 400 GWh in 2030 and again to 1300 GWh by 2040 (Tsiropoulos, Tarvydas, & Lebedeva, 2018). In this regard, optimistic scenarios for B2U, which assume a 70% repurposing rate of EoL batteries, suggest that in Europe alone, more than 10 GWh of storage capacity can be available from repurposed EV batteries by 2030, which thus would satisfy around 2-3% of the global stationary BESS demand at that time (Bobba et al., 2019).

For implementing B2U, different typologies of business models are identified in scientific literature, which describe the degree to which the manufacturer engages with the SLBESS end customer in energy markets or instead establishes collaborations with B2U system providers at different levels of integration (Jiao & Evans, 2017). This raises the question of whether the chosen approach, i.e. B2U via 3rd party contractors or via own sales operations, affects the ability of manufacturers to capture environmental or economic value from B2U as a CBM. Research here suggests that multi-stakeholder approaches seem to be the preferred option, but emphasize the need for validation through rich case studies (Reinhardt et al., 2019).

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[4] Regarding the use of the different terms, there is no consistent pattern in scientific literature. It appears that "battery repurposing" is the most common term and is also used when referring to the specific processes of qualifying batteries for further use in BESS, i.e. testing, technical refurbishment and integration in the BESS; "battery second use" is mostly used when referring to the business model, i.e. as a short form for the CBM pattern "cascading/ repurposing" as defined by (Lüdeke-Freund et al., 2019) when applied to the case of batteries; "battery second life" seems to be mostly used to label BESS from repurposed batteries, i.e. as SLBESS.

[5] Due to the Russian invasion of the Ukraine in February 2022.

CHAPTER 3. METHODOLOGY

The following chapter describes the methodological approach to answering the overall research question through the defined sub-research questions. Detailed descriptions of the assumptions made in each method applied can be retrieved from the individual papers.

3.1. RESEARCH APPROACH

As presented in section 1.2 and further described in chapter 2, the overall research question of the project is derived from knowledge gaps identified in scientific literature. Meanwhile, an industrial PhD project is always partially driven by practical problems occurring in the setting in which the research takes place. From this point of view, the present research project can be seen as being rooted in the research philosophy of pragmatism, which in short can be described as follows:

"For a pragmatist, research starts with a problem, and aims to contribute practical solutions that inform future practice" (Saunders, Lewis, & Thornhill, 2019, p.151).

This implies that "*pragmatists recognize that there are many ways of interpreting the world and some are better for this than others*" (Kelemen & Rumens, 2008, p. 4). In this sense, the pragmatist accepts that no method can ever capture the full picture, but instead is interested in what works. Additionally, findings on how and why it works is translated into knowledge directed to problem-solving (Saunders et al., 2019). Furthermore, the other authors again refer to (Kelemen & Rumens, 2008) and point out that "*this does not mean that pragmatists always use multiple methods; rather they use the method or methods that enable credible, well-founded, reliable and relevant data to be collected that advance the research*" (Saunders et al., 2019, p.151).

While acknowledging this focus on creating practical solutions, the advantage of an industrial PhD is given by access to real-world data and insights into the underlying root causes of problems and phenomena. Based on this rationale, this project takes an inductive research approach, which means that the real-world data is "*used to explore a phenomenon, identify themes and patterns and create a conceptual framework*" (Saunders et al., 2019, p. 153).

For industrial PhD researchers, this implies being sensitive to the extent to which the acquired knowledge and the generated contributions to theory can be generalized. In the present thesis, the objective is to derive knowledge, which can be applied to bring forward the deployment of a CE for LIB in automotive industry. Any further applicability of results will be discussed carefully, taking into account the defined scope and limitations outlined in section 1.5.

3.2. ANALYTICAL FRAMEWORK

As described in section 1.2., this project engages with the three research fields of LCA, CBM and CE indicators. In order to define the analytical framework which can combine the results and address the overall research question, it is necessary to understand the degree to which each research field can be considered a discipline, and whether or not the research takes a multi- inter- or transdisciplinary approach (Menken & Keestra, 2016) (see Figure 5).

Firstly and regarding the disciplines involved, both research fields of LCA, as well as CBM as a sub-branch of business model research are historically established, institutionalized and applied in widely accepted and standardized frameworks and can be considered own disciplines (see e.g. ILCD handbook, business model canvas) (EC-JRC, 2011; Osterwalder et al., 2010). At the same time, both LCA and CBM are integrated with energy-flow modelling as a key method within energy system analysis as part of this project, which can be considered another research discipline (Fragkos & Siskos, 2022). This implies that both S-RQ1 and S-RQ2 can – individually - be considered inter-disciplinary at the method level, or even trans-disciplinary, depending on where the boundary is drawn between academic and non-academic knowledge for CE. Meanwhile, the field of CE indicators does not itself qualify as a research discipline as it is relatively new and belongs to the general discipline of life cycle management (Sonnemann & Manuele, 2015; UNEP, 2007).

Furthermore and from the perspective of the overall result, an interdisciplinary research approach requires using the same unit of analysis across disciplines. In this regard, the object studied in the research field LCA in relation to S-RQ1 is the SLBESS project at Mercedes-Benz as one specific case of B2U. Similarly, the object of the research in S-RQ2 involves the SLBESS and the case-specific services provided to the energy system under investigation. At a detailed inspection, it is debatable whether studying a project implies a focus on the product, or whether the CBM becomes the main object of the study, i.e. the unit of research. Based on previous studies, it is both possible to interpret a business model as a unit of research at the level between a firm and industry (Nußholz, 2020), and to conduct LCAs of business models (Goffetti, Böckin, Baumann, Tillman, & Zobel, 2022). However, neither is the case in the present project. Instead, the focus lies on the real-world (circular) project under investigation, which is thus seen as the central unit of analysis in this case for S-RQ1 and S-RQ2. Meanwhile, the objects studied in the research field of CE indicators for S-RQ3 involves the organization of the automotive manufacturer, which is expressed through its material consumption and business processes, as well as the different stakeholders of the company, i.e. people and their function.

Consequently and in relation to the overall RQ, the three research fields and the underlying disciplines addressed do not consistently refer to the same unit of analysis, and ultimately are not integrated at a methods level. Therefore, the project can be considered inter-disciplinary at the level of individual S-RQs, but remains multi-disciplinary at the level of the overall result. This enables a joint interpretation of the individual disciplines and contributions, e.g. by comparison and identification of common elements. Furthermore, it allows combining results from different disciplines to respond to the RQ.

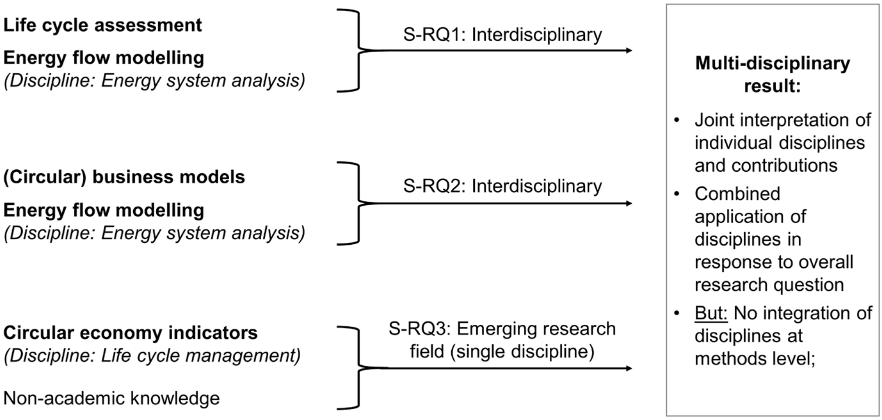

Figure 5. Visualization of disciplines included in the project

For the analytical framework of this thesis, this implies that an *integration* of methods in response to the research question is not feasible within the scope of the present project. Instead, the analytical framework needs to be able to accommodate – i.e. *combine* – the findings on the SLBESS project, as well as the organization of the automotive manufacturer. Therefore, the battery life cycle is chosen as the analytical framework of this thesis, meaning that the results of the individual research fields are interpreted and compared based on the implications for the two product systems of automotive system and energy systems (see Figure 4, section 2.3.2). While this addresses the need for a structured approach on implementing a CE in the life cycle management of batteries, it represents a practical framework, which is commonly used in industry to analyze sustainability-related challenges and thereby serves the purpose of delivering a practical result.

3.3. RESEARCH METHODS

In the project, different qualitative and quantitative methods are applied to investigate the implementation of EV battery repurposing at automotive manufacturers. The main method used is a single case study on the B2U project at Mercedes-Benz in Sindelfingen. In some instances, grounded theory is applied to derive implications from qualitative data. Other methods used to address the defined S-RQs include a systematic literature review.

The following sections introduce the methods used together with the corresponding paper. A summary of all methods used is provided in Table 5 (see end of chapter 3).

3.3.1. CASE STUDY

In order to address all three S-RQs, case studies represented an ideal research method. In relation to the question *How can automotive manufacturers apply life cycle assessment (LCA) to assess the environmental impacts of EV battery repurposing?*, a case study was used to derive requirements for assessing the SLBESS project under investigation and to develop the corresponding LCA approach based on energy flows (*paper J1*). Thanks to its purpose of collecting explanatory data (Ridder, 2020), the case study method provided important insights into real-world phenomena, e.g. the effects of multi-use cases on energy-related environmental benefits, which lead to novel insights on assessing B2U in LCA.

Similarly, *paper J2 and J3* used case studies on the sustainability strategy of Mercedes-Benz and the material flows of a fictional automotive manufacturer to investigate the role of CE indicators. In both cases, it was particularly important to take into account the specific characteristics of the company under investigation, which is an important aspect of case study research (Ridder, 2020).

For *paper J4*, a case study was combined with a grounded theory method (see following section) to investigate the question *What are the key tasks for capturing economic value from EV battery repurposing as a CBM?* Here, the case of implementing the SLBESS in the production facilities of Mercedes-Benz was studied over a time period of 2 years. This mixed-method approach enables the study to both explore qualitative data regarding stakeholder views on implementing B2U and match the findings with quantitative data on economic results for the case. Here, the complementary character of both methods was used to generate richer results (Saunders et al., 2019).

3.3.2. GROUNDED THEORY

Grounded theory is a qualitative research method which has been developed in 1967 for the purpose of building theory from data (Strauss & Corbin, 2008). For that, a certain phenomenon is observed to generate data, which provides comprehensive insights needed to develop new concepts in theory (Ridder, 2020). This process is usually carried out by grouping and organizing information and by identifying common characteristics, i.e. patterns or categories, also often referred to as ”coding” (Ridder, 2020). These can become concepts by obtaining explanatory power, and thereby build a basis for discourse and shared understanding (Strauss & Corbin, 2008).

In the present study, grounded theory is applied in *paper C2*, where it was used to investigate the case of an automotive manufacturer seeking to implement a CE for batteries. The goal is to generate new knowledge from the exploratory data on CE decision-contexts in the organization, taking into account the social context and culture of the interviewees (Saunders et al., 2019). Additionally and as explained in the previous section, *paper J4* used a case study method in combination with qualitative data on key activities in the planning and implementation process for stationary BESS. The goal was to identify key tasks for capturing economic value based on the collected information from different stakeholders.

3.3.3. LITERATURE REVIEW

A systematic literature review of existing LCA studies on B2U was performed to address S-RQ1 on *How can automotive manufacturers apply life cycle assessment (LCA) to assess the environmental impacts of EV battery repurposing?* within this project. Systematic reviews of literature use pre-defined criteria (e.g. key words, databases, publication dates etc.) to provide a transparent and comprehensive overview of the research field. However, such study method may only be applicable for research questions for which a certain body of literature exists already and might not provide insights in young research fields (Grant & Booth, 2009).

In the present project, a systematic literature review was performed in order to identify available approaches in LCA for the case of B2U (*paper C1*). The findings were later used to guide the definition of the LCA framework in *paper J1*. The specific and systematic search criteria and the literature database can be obtained from the descriptions in *paper C1*.

3.4. DATA COLLECTION

Most of the data collection as part of the PhD project took place at Mercedes-Benz. Different types of data was acquired through different channels and methods. The following sections describe the processes, taking into account the type of data collected and the relationship of the researcher to the corresponding data sources.

3.4.1. TECHNICAL DATA

The technical data required for the research project focuses on the life cycle inventory of the SLBESS and its functional parameters such as usable capacity and state-of-health, i.e. the remaining capacity of the repurposed batteries. Furthermore, the energy consumption profile of the energy system under investigation was required to determine the energy-related benefits of SLBESS deployment. Lastly, detailed data on several processes in relation to battery repurposing, remanufacturing and recycling were needed both for the LCA modelling and for the economic assessment.

Access to such data on the SLBESS was possible because in 2016, the implementation of a SLBESS in one of the new factories has been initiated at the production site of Mercedes-Benz in Sindelfingen, Germany. The project was closely linked to a pilot project of building an industrial micro-direct current (DC) grid. The DC grid offers the potential for increasing energy efficiency by 10% at the system level through the reduction of conversion losses and the use of recuperation energy from production automation equipment (Sauer, 2020). At the same time, locally produced renewable energy (RE) from the PV system can be integrated efficiently.

In this context, the SLBESS under investigation was built up in 2020 during the course of the PhD project. The storage unit consists of 112 retired NMC-based Plug-in hybrid electric vehicle (PHEV) batteries with an individual capacity of 13,8 kWh. At a usable depth-of-discharge of [5-95%], this results in a total, usable capacity of appr. 1,4 MWh[6]. The system consists of two containers, of which one contains the repurposed batteries, i.e. the capacity, and the other one contains the required electronics and control technology, i.e. the power (see Figure 6). The SLESS is intended to be used for multiple applications within the DC grid, including the support of RE integration, reduction of power peaks, power filters and on the long-term also the provision of uninterrupted power supply for sensitive equipment such as IT systems.

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[6] Based on company-internal technical documentation. Further details are provided in the supplementary materials of *paper J1*.

Figure 6. Second Life Battery Energy Storage at the Mercedes-Benz production site in Sindelfingen, Germany[7]

The data collected includes primary data retrieved from technical documentation on the SLBESS project. This was directly made available to the researcher through his active involvement in the project. Furthermore, the energy consumption profile from the consumers within the DC grid of the automotive production facility was provided through internal colleagues working in the factory planning department.

Additionally, the close collaboration with the SLBESS supplier Mercedes-Benz Energy, a daughter company of Mercedes-Benz Cars located in Kamenz, Germany, supported the collection of data as part of the PhD project. Especially since many of the SLBESS components were customized and thus lack documentation of materials used and weight, the collection of life cycle inventory data based on physical observations and visits at the site in Kamenz were helpful for modelling the processes associated with batteries but also the production of the SLBESS hardware.

The collection of the primary data on the life cycle inventory for the LCA included visits to one of the suppliers of the SLBESS architecture, as well as another visit to the Mercedes-Benz battery remanufacturing center in Mannheim, Germany. Most importantly, the B2U customer in the case study was the company-internal production planning department. In this sense, one particularity of the project is given by the accessibility to data on both the perspective of the manufacturer on B2U, as well as

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[7] Picture retrieved from: https://group.mercedes-benz.com/sustainability/resources/battery.html

that of the targeted customer. The implications of this circumstance for the research project are further discussed in section 4.5.

3.4.2. ECONOMIC DATA

Besides technical data, general data on LIB technology, SLBESS system architecture, as well as data on economic implications (cost, invest, revenue) of B2U are gathered from company-internal sources and documentation. However, the company policy does not allow publishing primary data on product cost or revenues of the company, which causes issues in the disclosure of relevant information. Therefore, secondary data sources were used to complement sensitive primary data, as these do not allow any conclusions on the real cost structure of an existing product.

For researchers, it is a common issue to face restrictions on publishing data and navigating the knowledge generation process must take into account legal or even personal limits of disclosure, e.g. when collecting data on the viewpoints of employees of a company. This leads to situations in which researchers need to justify the validity of their knowledge and expertise in the absence of publically available primary data and evidence. Recent research shows that this inter – or trans-disciplinary research approach can lead to credibility issues in the scientific community, especially in small and distinctive academic disciplines (Fini, Jourdan, Perkmann, & Toschi, 2022).

3.4.3. STAKEHOLDER INTERVIEWS

As part of the PhD project, a close collaboration was established with the strategic sustainability department of Mercedes-Benz, which has established a center of competence for CE-related activities and particularly around the recycling of LIB. The strong connections of the team to different company functions in relation to implementing a CE for batteries enabled the present research project access to a number of industry experts. This opportunity was used to address S-RQ3 and conduct 22 stakeholder interviews within the organization of Mercedes-Benz, aiming at exploring the contexts for making decisions towards a CE (*paper C2*).

The interviews were conducted online in Spring 2020, immediately after the outbreak of the Covid pandemic. Following a semi-structured qualitative approach (Ridder, 2020), the analytical framework was based on previous studies in the field and provided clear categories for clustering the responses. For that, the interviews were recorded, transcribed and analyzed, following a grounded theory approach (see section 3.3.2).

The study enabled the collection of data on the goals of different actors within an organization, their existing methods used to address everyday challenges, as well as forms of collaboration with typical partners for specific purposes. From this data followed the identification of key-decision contexts (*paper C2*), which later inspired the work on testing company-level CE indicators (*paper J3*).

3.5. DATA ANALYSIS

The following sections describe the methods, which have been applied to analyze the collected data.

3.5.1. ENERGY FLOW SIMULATION

The energy consumption data of the production factory in Germany was used for the simulation of energy flows and the resulting energy-related benefits of using the SLBESS. To carry out the analysis, the software "TOP-Energy" was used, which has been developed by the Institute of Technical Thermodynamics RWTH Aachen University in collaboration with the Gesellschaft für Angewandte Informatik (GFAI) (GFAI, 2017).

TOP-Energy utilizes a hybrid simulation and optimization algorithm in order to convert the energy system, which has been modelled in a graphical interface, into a set of equation systems and solve it (see Figure 7). The optimization is carried out as a mixed-integer linear programming (MILP), meaning that the operational problem is firstly solved for each time step and is then structurally optimized for the entire simulation period to achieve the lowest cost of energy possible for the energy system under investigation. The simulation is realized in the TOP-Energy module "eSim" and uses a commercial solver such as GUROBI or CPLEX for the optimization.

The required input parameters include relevant technical specification of the BESS, economic parameters on investments, cost of operation and maintenance, electricity prices, as well as the time-series data on energy consumption and solar generation. The output parameters include economic parameters such as net present value (NPV) and the time for amortization of the investments included in the model. Furthermore, TOP-Energy provides technical parameters for the resulting operation of the SLBESS such as the development of the state-of charge in a given timeframe.

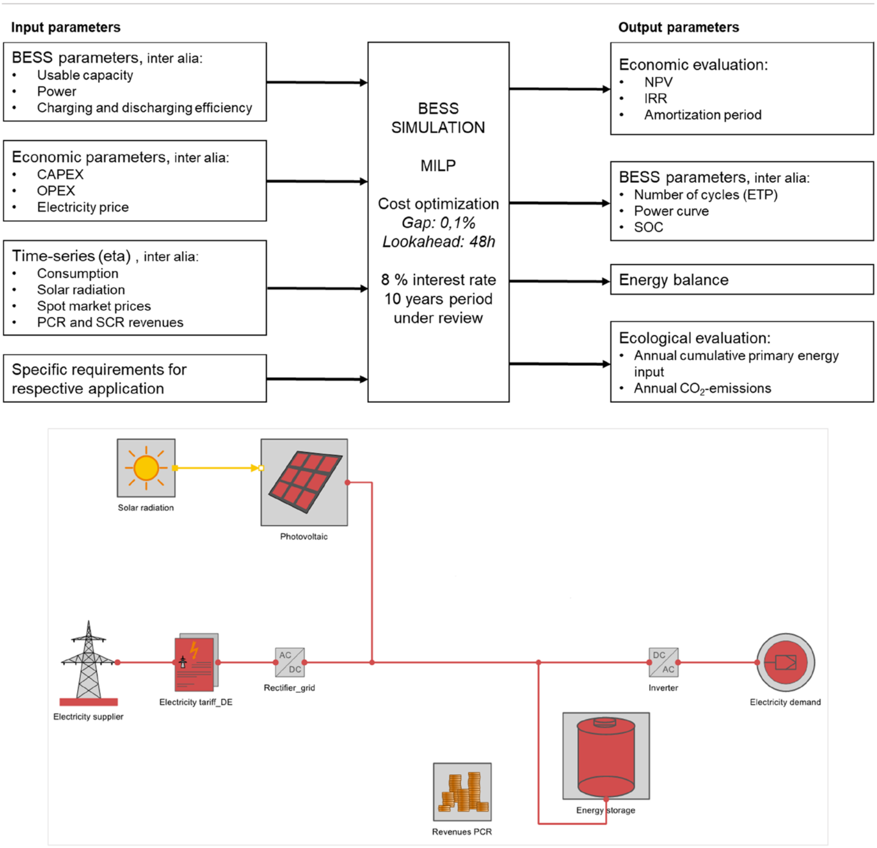

Figure 7. Illustration of the energy flow simulation in TOP-Energy (GFAI, 2017)

A key advantage of TOP-Energy is that it is possible to compare different energy systems in the module “eVariant”. In the present project, this was mainly used to compare different BESS operation modes and economic results from different use cases. While the main system components remain the same, it was possible to duplicate models, adapt specific parameters and then carry out the comparison in relation to a pre-defined business-as-usual. Thereby, the energy flow simulation could directly be integrated in the comparison of scenarios in both LCA (see *paper J1*) and in the analysis of economic profitability of circular projects (see *paper J4*).

3.5.2. LIFE CYCLE ASSESSMENT

Life Cycle Assessment was used to investigate the environmental benefits of EV battery repurposing in relation to S-RQ1. For that, the study firstly simulated and assessed the energy-related impacts of an energy system with a SLBESS compared to one without any storage technology. Afterwards, the results were integrated in a different LCA scope in order to compare the contributions of EV battery repurposing to the reduction of emissions within the battery life cycle and in relation to alternative CBM options *(paper J1)*.

The LCA follows the guidelines provided in the ISO 14040:2006 standard (ISO, 2006) as well as the provisions on determining the scope based on the decision-context of the target audience as described ILCD handbook (EC-JRC, 2010). The modelling and calculation of environmental impacts was carried out in SimaPro software v9.0.0.48 (PRé, 2016) and using Ecoinvent 3.4 database (Wernet et al., 2016).

In order to determine the suitable reference flow and allocation approach, the study built on the findings of the literature review in *paper C1*, which discusses the CE considerations in choices of LCA methodology for the case of B2U.

3.5.3. ECONOMIC VALUE ANALYSIS

In terms of the analysis of economic value from B2U in the present case, the main object for the case study was the SLBESS project in Sindelfingen, Germany. This project was a pilot project, aiming at the implementation of the SLBESS in the production facilities of Mercedes-Benz. The customer, i.e. the production planning department, here seeks to collect information on how using repurposed batteries can reduce the cost of energy provision for the production system.

As described previously in section 3.5.1, the analysis of economic profitability was based on the results of the energy flow simulation and the NPV of the investment in the SLBESS. In this way, the economic value analysis takes a realistic view on B2U as a business model from the perspective of a customer, including the context of implementing stationary BESS in general (see *paper J4*). Here, the use of the NPV as a key figure for analysis of BESS projects is suggested in scientific literature (Balducci et al., 2018; Hartmann, Divényi, & Vokony, 2018; Heymans, Walker, Young, & Fowler, 2014; Staffell & Rustomji, 2016).

Furthermore, life cycle costing (LCC) is stated as a key method for managing product life cycles (UNEP, 2007). As such, the method is also based on the ISO 14040 standard like LCA and supports the adoption of a life cycle perspective on economic performance of products (Sonnemann & Manuele, 2015; ISO, 2006). Based on that rational, the goal of applying LCC is to interpret the benefits of B2U in the context of the cost associated with EV battery provision (see *paper J4*).

3.5.4. MATERIAL FLOW ANALYSIS

While a material flow analysis (MFA) is stated as one of the key methods in life cycle management of products in general (Sonnemann & Manuele, 2015), it is particularly relevant for the field of a CE, given the focus on material and resource flows (Pauliuk, 2018). Many software solutions support practitioners in conducting MFA, but are often connected to high cost.

In the present project, the MFA as a method of analysis has mainly been used in *paper J3*, besides the use of material flows as part of every LCA and thus also in *paper J1*. However, the main goal in *paper J3* was to model and calculate the total material consumption of battery raw materials of a fictional manufacturer. The objective was to provide the material flow data, which is required for the calculation of CE indicator methods.

For the calculation of CE indicators based on material flow data, an Excel-based calculator tool for the material circularity indicator is provided by the Ellenmcarthur foundation and Granta design and was used in the corresponding study (EMF, 2020). Additionally, the Circular Transition Indicators online tool, which was developed by World business Council for Sustainable Development and Circular IQ was used to calculate the results at company level (see Figure 8) (Circular IQ, 2020). For the latter, access to an annual license was provided by Mercedes-Benz. The collaboration with the strategic sustainability department has supported the collection of company-level material flow data and the investigation of the corresponding CE indicator method.

Percentage circularity refers to the weighted average of % circular inflow and % circular outflow of the business level selected for this assessment.

Figure 8. Screenshot of the material circularity analysis in the Circular Transition Indicators online tool (Circular IQ, 2020).

As an additional supporting tool, a visualization of material flows in a Sankey diagram was included in the project. For that, the tool “eSankey” was selected, which does not provide functionalities of automated calculations stocks and flows but only visualizes material or energy flows based on direct links to the provided input files, e.g. in MS Excel. As a summary of chapter 3, Table 5 provides an overview of the methods, data types, data sources and methods of analysis used in the project and in relation to the specific S-RQs.

Table 5. Overview of methods and data sources used in the project

Article	**C1**	**J1**	**J2**	**C2**	**J3**	**J4**
S-RQ addressed	S-RQ1	S-RQ1	S-RQ3	S-RQ3	S-RQ3	S-RQ2
Main method	Literature review	Single case study	Single case study	Case study/ grounded theory	Single case study	Single case study/ grounded theory
Data type	Qualitative (secondary data)	Quantitative (primary, secondary data)	Qualitative (secondary data)	Qualitative (primary data)	Quantitative (secondary data)	Qualitative (primary data) Quantitative (primary, secondary data)
Data source	Scientific literature	Case company (energy use profile)	Expert knowledge Publically available company data (e.g. sustainability report)	22 Semi-structured interviews (single company)	Battery market forecasts Scientific literature	Stakeholder interviews Case company (energy use profile) Scientific literature Public energy price data
Data analysis	Qualitative analysis	Energy flow simulation Life cycle assessment	Qualitative analysis	Qualitative analysis	Material flow analysis Circular transition indicators (CTI) Material circularity indicator (MCI)	Interview analysis Energy flow simulation Net present value analysis Life cycle costing
Year of data collection	2020	2020	2020	2021	2021	2019 – 2022

CHAPTER 4. RESULTS AND DISCUSSION

This chapter summarizes the findings collected within the project and discusses them in relation to recent literature. The presentation of results is structured based on the individual S-RQs (section 4.1 to 4.3), following a summary and discussion of results in light of the overall RQ (section 4.4). Furthermore, this chapter includes reflections on the chosen methodological approach and the analytical framework (sections 4.5 and 4.6).

4.1. S-RQ1: ENVIRONMENTAL SUSTAINABILITY OF EV BATTERY REPURPOSING

The first S-RQ1 asked *how can automotive manufacturers apply LCA to assess the environmental impacts of EV battery repurposing?* As presented in section 2.2., there are few common rules on how to account for the GHG reduction in product life cycles through CE strategies (Wolf et al., 2019). As a result, there is no agreed method for assessing the environmental benefits of EV battery repurposing in scientific literature today. Meanwhile, existing LCA studies on the case lack reference to the different ambitions for pursuing B2U in a CE context, taking into account both the perspective of the automotive system and the energy system. Thus, clarification is needed on the available approaches in LCA to assess the case, their link to specific decisions of stakeholders involved in B2U, and the corresponding results in relation to alternative CBM options for batteries.

Paper J1 and *paper C1* contribute to answering S-RQ1. A key argument derived from both studies is that automotive manufacturers and energy consumers have specific expectations regarding the environmental benefits resulting from B2U. These need to be reflected in the development of dedicated LCA approaches, i.e. in terms of scope, functional unit and reference flow, in order to be able to describe the key aspects relevant to their decision-context.

Taking departure from the definition of repurposing as “utilizing a product or its components in a role that it was not originally designed to perform” (British Standards Institution, 2009), *paper C1* aimed at shedding light on the question of what that role of repurposed batteries in SLBESS *is* from an environmental perspective. By reviewing and classifying existing LCA studies on B2U, *paper C1* derives a link between available allocation approaches for B2U and the degree of collaboration between automotive and energy sector in a CE. In addition, a key finding is that B2U can be assessed using three different reference scenarios, which determine the affected life cycle stages and the corresponding impacts (Schulz, Bey, Niero, & Hauschild, 2020):

1) Displacement of new batteries, thus focusing on the reduction of manufacturing impacts of BESS in the energy sector;
2) Comparison to other technologies, e.g. gas power plants for peak power provision, thus focusing on the relative environmental benefits of using SLBESS in relation to existing alternatives;
3) Introduction of new functions, i.e. to compare energy systems with SLBESS to those without a storage technology, thereby focusing on the environmental benefits of battery storage deployment in general;

In relation to existing literature, these findings potentially provide a classification of cases for assessing repurposing as a case of product reuse in LCA as described in (Ardente, Talens Peiró, Mathieux, & Polverini, 2018). The findings could thus potentially be included in relevant standards in the future (British Standards Institution, 2009; EC-JRC-IES, 2011)

Meanwhile, *paper C1* explicitly states that each of the identified approaches can be justified from the context of the LCA practitioner and is thus applicable under certain circumstances. Hence, the following *paper J1* then built upon those findings and discussed the relevance of different approaches from the perspective of an energy consumer in a real-world case. The study argues that for energy consumers today, the key motivation for investments in BESS is the energy-related benefit, e.g. in terms of additional local RE self-consumption or for achieving energy cost reduction. This includes the assessment of diverse combinations of BESS applications in so-called “multi-use cases” and their effects on the environmental benefits (Tepe et al., 2021). From these observations, the study concluded a focus on the SLBESS use stage rather than on manufacturing impacts. This was addressed by integrating energy flow modelling in the LCA approach and by conducting the assessment in two steps:

- **Step 1**: Energy consumer perspective focusing on energy-related benefits for the energy system under investigation
- **Step 2**: Manufacturer perspective, focusing on the alternative CBM options in the context of the EV battery life cycle

For step 1, the results show that multi-use cases, which aim at improving the economic profitability of BESS, in fact reduce the energy-related benefits of B2U for the energy consumer by 22% compared to single applications in the case study. This finding thereby indicates the relevance of taking into account considerations of energy flows in LCA for SLBESS to avoid sub-optimization of potential environmental benefits (Schulz-Mönninghoff, Bey, Nørregaard, & Niero, 2021). Afterwards in step 2, *paper J1* addresses the decision-context of automotive manufacturers by contextualizing the results in relation to alternative CBM options for batteries, namely remanufacturing and recycling. Besides showing that B2U provides the highest environmental benefit in the climate change impact category, the results reveal additional benefits from postponing battery recycling by 10 years.

For the research field of applying LCA in a CE context, this approach reveals how the environmental benefits of B2U are dependent on the respective case investigated, e.g. regarding the energy-mix of the location of use, the selected SLBESS use cases and the lifetime resulting from use intensity and battery ageing (Casals et al., 2019). When using the approach presented, this dependency causes difficulties in achieving harmonized and comparable results in environmental certificates for the case of batteries (Recharge, 2018) and potentially for product repurposing in general (European Commission, 2013). It is thus to be clarified whether repurposing as a CE strategy can or should be accounted for in environmental declarations. Given that the results in *paper J1* show benefits of B2U in the magnitude of the original battery production impacts, such approaches could harm the integrity and transparency of environmental impact reporting and should thus be revised carefully (EEB, 2018). At the same time, the results provide insights on methodological approaches for addressing the decision-context of manufacturers in a CE in business processes (EC-JRC-IES, 2011). Examples include the chosen functional unit of “production of 1 kWh of LIB […]”, which is necessary to compare different LIB types in terms of cell technology and results for different CBM options.

Based on these findings, the key contributions to the research field of LCA from answering S-RQ1 are:

- Review and classification of methodological approaches for assessing B2U in LCA
- Development of a two-step framework for assessing B2U in LCA based on energy flow modelling
- Differentiation of (SL)BESS use cases and identification of a potential target conflict between environmental and economic benefits for multi-use cases
- Repurposing is the preferred CBM option for EV batteries in the climate change impact category;

4.2. S-RQ2: ECONOMIC SUSTAINABILITY OF EV BATTERY REPURPOSING

The second S-RQ aimed at understanding how B2U can lead to economic benefits by means of addressing the question *What are the key tasks for capturing economic value from EV battery repurposing as a CBM?* This question reflects the need to gain an in-depth understanding of how B2U creates economic value for both energy customers and automotive manufacturers. In addition, it expresses the required practical guidance on how to implement B2U as a CBM in order to capture this economic value.

This S-RQ was mainly addressed in *paper J4*. The key message conveyed by this study is that a successful implementation of B2U as a CBM requires manufacturers to address customer requirements by fully developing the circular product- or solution and to develop the business model for B2U as a combination of revenues and cost savings.

In order to gain insights into the value creation of SLBESS for energy consumers, *paper J4* presents a case study on the real-world SLBESS project at Mercedes-Benz in Sindelfingen. This on the one hand involves qualitative data, which has been collected through interviews with project stakeholders over a time frame of more than 2 years. In this way, the study provides insights on energy markets, which in combination with an in-depth quantitative assessment of the net-present value (NPV) of the SLBESS project lead to a comprehensive view of economic key parameters for B2U customers. To the knowledge of the authors, such a study was not present in literature before. Despite confirming that single-use cases are characterized by profitability issues, the results indicate that SLBESS can indeed be operated economically in some of the multi-use scenarios considered. Results show NPVs between ~110-500k€ for selected use cases over a time frame of 10 years and depending on the assumed market conditions and price parameters (Schulz-Mönninghoff & Evans, 202X).

Additionally, *paper J4* assesses the resulting contributions of B2U for reducing the LCC of the LIB from the perspective of the automotive manufacturer. Here, the study shows how besides revenues from sales of repurposed batteries, B2U potentially creates additional benefits from recycling and closed material loops in the future, leading to a total reduction of battery LCC by 105€/kWh. Meanwhile, the potential gains from recycling has implications for the ownership over repurposed batteries and suggests to engage in service-based models, i.e. "storage-as-a-service", in order to ensure access to LIB at their EoL. This is also found to addresses customer anxiety regarding lifetime of repurposed batteries and at the same time reduces the pressure resulting from the cost of capital on SLBESS investments, as suggested in previous studies (Brauer et al., 2016).

Based on these findings for the case of B2U, *paper J4* concludes seven key tasks for capturing economic value from circular projects (Schulz-Mönninghoff & Evans, 202X):

1. Develop the circular product
2. Unlock value streams from the network of circular benefiters
3. Leverage on resource value
4. Provide risk assurances on circular product quality
5. Observe trends in downstream markets
6. Acquire access to "circular" financial capital
7. Carry out pilot projects under market conditions

The findings are linked to previous studies in CBM implementation and thereby offer practical guidance to overcome some of the identified barriers. The link between the identified key tasks and mechanisms for value capture can support manufacturers in building relevant competencies (Lewandowski, 2016), establishing the required cross-industry partnerships and inter-organizational collaboration (Korhonen et al., 2018) and strategically determine the level of vertical integration in B2U deployment, for which different options are identified in literature (Jiao & Evans, 2017).

Based on this finding on the relevance of addressing customer requirements, further research activities are currently prepared and planned on how to engage customers in CBM innovation, using methods from design thinking in an action research approach (Santa-Maria, Vermeulen, & Baumgartner, 2022). This represents an attempt to move away from the manufacturer-centric view of CBM (Lüdeke-Freund et al., 2019). Instead, the goal is to achieve an actual business model approach to CE implementation (British Standard Institution, 2017), which includes an active integration of customers practices during the use stage of products and services in the CBM design (Kjaer, Pigosso, Niero, Bech, & McAloone, 2019; Lewandowski, 2016; Nußholz, 2020; Tukker, 2015). A corresponding study on workshop-based methods for involving customers in CBM innovation has been initiated as part of the PhD project and will be pursued further to address this gap in research[8].

Lastly and from a theoretical perspective on the categorization of analytical frameworks for CBM presented in (Pieroni, McAloone, & Pigosso, 2019), the findings contribute to the field of “methods”, i.e. procedures and guidelines on how to perform business models in a CE. According to (Geissdoerfer et al., 2020), this is the least addressed category in scientific research and shows fewer results than the other two categories “conceptual frameworks”, e.g. typologies, taxonomies, morphological charters, as well as “tools” which support the execution of CBM innovation, e.g. canvas, software[9].

In summary of these findings, the key contributions to the research field of CBM in relation to S-RQ2 are:

- Provision of quantitative evidence of profitable scenarios for operating SLBESS in Germany today and the resulting potential of B2U to support the deployment of storage technologies for the energy transition;

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[8] Study concept developed in collaboration with University of Cambridge and Mercedes-Benz; workshop on “innovation for circular mobility” scheduled for September 9th 2022 in Böblingen, Germany.

[9] Geissdoerfer et al. (2020) re-name the categories to a) “classifications”, which corresponds to conceptual frameworks, b) “requirements”, which corresponds to methods, and c) “reference models”, which corresponds to tools. Their review only identifies one study in the category of requirements.

- Integrated LCC analysis for manufacturers, taking into account economic value capture from B2U in terms of both revenue and cost reduction;
- Identification of seven key tasks for capturing economic value from implementing B2U as a CBM;

4.3. S-RQ3: IMPLEMENTATION IN ORGANIZATION

Whereas S-RQ2 has focused on the customer-related key tasks for implementing B2U as a CBM, S-RQ3 focuses on the internal requirements for implementing CE decision-making for EV batteries within the organization. This was done by asking the following sub-research question: *Which methods can support automotive manufacturers in implementing a circular economy in decision-making for EV batteries in the organization?* Addressing this question on the one hand implies obtaining an understanding on what and whom CE decision-making entails for the case of LIB. On the other hand, there is a need for selecting, testing and discussing the benefits of using material circularity indicators in decision-making for the case.

The S-RQ 3 was addressed in *paper J2*, *paper C2* and *paper J3*. In summary, the results suggest that decision-making for CE involves numerous different departments within an organization, which can each be characterized by specific goals pursued in relation to material circularity and typical measures addressed. In order to enable and manage a full implementation of the CE concept across departments and functions, companies can apply methods such as CE indicators, which can enable collaboration and alignment of activities according to a joint target.

In *paper J2*, an introduction to the challenges of implementing a CE in the context of a Mercedes-Benz’ sustainability strategy is provided based on insights from different departments. The article describes the different CE strategies for the case of LIB and explains how implementing a CE is a joint task between product designers, developers and EoL management. From that, it is concluded that implementing a CE is not only a technological challenge, but also involves organizational changes and new forms of collaboration (Schulz, Michel, & Hintennach, 2020). This aspect is further linked to the results in *paper C2*, which used 22 interviews with stakeholders from Mercedes-Benz to identify four key decision-contexts for a CE in the organization of an automotive manufacturer (Schulz, Niero, Rehmann, & Georg, 2021) (See Table 6).

Table 6. Key decision-contexts for a circular economy for lithium-ion batteries in automotive industry based on (Schulz et al., 2021)

Business process	Decision context 1	Decision context 2	Decision context 3	Decision context 4
Product development	X	-	X	-

Supply chain	X	X	-	-
Production	-	-	X	-
Business model	-	-	-	X
End-of-life	-	X	X	X

These decision-contexts were then used further in *paper J3* to investigate how company-level CE indicators address the specific tasks in each context. For that, the study develops a 3-step framework inspired by existing guidelines on CE indicator selection (British Standard Institution, 2017; Kravchenko et al., 2020b), which aims at testing the effectiveness of CE indicators for decision-making. The framework comprises the following three steps: (Schulz-Mönninghoff, Neidhardt, & Niero, 2022):

1) **Mapping of material flows** (based on LIB material flow data)
2) **Definition of key questions** (based on insights collected in *paper C2*)
3) **Calculating the company-level CE indicator** (to answer the key question in each decision context)

Based on the case study, *paper J3* reveals that the material circularity for key battery materials Ni, Mn, Co and Li can be increased from 5% today to a maximum of appr. 23% by 2030, taking into account different scenarios of innovation in LIB cell technology and benefits from remanufacturing, repurposing and recycling in a closed-loop production (Schulz-Mönninghoff et al., 2022). The study builds upon previous studies on assessing LIB flows in a CE and provides an Excel-based tool to analyze the interplay between remanufacturing, repurposing and recycling of LIB (Ali et al., 2021; Bobba et al., 2019; Neidhardt et al., 2022; Richa et al., 2017; Xu et al., 2020). Such results, including the resulting forecasts, can be used to position the company in relation to existing regulations for LIB, e.g. in terms of the availability of secondary materials to achieve minimum rates of recycling content of 20% for Co, 10% Li and 12% Ni as proposed in the revision of the EU battery directive (European Commission, 2020c).

Furthermore, *paper J3* derives characteristic ways of how decision-makers can affect company-level material circularity of a company, e.g. for product development and production to focus on process optimization and efficiency to reduce waste (Schulz-Mönninghoff et al., 2022). It thereby complements existing literature on categorizing CE indicators based on their methodological characteristics (Parchomenko et al., 2019; Saidani et al., 2019) and adds to research on user-oriented perspectives to the indicator selection process (Kravchenko et al., 2020b). The results thereby address the research gap outlined in section 1.3. in terms of the integration of CE assessment methods and measures for implementation in an organization (Pauliuk, 2018). In this context of managing allocation issues in a CE, the results suggest that more research is needed on how to resolve sustainability-related trade-offs and prioritize CBM options based on their characteristic value provided to the company (Haines-Gadd & Charnley, 2019; Kravchenko, Pigosso, & McAloone, 2020a; Lüdeke-Freund et al., 2019). Besides pursuing this through more sophisticated metrics, enabling deeper collaboration and co-design for CE among stakeholders in an organization seems necessary (Pedersen & Clausen, 2019).

In summary, the findings in relation to S-RQ3 provide the following key contributions to the research field of CE indicators:

- Organizational challenges of CE implementation
- Identification of key decision-contexts for CE for the case of LIB in automotive industry
- Calculation of a maximum company-level material circularity for key battery materials of appr. 23% by 2030;
- Provision of an MS Excel-based model for estimating future LIB material flows of a company based on different CE indicator methods;
- Identification of characteristic links between company-level CE indicator results and CE decision-makers in an organization;

4.4. FINDING NEW PURPOSE: RESPONSE TO THE OVERALL RESEARCH QUESTION

This chapter presents the response to the overall research question based on a revision of the contribution to the individual research fields. The response is then discussed in light of existing literature and lastly positioned in relation to the previously outlined goals in a CE.

4.4.1. DEVELOPMENT OF THE RESPONSE

The overall research question of this project asked *How can automotive manufacturers implement electric vehicle battery repurposing in order to achieve economic and environmental sustainability of battery life cycles in a circular economy?*

In response to this question, the project has engaged with three research fields - LCA, CBM and CE indicators - in order to investigate aspects of environmental and economic benefits of EV battery repurposing, as well as methods for supporting the implementation within the organization of an automotive manufacturer. The key results outlined in the previous chapters are summarized and translated into final recommendations (see Figure 9).

Firstly and as a common element, the methods applied in each of the research fields are characterized by an explicit focus on the different stakeholders involved. In the LCA approach, the 2-step procedure starts from the benefits at the customer and then translates these into the context of the battery life cycle impacts. Similarly, the economic assessment is carried out by firstly calculating the cost-benefit analysis in the form of the NPV over the entire BESS lifetime. These are then – again – interpreted in the context of the LCC. Consequently, the findings suggest that the implementation of EV battery repurposing requires automotive manufacturers to apply dedicated methods from the realm of energy system analysis in order to fully understand and capture the role of repurposed EV batteries in energy systems and the corresponding environmental and economic implications at the customer. These methods include energy flow modelling and planning processes for BESS. These need to be integrated with methods of analysis such as life cycle assessment, NPV calculation and LCC analysis in order to allow an interpretation in the context of an automotive system.

Secondly, the research shows that the environmental and economic results of EV battery repurposing are affected by - and must be derived from - the specific application of the SLBESS at the energy consumer, i.e. the customer of the CBM. Understanding the customer requirements of B2U in the respective case and developing the product and the business model accordingly to ensure sustainable value creation is thus identified as a key finding.

Thirdly, the results on the implementation of EV battery repurposing within the organization is presented as a task, which requires collaborative engagement of many different stakeholders from within a company – and potentially beyond - to work together. To achieve this, the key task is to develop a thorough understanding of the corresponding requirements for decision-making and applying CE indicator methods in collaborative design processes to align different measures, e.g. CBM options, towards a joint material circularity target.

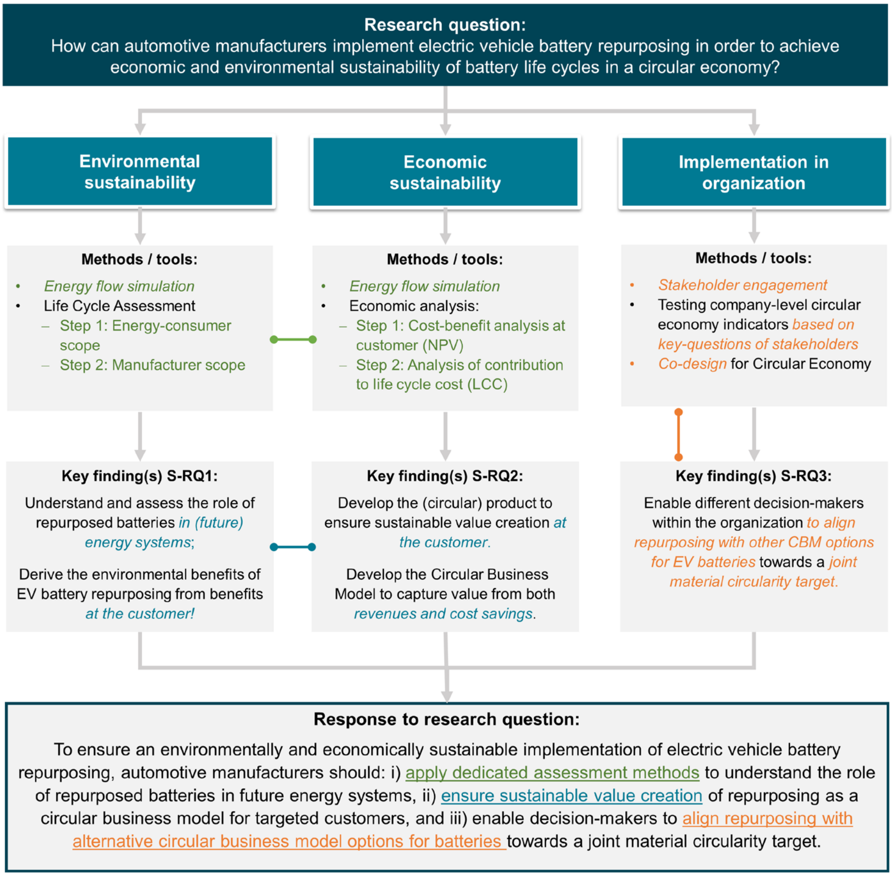


Figure 9. Development of the response to the overall research question

Based on these findings and the overlaps outlined above, the response to the overall research question can be formulated as follows:

Response to the overall research question: To ensure an environmentally and economically sustainable implementation of electric vehicle battery repurposing in a circular economy, automotive manufacturers should:

i) apply dedicated assessment methods such as energy flow simulation and planning processes for stationary battery storage systems to fully understand the role of repurposed batteries in future energy systems,
ii) ensure sustainable value creation of repurposing as a CBM by focusing on the targeted customers, and
iii) enable decision-makers to align repurposing with alternative CBM options for batteries towards a joint material circularity target.

The following section discusses this response in the context of the EV battery life cycle as the analytical framework and in relation to existing literature.

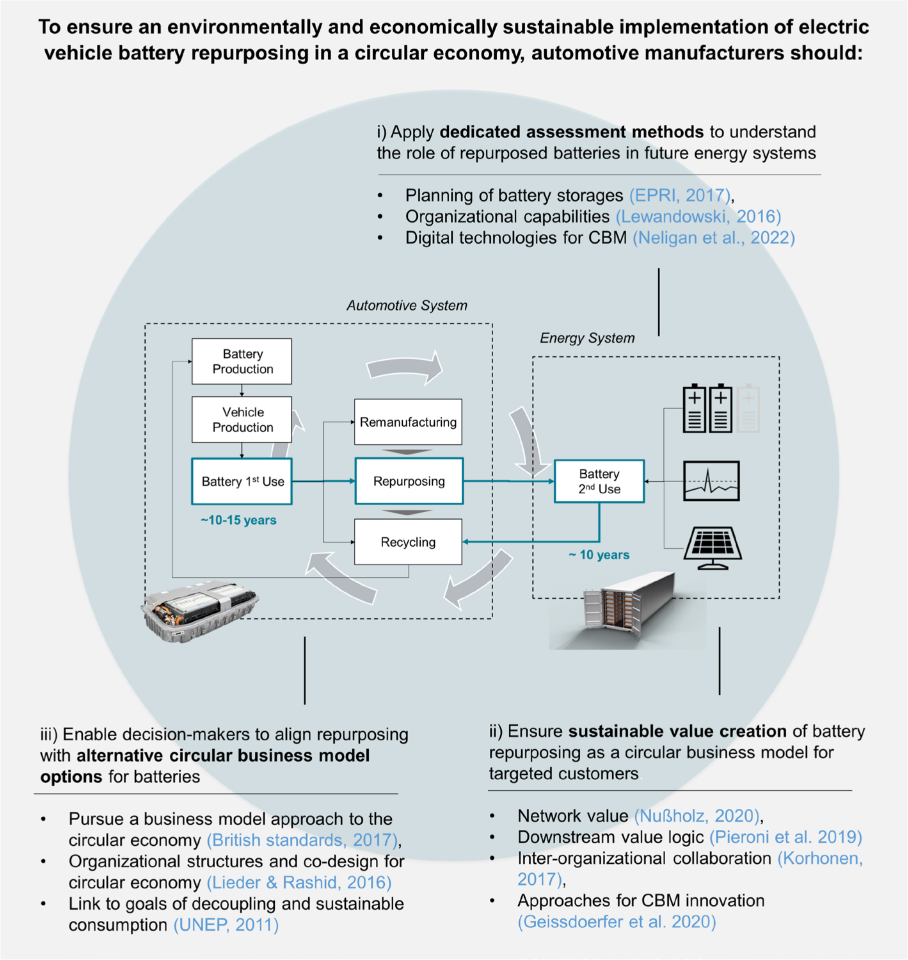
4.4.2. DISCUSSION IN RELATION TO EXISTING LITERATURE

A visualization of the response to the overall research question in relation to the life cycle of an EV battery is provided in Figure 10. The goal is to assign the recommendations included in the response to the relevant product system and link them to related topics in existing literature.

In terms of the application of dedicated assessment methods to support the implementation of B2U, the key aspect is to gain an understanding of the role of repurposed batteries in future energy systems. As illustrated in Figure 10, this requires manufacturers to acquire knowledge in terms of the methods for assessing SLBESS from a technical and economical perspective as described in (EPRI, 2017). Especially the analysis of the NPV of investments in battery storages as a multi-purpose technology requires a thorough understanding of the ways in which BESS can support future energy systems (Balducci et al., 2018; Müller, 2018). As such, the response addresses the aspect of organizational capabilities for CE and downstream markets, as described in previous studies (Lewandowski, 2016; Pieroni et al., 2019). For manufacturers, implementing B2U requires the acquisition of both knowledge and competencies to carry out market analysis and energy flow analysis of B2U projects and thereby understand the environmental and economic contributions of a CBM. In this regard and when revising the software tools and data sources used in the project, it becomes evident that digital technologies play a key role for enabling the implementation of B2U. As mentioned in previous studies, the availability of data for future use cases of products and materials can be an enabler for CBM (Neligan, Baumgartner, Geissdoerfer, & Schöggl, 2022). For the case of B2U, such digital infrastructures can especially support data sharing between automotive and energy system, e.g. in terms of load profiles, technical specifications of equipment and energy generation at targeted energy systems (CEID, 2020).

Moreover, ensuring sustainable value creation for the case of B2U is linked to the possibility of addressing multiple stakeholders in energy systems. This resonates with the findings of (Nußholz, 2020), who applies an analysis of the network value for value retention as a CBM. This implies an understanding of the value perception of different stakeholders involved in the CBM. Other authors here refer to the downstream value logic of CBM (Pieroni et al., 2019). From this standpoint, the response to the research question addresses the need for increasing inter-organizational collaboration with energy systems in the adoption of EVs and encourages deeper collaboration with CBM customers across the boundaries of a single company (Korhonen et al., 2018). Based on this framework, automotive manufacturers can take on the task of addressing both environmental and economic results of B2U at the customer while maximizing the contribution to the sustainability of EV battery life cycles (Fischhaber et al., 2015; IRENA, 2017). In this regard, the different types of CBM innovation additionally come to mind, which suggest different forms of establishing business relationships for CBM, particularly in relation to the existing linear model (Geissdoerfer et al., 2020). Future studies could in this regard investigate the benefits and drawbacks of approaches for establishing such collaborations with network partners, e.g. through the “circular startup” versus CBM transformation (ibid). Particularly in light of the urgently needed decarbonization of electricity systems and the formation of market constellations for providing RE at a different scale, B2U can represent an opportunity to establish partnerships and integrate mobility with energy provision networks.

Lastly, enabling decision-makers to compare different CBM options for batteries is an aspect which is not explicitly outlined in existing guidelines for implementing a CE (British Standard Institution, 2017). In this regard, the results emphasize the need to expand on existing standards for CE implementation and provide further guidance, not only on *who* needs to be responsible for *what*, but also *with whom* such responsibilities need to be addressed jointly. Given that different CE strategies address different goals of companies, the combination of different CBM options thus requires an alignment towards an overall target of the company. For that, literature states that the deployment of a CE for companies is affected by both top-down measures in the context of regulation and competition (European Commission, 2020a), but also as bottom-up tasks in working culture and co-design methods for CE to achieve a competitive advantage (Lieder & Rashid, 2016). Additionally, future studies should further investigate how CE indicator methods and alignment of CBM can take into account aspects of achieving decoupling and sustainable consumption patterns (UNEP, 2011) (see also following section 4.4.3).



To ensure an environmentally and economically sustainable implementation of electric vehicle battery repurposing in a circular economy, automotive manufacturers should:

i) Apply **dedicated assessment methods** to understand the role of repurposed batteries in future energy systems

- Planning of battery storages (EPRI, 2017),
- Organizational capabilities (Lewandowski, 2016)
- Digital technologies for CBM (Neligan et al., 2022)

ii) Ensure **sustainable value creation** of battery repurposing as a circular business model for targeted customers

- Network value (Nußholz, 2020),
- Downstream value logic (Pieroni et al. 2019)
- Inter-organizational collaboration (Korhonen, 2017),
- Approaches for CBM innovation (Geissdoerfer et al. 2020)

iii) Enable decision-makers to align repurposing with **alternative circular business model options** for batteries

- Pursue a business model approach to the circular economy (British standards, 2017),
- Organizational structures and co-design for circular economy (Lieder & Rashid, 2016)
- Link to goals of decoupling and sustainable consumption (UNEP, 2011)

Figure 10. Visualization of response to overall research question and identified links to existing literature.

In this way, the resulting framework for implementing B2U is based on the battery life cycle and includes the identified key recommendations derived from the PhD project while establishing links to the existing body of literature on CBM implementation in general. Meanwhile, the result can be seen in comparison to a framework for sustainable business model innovation for B2U presented by (Reinhardt, Christodoulou, García, & Gassó-Domingo, 2020). The authors provide links to other sustainability dimensions and differentiate between aspects at the level of the business environment and at the organizational level. In this sense, the framework presented in response to the overall RQ in this project cannot be considered a conceptual framework for B2U in the sense of an exhaustive assembly of relevant aspects. However and taking into account the pragmatist research philosophy applied in the project, the framework addresses current, relevant issues in practice while providing novel insights into the interplay of different disciplines for the implementation at an organizational level.

From a holistic perspective, the framework provided can serve as the basis for further developing existing guidelines for CE implementation. Based on the identified shortcomings of these guidelines outlined in chapter 2, the framework presented provides relevant insights on the use of assessment methods, sustainable value creation of CBM for customers and comparison of CBM options (British Standard Institution, 2017; Pauliuk, 2018). As new standards are currently under development, the results for the case of B2U can be revised and potentially serve to address other cases of CBM in the future (ISO, 2018).

4.4.3. POSITIONING IN RELATION TO GOALS IN A CIRCULAR ECONOMY

As outlined in section 2.1, the aspirations for the deployment of a CE at scale reach from the creation of job opportunities, reduction of waste, resource consumption and cost to the realization of environmental benefits (Stahel, 2016). In this regard, the goal of decoupling stands at the core of the CE concept (Ghisellini et al., 2016), which implies that achieving environmental benefits while maintaining or increasing economic results is a necessary condition for a successful implementation of a CE for companies (Lieder & Rashid, 2016).

In this regard, the findings of the present project support the assumption that a CE can lead to both environmental and economic benefits for companies. As presented in *paper J1* and *paper J4*, the case of B2U can provide environmental benefits through the support of the energy transition towards RE while at the same time allowing for a reduction of energy cost and the LCC of EV batteries. In this sense, the results generally support the pursuit of a CE to achieve some of the outlined goals and underline the role of B2U in the political agenda for implementing a CE for EV batteries (European Commission, 2020a; Stahel, 2016).

Meanwhile, the question of how B2U contributes to the goal of decoupling of resource consumption from growth in EV battery - or LIB markets in general - cannot fully be answered based on the results presented in this thesis. Such contribution requires that B2U as a CBM leads to an absolute reduction of primary resource consumption in the provision of LIB (UNEP, 2011). For that, the results suggest that B2U can both be interpreted as a CBM strategy of “recycling” and as “extending”, meaning that it combines the effects from recycling battery resources within the system while at the same time extending the use phase of batteries (Geissdoerfer et al., 2020) (see Figure 11).

In terms of cycling, the findings in *paper J1*, *paper J2, paper J3 and paper J4* show how postponing LIB recycling by appr. 10 years through B2U can enable more efficient material recovery processes and thus increase the availability of secondary LIB materials for closed-loop production in the future. This would reduce the primary material demand for LIB production. Additionally and in terms of extending, especially the findings in *paper J4* on the one hand suggest that B2U can support the deployment of BESS in general and thereby transition to RE supply. This would result in a reduction of fossil resource consumption in energy systems, but not in LIB markets. On the other hand, the discussion in *paper C1* states that B2U can indeed be interpreted as a means to substitute new batteries for the provision of stationary BESS and thereby reduce resource consumption for LIB markets. The latter has however not been further investigated as part of this research project.

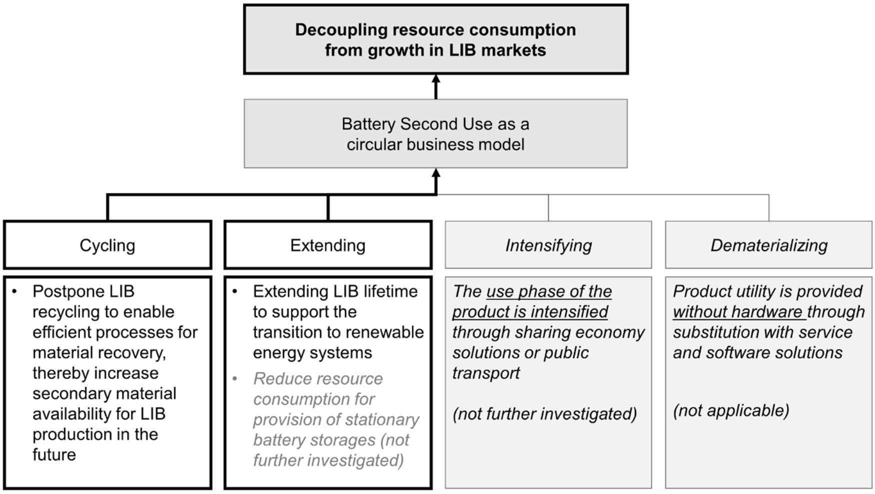


Figure 11. Contribution of battery second use to the goal of decoupling resource consumption from growth in lithium-ion battery (LIB) markets; based on circular business model strategies presented in (Geissdoerfer et al., 2020).

Consequently, the approaches and results results presented in this PhD project suggest an interpretation of B2U, which does not primarily focus on the resource savings but instead on the benefits of using circular solutions, i.e. the *purpose* these serve in the context of an energy system. As described in *paper J4*, the results thereby offer a perspective on B2U as a way to overcome barriers in the deployment of BESS and to ”increase substantially the share of renewable energy in the global energy mix by 2030” as mentioned in SDG 7.2 (United Nations, 2015). This approach puts circular solutions at an equal market level with new products and thus focuses on their competitiveness at scale.

However, a shortcoming of such approaches can be identified in establishing a clear link between B2U and the achievement of decoupling performance of companies in relation to SDG 12.3 (United Nations, 2015). While the methods assessed in *paper J3* would enable such an analysis (WBCSD, 2021), further research is needed on how repurposing as a CBM contributes to the reduction of absolute resource consumption, e.g. by displacing new batteries in stationary BESS provision (Fischhaber et al., 2015). Such approaches however would need to be sensitive towards changes in LIB technology (Cano et al., 2018), which determine the benefits of displacement (Vadenbo, Hellweg, & Astrup, 2017).

In summary, the implementation of a CE can be seen as a two-fold exercise. Based on the findings of the project, the successful implementation of CBM should pursue *purpose*, which in a nutshell can be described as a meaningful integration of circular solutions in downstream markets for both economic and environmental benefits. At the same time, implementing a CE must be linked to *absolute reductions* in resource consumption for providing products and services in order to achieve decoupling and prevent damages to global eco-systems (Meadows et al., 1972). In light of this finding, one can expect that the enherent ambiguity of adding meaning while pursuing reduction in implementing a CE will continue to stir discussions in the scientific community in the future (Schultz, 2022).

4.5. REFLECTIONS ON THE METHODOLOGICAL APPROACH

Despite the research contributions generated from applying the methodological approach defined for this study, a number of critical reflections can be drawn retrospectively and regarding the ambitions outlined in this project.

As a recurring element, the project required simultaneous engagement with two product systems, i.e. the automotive system and the energy system. While this was intentionally included in the analytical framework and is an inherent characteristic of the case of EV battery repurposing (Bowler, 2014), this double-perspective has certainly shaped the data collection process and the development and application of the corresponding methods. Based on the ambition to address both systems in a single analysis in both S-RQ1 and S-RQ2, it was necessary to acquire and apply knowledge and in-depth understanding of many different contexts surrounding B2U. As an example, the interpretation of SLBESS as an asset in energy systems required the development of a dedicated LCA approach and an energy-flow based assessment of economic and environmental benefits. Using these results to understand B2U in the context of an EV battery life cycle resulted in the parallel development of another LCA approach on comparing CBM options (see *paper J1*) and in additionally carrying out an LCC analysis (see *paper J4*). From today's perspective and albeit leading to the contributions at hand, the simultaneous application of two perspectives in the project has lead to considerable complexity within the PhD project.

The fact that the project has nonetheless produced results addressing the defined S-RQs leads to another important reflection, namely on the resources available throughout the project. Ultimately, many of the assessments and analyses would have been challenging, or impossible, without the financial resources to acquire the required tools and software applications or without the support of supervised full-time student projects. Especially for *paper J4*, the work and knowledge required for an in-depth, longitudinal and mixed-method study on a single case of CBM implementation retrospectively seem challenging without an industrial research partner (Mercedes) and a multi-disciplinary team (two thesis projects and financially supported international research collaboration).

Based on these reflections, it can be stated that the unique perspective for research, namely having direct access to both manufacturer and customer perspective on B2U, has provided substantial leverage to successfully achieve the defined goals and outcomes of the PhD project. Nevertheless, being sensitive to the methodological implications and resource requirements associated with certain research goals – especially in multi-disciplinary research with mixed-method approaches – is an important learning from the present project (Menken & Keestra, 2016; Saunders et al., 2019).

In this regard, the setup of the PhD project and access to the SLBESS project in Germany as a case the investigation was particularly favorable to acquire the necessary data. The fact that the CBM customer was represented by the own production system of Mercedes-Benz has favored the data collection process, but to the knowledge of the author has not affected the objectivity of results. In this sense, it can be assumed that with appropriate access to data, the results would have been similar or equal if the industrial energy consumer would have been outside the factory of Mercedes-Benz.

Additionally, a last critical reflection concerns the work on S-RQ3, in which a lot of focus has been dedicated to the quantitative results, i.e. the aggregated material circularity results at company-level. Meanwhile, some activities conducted as part of a course project in the Sustainable Design course at Aalborg University have revealed that it is debatable whether quantitative CE indicators alone can provide a solution for assessing and managing CE strategies within an organization. Instead, the learnings suggest that the educational character of conceptualizing a CE offered by the Circular Transitions Indicators framework is clearly a benefit for enabling co-design for CE – regardless of the actual numerical results calculated. Instead, the framework and the underlying input-output-based visualization offer a point of reference for diverse actors, thereby creating a common ground for negotiating what a CE entails and how it should be supported (Pedersen & Clausen, 2019). Consequently, a thorough debate on whether the rather old-fashioned saying “only what gets measured gets managed” still holds true in light of progressive and effective guidance on collaborative design methods could be part of future investigations (Walzberg et al., 2021).

4.6. REFLECTIONS ON THE ANALYTICAL FRAMEWORK

In terms of the analytical framework, which is represented by the EV battery life cycle and derived from the combination of the addressed research fields, it can be stated that an inter-disciplinary or even a trans-disciplinary approach would not have been feasible within the scope of a PhD project. In this regard, examples exist in literature which integrate disciplines of LCA with the research field of CE indicators (Lonca et al., 2018; Niero & Kalbar, 2019; Rigamonti & Mancini, 2021). Similarly and as mentioned in section 3.2, combining the disciplines of LCA and business model research seems feasible in general (Goffetti et al., 2022). However, such approaches must be rooted in existing frameworks and capture the full picture of relevant aspects.

At the same time and based on the research philosophy of pragmatism, the framework of this thesis is mostly derived from identified research gaps, which are partly inspired by the real-word challenges and problems observed in the automotive industry. This means that part of the objective of the project was to address those real-world challenges and provide practical support to relevant decision-makers. In this regard, the experiences collected as part of the research project suggest that the application of LCA is still a centralized competence in industrial settings, meaning that few employees within an organization actually apply LCA as part of their daily decision-making processes. In contrast to that, the use of CE indicators seems to provide an opportunity to offer less complex but effective methods to a wide range of stakeholders and business processes (see *paper C2*). Consequently, the integration of the underlying disciplines would not necessarily address the practical issues, which have inspired the development of the S-RQs. From that perspective, the additional theoretical work required to further develop integrated and multi-disciplinary methods for assessing CE strategies would not bear relation to the benefit provided to the body of research on EV battery life cycles and B2U specifically.

Consequently, a key reflection on the analytical framework is that expanding the toolbox for assessing and managing CE strategies for EV batteries seems to be a suitable way forward to support the adoption of CE in industry. This also holds true in comparison to approaches focusing on further developing more sophisticated, precise or powerful methods. It is the conviction of the author that combining existing methods in practice-oriented frameworks can be an alternative to deepening expert knowledge in certain domains. Based on this premise, the analytical framework is considered suitable for addressing the goals of the project.

CHAPTER 5. CONCLUSIONS

This chapter summarizes the findings of the PhD project. Overall, the thesis provides guidelines for manufacturers for a sustainable implementation of EV battery repurposing, taking into account the interplay between the automotive and the energy sector at both a methods- and results level. The findings are presented based on contributions to practice (section 5.1) and contributions to theory and methods (section 5.2), before providing directions for future research (section 5.3).

5.1. CONTRIBUTIONS TO PRACTICE

In terms of contributions to practice, the thesis firstly shows how implementing EV battery repurposing to achieve environmental benefits implies for practitioners to acquire a thorough understanding of how B2U addresses issues and needs for sustainable energy supply in future energy systems. Rephrased more broadly, it seems that in order to create additional value – or “purpose” – from extending the lifetime of LIB, we need to understand what exactly purpose *means* in that new product system and function. For automotive manufacturers, this calls for building new knowledge on the application fields of repurposed LIB and their environmental benefits. The case study on the real-world SLBESS project in Germany here reveals how different combinations of storage applications can provide different energy-related environmental benefits. One of the key findings in this regard is that multi-use cases can, as a way of improving the economic results of SLBESS, lead to a reduction of the potential environmental benefits. This aspect should be managed carefully with the deployment of SLBESS at scale. Meanwhile, the results of the comparison of CBM options for LIB show how B2U is the preferred option in terms of the climate change impact category and should thus be pursued where technically possible.

Secondly, the contribution to the practical implementation of B2U as a CBM firstly entails a list of seven key tasks for capturing economic value from EV battery repurposing. These include concrete recommendations on value creation, value delivery and value capture and thereby go beyond the often used conceptualization of results as drivers and barriers in terms of applicability in industry. Furthermore, the quantitative evidence for the profitability of B2U in the case study in Germany at the time of the investigation provides guidance for CE managers in the automotive system, but also SLBESS customers in the energy system to pursue favorable project setups. In this way, one practical contribution is that this thesis confirms the potential of B2U to support the deployment of storage technologies for the energy transition from an economic standpoint.

Thirdly, the project contributes to the research field of CE indicators through practical recommendations on *who* within an organization can - or should - take *which* specific action to improve the material circularity of a company. The identification of characteristic links between decision-makers for CE and the quantitative headline indicator of a business enables allocation of responsibilities, setting dedicated targets and establishing meaningful collaborations across organizational functions. As a practical result, the findings thus enable a more coordinated approach to managing material circularity more holistically. In this regard, the Excel-based tool provided with the study encourages practitioners to experiment with company-level indicators, which still suffer from slow adoption in industry.

From the perspective of maintaining a competitive advantage over other market players, the publication of quantitative results, e.g. a maximum of appr. 23% material circularity for key LIB materials by 2030, can provide a benchmark for practitioners and help them to argue and defend imperfect CE performance results in public. In times in which “net-zero” and “zero-waste” claims are often communicated without being backed up with suitable measures, transparency and scientifically sound application of methods can help companies to reclaim credibility in their sustainability reporting and to proactively inform the public about ongoing challenges. Similarly, policymakers, investors and shareholders can apply such quantitative figures for allocation of resources, e.g. by ranking companies and industries or for identifying sectors in which further regulatory incentives for increasing material circularity are necessary.

5.2. CONTRIBUTIONS TO THEORY

In terms of contributions to the applicability of LCA in the context of a CE, the present project provides several relevant findings. Firstly, the classification of approaches for assessing B2U in LCA based on CE considerations provides guidance for the process of defining scope, reference flows and allocation rules across multiple life cycles. Similarly, the development of a two-step LCA approach, which provides a dedicated assessment scope according to the requirements in each product system and then integrates them methodologically should be highlighted. It thereby contributes to the theoretical toolbox for applying LCA in a CE context. Furthermore, the integration of energy flow modelling and LCA stands exemplarily for the need to link more closely the different disciplines, which are required for a meaningful assessment of certain CE strategies. In light of future standards for assessing the case of B2U, the results suggest that such approaches should be derived from – or at least be sensitive to – the decision-context and GHG profile of the targeted customer, i.e. the energy consumer in the present case.

Secondly, the findings add to the body of theory on CBM implementation by contributing to the category of “procedures and guidelines on how to perform business models in a CE”, which, as shown in this thesis, is the least addressed category in scientific literature until today. The project thereby leverages on its unique access to data on both manufacturers and CBM customers in order to provide specific theoretical contributions, which are rarely feasible within a single PhD project.

Furthermore and from a methodological perspective, the results show the benefits of an in-depth, longitudinal and multi-method study on single cases of CBM implementation. As illustrated in the study, such research approaches, albeit being time- and resource intensive, can offer insights into the effects of market dynamics and project setup on implementing B2U as a CBM. More specifically for the case of B2U, a key contribution is the finding that the extended business case for EV battery repurposing should take into account both additional revenues and avoided cost resulting from postponing recycling. In this sense, the application of LCC as a method, which allows for a detailed revision of each life cycle stage and the contribution to the economic profitability of a CBM is developed further through this work.

Thirdly, the project contributes to the body of literature on CE indicators mainly by providing insights into the methodological strengths and weaknesses of applying the two specific indicator methods used, namely the Circular Transition Indicators framework and the Material Circularity Indicator at company-level. By contrasting both methods and reflecting on the ability of highly aggregated metrics to respond to individual decision-contexts, the research project reveals challenges, which can be addressed through either further development of the method or further guidelines for usability or interpretation. While at the same time showing that company-level CE indicators are particularly powerful for summarizing and aligning different CBM options for EV batteries towards a common target, the underlying contribution to theory lies in the provision of methods for resolving sustainability-related target conflicts. As results show how each CBM provides different value to companies, establishing material circularity as a common dimension for decision-making is presented as a way to resolve competing interests and create a common ground for negotiations among actors.

5.3. DIRECTIONS FOR FUTURE RESEARCH

Based on the findings presented in this thesis, several promising directions for future research can be identified.

Starting from the limitations of this study, this thesis focuses exclusively on the case of EV battery repurposing in automotive industry based on a real-world case of implementing a SLBESS in Germany. Future studies could build on the methodological guidance provided in this thesis and carry out multi-case studies on B2U across regions, or assess the degree to which the findings are applicable to LIB from consumer electronics, such as e-bikes and e-scooters.

Furthermore, findings on the need for cross-stakeholder collaboration for CE decision-making calls for advanced research in the realm of co-design for CE and sustainability in general. Rather than focusing exclusively on providing more sophisticated assessment methods, the findings suggest that investigating the interplay of internal and external stakeholders, innovation in organisational structures and ways for creating an entrepreneurial culture for CE seems to be promising avenue in research.

Regarding the latter, further investigating methods of how to engage customer in the CBM innovation process could shed light on the underlying root causes for slow adoption of truly circular products and services. Based on this rationale and as mentioned in section 4.2, a workshop-based concept has been developed as part of this project, which aims at engaging potential customers in a CBM design process through design-thinking methods. These include backcasting, imagining circular perfection and testing of prototypes. As the next steps are going to be finalized beyond the scope of the PhD project, future studies are invited to join this endeavour of exploring the role of customers in business model innovation.

Lastly, the need for respecting the absolute limits of our ecosystems calls for more dedicated efforts to provide practical tools and managerial guidelines for considering aspects of absolute sustainability in every-day decision-making. In this sense, and given that the CE indicator methods investigated as part of this project can be used to assess the decoupling performance of a company, future studies can build on the present work and establish links to other frameworks such as the planetary boundaries. This could open the space for service-based solutions, dematerialization of mobility and other measures, which truly help us as a society to take responsibility and prevent another fatal update on Limits and Beyond by the Club of Rome in the year 2072.

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APPENDICES

Appendix A. Other contributions

Journal papers

Neidhardt, M., Mas-Peiro, J., Schulz-Moenninghoff, M., Pou, J.O., Gonzalez-Olmos, R., Kwade, A., Schmuelling, B., 2022. Forecasting the Global Battery Material Flow: Analyzing the Break-Even Points at Which Secondary Battery Raw Materials Can Substitute Primary Materials in the Battery Production. Applied Sciences 12, 4790. https://doi.org/https://doi.org/10.3390/app12094790

Picatoste, A., Schulz-Mönninghoff, M., Niero, M., Justel, D., F. Mendoza, J.-M. (202X). Circularity performance and environmental sustainability of batteries for electric vehicles. *Manuscript in preparation.*

Schulz-Mönninghoff, M., Braun, D., Evans, S. 202X. A workshop concept for engaging customers in circular business model innovation in automotive industry. *(Manuscript in preparation)*

Extended abstracts

Schulz-Mönninghoff, M. (2020) Measuring circularity: A case study on circular economy indicators for electric vehicle batteries. International Circular Economy Conference (ICEC) 2020, Freiburg, Germany *(oral presentation)*

Schulz-Mönninghoff, M., Eigenbrodt, L. (2021) Economic analysis of multi-use cases for industrial battery energy storage systems in automotive production facilities. International Renewable Energy and Storage (IRES) Conference 2021. Düsseldorf, Germany *(oral presentation)*

Schulz-Mönninghoff, M., Bey, N., Niero, M. (2021) Circular business model implementation in practice: Learnings from the case of electric vehicle batteries. International conference on Life Cycle Management (LCM) 2021, Stuttgart, Germany. *(oral presentation)*

Contributions to reports

Circular Economy Initiative Deutschland (Ed.): Resource-Efficient Battery Life Cycles – Driving Electric Mobility with the Circular Economy, Kwade, A., Hagelüken, C., Kohl, H., Buchert, M., Herrmann, C., Vahle, T., von Wittken, R., Carrara, M., Daelemans, S., Ehrenberg, H., Fluchs, S., Goldmann, D., Henneboel, G., Hobohm, J., Krausa, M., Lettgen, J., Meyer, K., Michel, M., Rakowski, M., Reuter, M., Sauer, D.U., Schnell, M., **Schulz, M.,** Spurk, P., Weber, W., Zefferer, H., Blömeke, S., Bussar, C., Cerdas, J., Gottschalk, L., Hahn, A., Reker-Gluhic, E., Kobus, J., Muschard, B., Schliephack, W., Sigel, F., Stöcker, P., Teuber, M. and Kadner, S., acatech/SYSTEMIQ, Munich/London 2020. *(working group report)*

World Business Council for Sustainable Development (Ed.), Circular transition Indicators V3.0. – Metrics for business by business; Geneva, Beijing, Delhi, London, New York, Singapore, 2021. *(Contribution as working group member)*

Mercedes-Benz and Circular IQ (2022) – Driving Circular Economy Performance with Company level Indicators in Automotive Industry. Learnings from a proof-of-concept on implementing company-level circular economy indicators *(company-internal case study report)*

Bachelor- and Master projects supervised

Patrick U. Nørregaard (2019) Development of a life cycle evaluation framework for remanufacturing of electric vehicle batteries in a circular economy. Technical University of Denmark, M.Sc. in Environmental Engineering – Environmental Management.

Mohamed Shaarawy (2019) Development of a life cycle evaluation framework for an industrial-scale Battery Energy Storage System (BESS) in automotive production. Technical University of Denmark, M.Sc. in Industrial Engineering and Management.

Leonie Eigenbrodt (2020) Relationship between profitability and requirements for the implementation of stationary battery energy storage systems in automotive production facilities. HTWG Konstanz, Master of Engineering (M.Eng.).

Lucas Nitsche (2022) Planung und Implementierung von stationären Batteriespeichern in den Werken von Mercedes-Benz. University of Applied Sciences Ulm, B.Sc. in International Energy Economics.

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