Environmental and economic assessments of electric vehicle battery end-of-life business models

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Zink and Geyer (2017) in Circular Economy Rebound:
"Circular economy activities can increase overall production, which can partially or fully offset their benefits"

Foreword

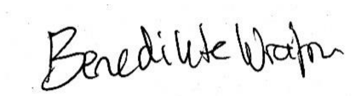
This doctoral dissertation targets to enhance a circular economy for used electric vehicle batteries globally. The research was part of the BATMAN research project (lithium-ion BATteries – Norwegian opportunities within sustainable end-of-life MANagement, reuse, and new material streams).

My educational background is an M.Sc. in Industrial Ecology. I have worked with environmental certification programs and assessments of contamination from the industry. Since I first heard about how industrial processes affect the climate and natural environment, I have been naturally drawn to find solutions to reduce environmental impacts. A circular economy is part of the solution.

My motivation for the doctoral program was to advance my knowledge within the field and gain competence and skills relevant to the future. I will use these competencies and skills wisely and productively. Continuous learning and new challenges have always been important for me, so I will not stop today. I sincerely hope those who read this dissertation will benefit from it.

I sincerely thank my supervisors, Magnus Hellström, Reyn O'Born, and Bernhard Faessler. Working with you is a great pleasure; I will always appreciate your mentorship.

I thank all my friends and family for co-creating a richer life. I give special thanks to my father, Torbjørn Wrålsen, who has always supported me with a cheerful smile.



Benedikte Wrålsen
Grimstad, April 5, 2023

Summary

The number of electric vehicles is rapidly and continuously increasing due to the transport sector's electrification to reduce emissions such as greenhouse gases. Each electric vehicle is powered by a battery that can contain remaining capacity after first use and several potentially valuable materials. The demand for stationary energy storage systems to balance renewable energy sources and support the grid infrastructure further accelerates the need for these batteries. Considering the upcoming volumes of used electric vehicle batteries, a circular economy for batteries is crucial to enhance environmental and economic sustainability.

Circular economy business models aim to strategically reduce the use of resources by closing, narrowing, and slowing material loops, enabling economically and environmentally sustainable business. However, the potential environmental benefits of such circular economy efforts are not explicit.

The aim of this work is to provide recommendations for global economic and environmental sustainability of used electric vehicles batteries by considering a circular economy. This objective requires an interdisciplinary approach, building on existing research fields and methods within business and engineering sciences. This interdisciplinary approach prevents problem shifting between environmental and economic sustainability performance of the circular business models identified and assessed.

In order to address the main thesis aim, four research questions were developed, and four corresponding publications were produced as a result. Paper I explores market opportunities and limitations for used electric vehicle batteries in Norway, a country with a high market share of electric cars in new car sales. The work qualitatively models the used electric vehicle batteries business ecosystem based on interviews with the industrial ecosystem actors. The globally relevant findings from paper I identify realistic end-of-life alternatives for paper II. Paper II identifies and discusses the globally recommended circular business model to enhance a circular economy for batteries from electric vehicles. The Delphi panel

method enables a battery expert panel to elaborate on a suitable circular business model for the upcoming volumes of used electric vehicle batteries. Paper III assesses the identified circular business model from paper II to discuss how such a business model can be economically viable and realistic. The techno-economic assessment considers multiple scenarios to detect economic factors for circular business model success. Paper IV assesses the identified circular business models from paper II to discuss how such a business model can benefit the climate and natural environment. Life cycle assessment methodology can calculate the environmental impacts of decisions between business models. Life cycle assessment can detect problems shifting between ecological impact categories, such as greenhouse gas emissions and contamination of the natural environment.

The research reveals that repurposing electric vehicle batteries in appropriate second-life applications can reduce their environmental impact and extend their useful lifespan. Eventually, the materials must be recycled to the extent possible. This circular business model's key environmental benefit is the potential reduction in the demand for new batteries, which could help displace primary production and avoid emissions and other environmental impacts from these industrial processes. However, there is a risk this circular business model may be economically unviable. Several factors must be considered to improve profitability and realistic commercial operations, including the state of health, ageing, lifetime of the battery after its first life, price of used batteries, ownership of the battery, location, second-life application, potential grid connection, and electricity profile of the battery system. A combination of different energy management strategies should be considered suitable for the application to maximize the financial returns of battery repurposing.

Sammendrag

Antallet elektriske kjøretøy øker raskt og kontinuerlig på grunn av transportsektorens elektrifisering for å redusere utslipp, som drivhusgasser. Hvert elektriske kjøretøy drives av et batteri som kan inneholde gjenværende kapasitet etter første gangs bruk og flere potensielt verdifulle materialer. Etterspørselen etter stasjonære energilagringssystemer for å balansere fornybare energikilder og støtte nettinfrastrukturen øker behovet for disse batteriene ytterligere. Med tanke på de kommende volumene av brukte elbilbatterier, er en sirkulær økonomi for batterier avgjørende for å forbedre miljømessig og økonomisk bærekraft.

Forretningsmodeller for sirkulær økonomi tar sikte på å strategisk redusere ressursbruken ved å lukke, begrense og bremse materialstrømmer, noe som muliggjør økonomisk og miljømessig bærekraftig virksomhet. De potensielle miljøgevinstene ved en slik sirkulærøkonomi-innsats er imidlertid ikke eksplisitt.

Målet med dette arbeidet er å gi anbefalinger for global økonomisk og miljømessig bærekraft for brukte elbilbatterier ved å vurdere en sirkulær økonomi. Denne målsettingen krever en tverrfaglig tilnærming som bygger på eksisterende forskning og metoder innen forretnings- og ingeniørvitenskap. Den tverrfaglige tilnærmingen forhindrer problemskifting mellom miljømessig og økonomisk bærekraftytelse for de sirkulære forretningsmodellene som er identifisert og vurdert.

For å imøtekomme hovedmålet med arbeidet ble det utviklet fire forskningsspørsmål, og fire tilsvarende publikasjoner ble produsert som et resultat. Paper I utforsker markedsmuligheter og begrensninger for brukte elbilbatterier i Norge, et land hvor elbiler har den høyeste markedsandelen av nybilsalget. Arbeidet modellerer kvalitativt forretningsøkosystemet for brukte elbilbatterier basert på intervjuer med industrielle økosystemaktører. De globalt relevante funnene fra papir I identifiserer realistiske end-of-life-alternativer for papir II. Paper II identifiserer og diskuterer den globalt anbefalte sirkulære forretningsmodellen for å forbedre en sirkulær økonomi for batterier fra elektriske kjøretøy. Delphi-panelmetoden gjør det mulig for et

batteriekspertpanel å utdype en passende sirkulær forretningsmodell for de kommende volumene av brukte elbilbatterier. Paper III utfører en teknoøkonomisk vurdering av den identifiserte sirkulære forretningsmodellen fra papir II for å diskutere hvordan en slik forretningsmodell kan være økonomisk levedyktig og realistisk. Analysen vurderer flere scenarier for å oppdage økonomiske faktorer for suksess med den sirkulære forretningsmodellen. Paper IV utfører en livsløpsanalyse (LCA) av den identifiserte sirkulære forretningsmodellen fra paper II for å diskutere hvordan en slik forretningsmodell kan være fordelaktig for klima og miljø. Metodikk for livsløpsanalyser kan beregne miljøpåvirkningene av beslutninger mellom forretningsmodeller. Slike analyser kan oppdage eventuelle konflikter mellom miljøkategorier, som klimagassutslipp og miljøforurensning.

Forskningen viser at gjenbruk av elbilbatterier i hensiktsmessige second-life applikasjoner kan redusere deres miljøpåvirkning. Materialene må deretter resirkuleres i den grad det er mulig. Den sentrale miljøgevinsten kommer fra mulig reduksjonen i etterspørselen etter nye batterier, som kan bidra til å redusere global produksjon og unngå klima- og miljøpåvirkninger fra disse industrielle prosessene. Det er imidlertid en risiko for at denne sirkulære forretningsmodellen kan være økonomisk ulønnsom. Flere faktorer må vurderes for å forbedre lønnsomheten og realistisk kommersiell drift, inkludert batteriets tekniske tilstand, aldring, gjenværende mulig levetid, pris på brukte batterier, eierskap, lokasjon, passende second-life applikasjon, kobling til strømnett, og strømprofil. En kombinasjon av ulike strategier for energistyring bør utnyttes og tilpasses gitte faktorer for å maksimere den økonomiske avkastningen av gjenbruk.

Abbreviations

CBM	Circular Business Model
CE	Circular Economy
EOL	End-of-Life
EV	Electric Vehicle
EVB	Electric Vehicle Battery
LCA	Life Cycle Assessment
RQ	Research Question

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1 Introduction

1.1 A circular economy for batteries

In 2021, 16.5 million electric vehicles (EVs) were on the road, with rapidly rising sales (IEA, 2022a; Winslow et al., 2018) and each is powered by a battery. Lithium-ion batteries are the most common in EVs as they have relatively high power and energy density combined with a relatively long lifetime (IEA, 2022a; Opitz et al., 2017). These batteries are also important for storing renewable energies (Ericson and Statwick, 2018; IEA, 2022b; Market Observatory for Energy, 2021; United Nations, 2015). The electric vehicle batteries (EVBs) will eventually reach end-of-life **(**EOL) and the used batteries must be managed while enhancing sustainability through a circular economy (CE).

All EVBs contain materials where some are defined by the European Union (EU) as critical raw materials (a list of 30 materials that is continuously updated) based on their economic importance and supply risk (Koppelaar et al., 2023). If battery materials are released into the natural environment, they can cause pollution (Liu et al., 2019; Velázquez-Martínez et al., 2019). A CE aims to reduce waste and pollution by lowering the use of finite resources (Kirchherr et al., 2017), so the efforts to achieve circularity in the battery industry are genuine (Tsiropoulos et al., 2018; World Economic Forum, 2019; Yang et al., 2021). Moving towards a CE is often profitable by using material resources and energy more efficiently.

Recognized CE strategies include reducing, reusing, remanufacturing, refurbishing, repairing, cascading, and upgrading (Ellen MacArthur Foundation, 2022; Korhonen et al., 2018). Reusing and repurposing EVBs before recycling the materials are increasingly recognized as CE efforts because this can reduce the demand for new batteries (due to second-life batteries) and battery materials (IEA, 2022c; Koppelaar et al., 2023). While this thesis refers to reuse as a second life in the same type of application as originally produced for, repurposing ensures the battery obtains a second life in another application after use in an EV. Commonly, remanufacturing is required to prepare the used EVB for its second life in a new, stationary application (Pagliaro and Meneguzzo, 2019). Remanufacturing can, for example, entail disassembling a battery pack before reassembling several used EVB cells or modules into a second-life battery pack with greater total storage capacity to be used in a stationary application. The EVB pack consists of several modules consisting of several cells. Regardless of whether the lifetime of batteries is extended through reuse or repurpose, eventually recycling is crucial to attain materials that can be used in production of new batteries. Such CE efforts can lower the demand for primary materials, thus reducing total resource consumption (Diaz Lopez et al., 2019; European Commission, 2014).

1.2 Circular economy problem shifting

A circular business model (CBM) is a plan for how a business can sustain profits while reducing resource consumption and contributing to a CE. The circular aspect of the business model can (ideally) concentrate on the complete product life: from production to EOL or a specific life cycle stage (Geissdoerfer et al., 2020; Lüdeke-Freund et al., 2019; Urbinati et al., 2017). A few studies considered CBMs to manage used EVBs (Chirumalla et al., 2022; Jiao and Evans, 2016; Olsson et al., 2018). Despite the research on CBMs for EVBs, the electrification of mobility is still developing and will require more research, especially regarding assessing economic and environmental sustainability for decision-making support. Despite the intention of CBMs to be sustainable, problem shifting occurs between economic and environmental sustainability and between different environmental impact categories. This questions a CE’s ability to contribute simultaneously to both economically and environmentally sustainable development (Manninen et al., 2018; Rigamonti and Mancini, 2021; Saidani et al., 2019). Life cycle assessment (LCA) methodology is considered appropriate (Haupt and Hellweg, 2019; Ncube et al., 2022; Peña et al., 2021; van Loon et al., 2021) to assess the consequences of CE efforts (e.g., environmental sustainability of CBMs). LCA methodology can quantify environmental impacts and assess consequences for the natural environment and climate from various human activities (Curran, 2006). Equally, CBMs must be economically viable to be sustainable. A few economic assessments of battery CE efforts have been performed (Braeuer et al., 2019; Rallo et al., 2020; Yu et al., 2021), but not in a CBM context. Through environmental and economic assessments of EV battery business models, CE problem shifting can be avoided. The thesis aims to identify the most appropriate CBM for used EVBs and assess this CBM concerning its environmental and economic sustainability performance to provide recommendations for the EOL phase.

2 Literature review

2.1 Circular business models for electric vehicle batteries

A CBM is recognized as a type of sustainable business model (Bocken et al., 2014; Reinhardt et al., 2019). Bocken et al. (2016) view CBMs as business model strategies that suits a CE and aims to close, narrow, or slow relevant resource loops. This is a well-recognized and complete definition, as other research sometimes includes only one or two of these three strategies (Geissdoerfer et al., 2020). Although a CBM is a strategy from an organizational level, circular strategies require interactions within the value chain (Lüdeke-Freund et al., 2019). Thus, analyzing a business ecosystem and business model in combination is logical.

Reports on the EVB value chain provide numerical scenarios for the industry's growth and efficiency, confirming a growing battery industry (Campagnol, 2019; IEA, 2022c; Niese et al., 2020; World Economic Forum, 2019). Despite the battery volumes that will eventually reach EOL, only a few studies hold a solution-oriented approach to promote sustainability for EVBs through CE. Sustainability is needed to advance economic growth while preserving the environment (United Nations, 2023), which can be enhanced through a CE. A CE is commonly presented with the 3R framework: reduce, reuse, and recycle to reduce the use of non-renewable resources (Kirchherr et al., 2017). Existing studies illustrate different approaches to mapping CE opportunities for EVBs. Recently, Schulz-Mönninghoff et al. (2023) mapped how much more circular EVBs can become using material flow analysis and discussed business models as having the potential to enhance circularity. Their findings showed that business models, including remanufacturing, will improve an organization's material circularity. Chirumalla et al. (2022) held a multiple-stakeholder approach when seeking business opportunities with used batteries from buses. Their main goal was to generate a win-win for several actors within the supply chain. Several challenges to identifying CBM opportunities for EVBs were found, including mapping the ecosystem actors to understand how stakeholders see each other. The business ecosystem pie model (Talmar et al., 2020) is useful to cover the gap of used EVB ecosystem mapping. This model is developed to map, innovate, and strategize for a business ecosystem – a network of organizations working for a common output (e.g., sustainable EOL treatment of EVBs). The ecosystem pie modelling approach was not applied to the battery industry before Hellström and Wrålsen (2020, n.d.), despite the recognized benefit of understanding risks and network dependencies among CBMs. The study applies the pie model (Talmar et al., 2020) to explore market opportunities and limitations for used EVBs from Norway. The country has in 2021 the highest market share (86%) of electric cars in new car sales in the world and the current national car deposit system for collection and EOL management is efficient (Hellström and Wrålsen, 2020; IEA, 2022a). This market is therefore relevant and interesting to study in terms of EVBs, but Hellström and Wrålsen (2020; n.d.) focus on globally relevant market dynamics to detect realistic CBMs in Wrålsen et al. (2021).

A few studies explored EOL business models for EVBs using interviews, workshops, and structured literature reviews as research methods (Jiao and Evans, 2016; Olsson et al., 2018; Reinhardt et al., 2020). Already in 2016, Jiao and Evans did a multiple-case study analyzing existing business models handling EOL batteries in China, Japan, and the USA and the potential effects of reusing or repurposing. They found that battery ownership, partnerships, and policy support are key to enhancing the CBMs. In 2018, Olsson et al. found that the stakeholders they interviewed saw potential in reusing and repurposing EVBs but identified barriers, such as resistance to allocating resources to the new business model. Reinhardt et al. (2020) identified different sustainable business model types for EVBs through a multiple-case study. The CBMs for batteries were found to be an integrated part of the business activities, motivated by profit and sustainability. Albertsen et al. (2021) examined current CBM practices among EV manufacturers through interviews, observation, and secondary data. Their findings suggest that EV manufacturers focus mostly on repairing, refurbishing, and repurposing. Guldmann and Huulgaard (2020) categorized barriers to CBM innovation and found that barriers at the market and institutional and value chain level are the most critical. Despite this, CBM assessment at the value chain level is lacking for EVBs. Before Wrålsen et al. (2021), the advanced Delphi panel method was new to the business model research field and battery context. Existing studies mainly hold an organizational-level approach at CBMs, while

Wrålsen et al. (2021) are relevant for policy-makers and several actors in the battery value chain.

2.2 Assessing circular business models

A business model's primary goal is to provide economic security by executing a strategy (Richardson, 2008). Financial viability is essential to secure a sustainable business model. Various economic analysis methods can be applied to assess profitability's potential. Previous studies performing economic analysis on energy storage systems with used batteries are case- or application-specific and with varied findings (Braeuer et al., 2019; Fallah and Fitzpatrick, 2022; Kamath et al., 2020; Rallo et al., 2020; Yu et al., 2021). Braeuer et al. (2019) conducted an economic analysis of battery energy storage system investment in Germany. Three strategies were examined: peak-shaving, primary reserve control, and electricity arbitrage. The last was the least lucrative, which may be attributed to the low price spread in the German day-ahead and intraday continuous market utilized for electricity arbitrage.

Conversely, Rallo et al. (2020) examined two real-life examples in Spain and determined that arbitrage was the most profitable strategy, as it indirectly enabled peak shaving. When electricity trading is frequent, resulting in a higher cash flow, the payback time on investment can decrease (Fallah and Fitzpatrick, 2022). For projects including the increased self-consumption of solar energy, Kamath et al. (2020) indicated a correlation between economic gains and solar irradiation. These studies contributed to understanding in which cases repurposing EVBs is economically viable.

Previous studies primarily aimed to assess the case rather than identify the factors affecting the economic viability of EVBs. Multiple scenario analysis is useful for generating generalizable findings, such as crucial model parameters, because numerous scenarios are tested. Wrålsen and Faessler (2022) perform a multiple-scenario analysis to identify globally generalizable factors for the economic viability of second-life battery investment (the CBM). Pagliaro and Meneguzzo (2019) illustrate several projects with used EVBs, but the scope and number of these have significantly increased since 2019. Existing research shows potential for economically viable battery repurpose projects; however, the investment cost and poor use of energy management strategies to generate economic value are two crucial barriers (Lombardi and Schwabe, 2017; Xu et al., 2016).

Technical parameters must be included in the economic analysis of battery systems because they significantly affect the results. Used battery performance is not well covered in current literature, but the number of cycles during operation is considered an important factor (Martinez-Laserna et al., 2018b; Quan et al., 2022). Cycle lifetime and calendar ageing are the recognized types of battery ageing, which is crucial for second life (Martinez-Laserna et al., 2018a). Several factors affect ageing, such as operation incentives and climate conditions.

CBMs intend to contribute to economic and environmental sustainability aligning with a CE (Nußholz, 2017). Environmental sustainability can be improved through CBMs due to the potential of reducing resource consumption through effectively using materials and energy (Canals Casals et al., 2019; Saidani et al., 2019). Simultaneously, existing research suggests that such CE efforts must often be assessed because of unintended consequences and problem shifting that can hinder environmentally sustainable development (Manninen et al., 2018; Rigamonti et al., 2017; Saidani et al., 2019). Problem shifting among environmental impact categories means, for example, if a new technology reduces greenhouse gas emissions but increases the pollution of freshwater. Zink and Geyer (2017) also illustrate the problem-shifting concept in their findings of CE rebound effects. The study showed that CE efforts could have unintended market consequences, affecting supply and demand and leading to unchanged or even increased consumption. Considering the CE rebound effect, repurposing batteries may lead to increased consumption of batteries instead of reduced demand for primary production. Fortunately, LCA methodology can examine several environmental impact categories (water use, greenhouse gas emissions, ecotoxicity) and can, therefore, detect potential problem shifts in a CE (Curran, 2006; Peña et al., 2021) for EVBs.

Previous LCA work suggests that repurposing batteries instead of purchasing new batteries can reduce environmental footprints (Ahmadi et al., 2017; Bobba et al., 2018; Cusenza et al., 2019; Ioakimidis et al., 2019; Kamath et al., 2020; Philippot et al., 2022; Richa et al., 2017; Schulz-Mönninghoff et al., 2021; Wang et al., 2022; Wilson et al., 2021; Yu et al., 2021). However, these do not 1) apply the methodology to explicitly assess CBMs, 2) include the market approach required to consider the potential for reduced demand and avoided production, 3) contain primary data for all remanufacturing processes, and 4) compare repurposing from the battery module and pack level. Schulz-Mönninghoff et al. (2021) applied LCA to assess CBMs in the battery context but aimed to integrate energy flow modelling in LCA rather than advancing the methodology for substitution coefficients. Wrålsen and O'Born (2023) assess the environmental consequences of EVB repurposing, considering the environmental sustainability potential of the highest-ranked CBM from Wrålsen et al. (2021).

2.2 Summary table

The existing research on CBMs and related circular strategies for economically and environmentally sustainable EOL management of EVBs is relatively new and limited because the electrification of vehicles is at an early stage considering the planned future scale. Table 1 shows the state-of-the-art research on the thesis topic, including the four papers of this thesis. The studies mostly cover repurposing or recycling batteries in a CE with a business model, economic, or environmental approach. The table also illustrates the range of research methods required to answer the thesis objective.

Table 1: Summary of the state-of-the-art literature.

Reference of the study	Year	End-of-life scope		Research method							
		Repurpose	Recycling	Economic modelling	Energy modelling	Delphi-panel	Life cycle assessment	Research-through-design approach	Material flow analysis	Structured literature review	Interview
Ahmadi et al.	2017	X			X		X				
Al-Wreikat et al.	2022	X		X	X						
Bobba et al.	2018	X			X		X			X	
Braueuer et al.	2019			X	X						
Chirumalla et al.	2022	X	X					X			
Cusenza et al.	2019	X			X		X				
Fallah and Fitzpatrick	2022	X		X	X						
Hellström and Wrålsen	Submitted	X	X								X
Iokaimidis et al.	2019	X					X				
Jiao and Evans	2016	X									X
Kamath et al.	2020	X		X			X				
Manninen et al.	2018	X	X								X
Martinez-Laserna et al.	2018	X								X	
Olsson et al.	2018	X	X								X
Philippot et al.	2022	X					X				
Rallo et al.	2020	X		X	X						
Reinhardt et al.	2019	X								X	
Reinhardt et al.	2020	X								X	
Richa et al.	2017	X	X	X			X				
Schulz-Mönninghoff et al.	2021	X			X		X				
Schulz-Mönninghoff et al.	2023	X	X						X		
Wang et al.	2022	X	X				X				
Wilson et al.	2021	X					X				
Wrålsen and O'Born	2023	X					X				
Wrålsen and Faessler	2022	X		X	X						
Wrålsen et al.	2021	X	X			X					
Yu et al.	2021	X	X	X			X				

3 Aim of the thesis

Considering the research gaps in chapter 2, this thesis aims to examine how batteries used in EVs can be managed as economically and environmentally sustainable after EOL. First, there was a need to study the business ecosystem of EVBs to identify opportunities and limitations in the market, such as stakeholder dependencies and risks. Second, the ecosystem mapping was used to identify and discuss the most likely CBM for these batteries. Third, the economic and environmental sustainability of the most likely CBM is assessed to avoid CE problem shifting. The aim of the thesis requires different disciplines and methods to propose a recommended CBM for used EVBs and to assess both environmental and economical sustainability of the recommended business model. The aim is to provide globally relevant recommendations.

Four research questions (RQs) were required to answer the main aim of the thesis: “How can used electric vehicle batteries be managed economically and environmentally sustainable?” Figure 1 presents the required steps and order of the thesis work, followed by the complete set of RQs. Each RQ studied resulted in a paper. RQ 1 resulted in paper I; RQ 2 in paper II; RQ 3 in III; and RQ 4 in IV.

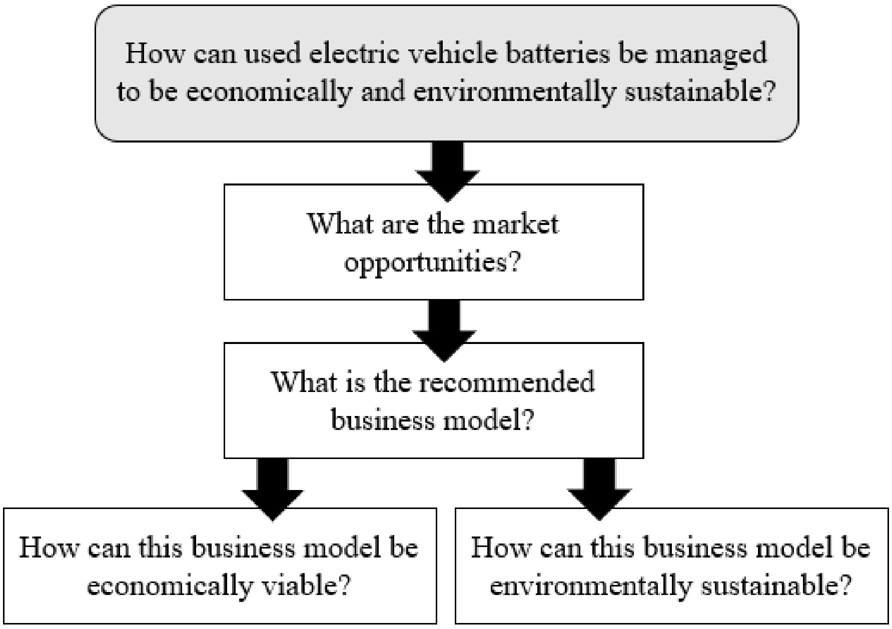

Figure 1: Aim of the thesis.

The thesis research covers current knowledge gaps by answering the four RQs:

1. What market opportunities and limitations exist for used EV batteries?
2. What is the recommended CBM for used EV batteries?
3. How can this CBM be economically viable?
4. How can this CBM be environmentally sustainable?

4 A note on interdisciplinarity

During the early thesis work, the complexity of the used EVB ecosystem implied a need for several disciplines to examine the realistic and environmentally preferred CBM. Thus, the work required several research methods: in-depth qualitative information (interviews), global battery expert perspectives (Delphi panel), a review of how the proposed CBM can be economically viable (techno-economic assessment), and a review of how the proposed CBM can be environmentally sustainable (life cycle assessment). Thus, the thesis work required research methods from research fields within a CE, business management, environmental and engineering science, cost analysis, and basic electrical engineering. The thesis papers (I–IV) detail each method applied. Figure 2 visualizes the thesis' research methods and the outcomes of using them. The figure shows how the methods from different disciplines are connected to answer the thesis's four RQs. The four steps represent the four RQs and the four papers of this thesis. The bottom grey box shows the main thesis outcome.

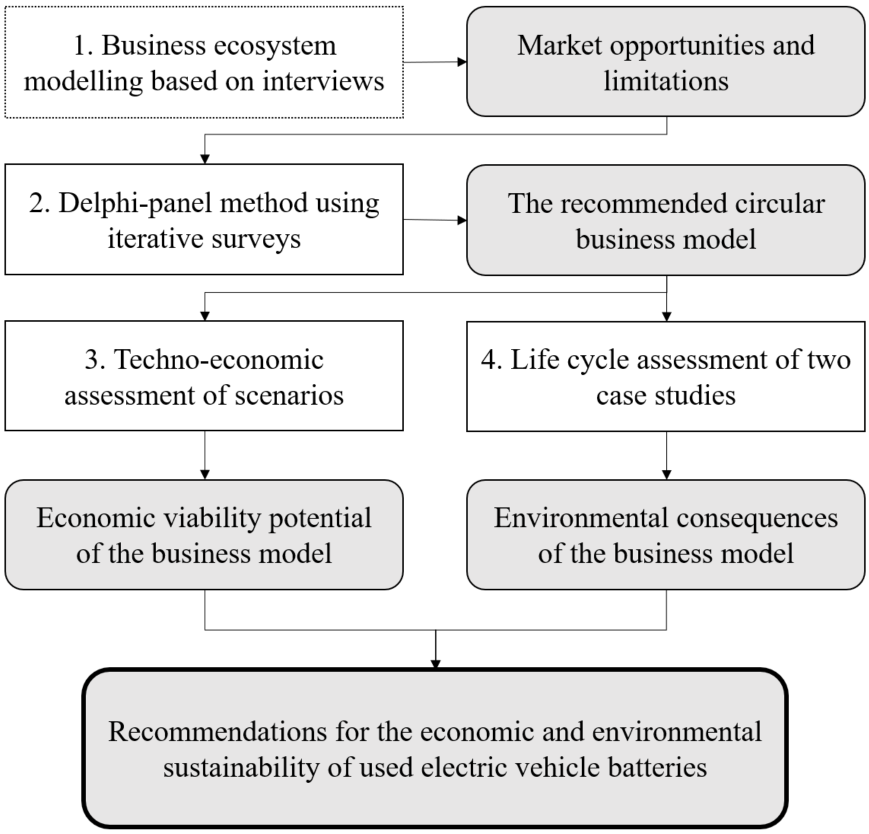

Figure 2: Illustration of thesis research steps using methods (white boxes) from different disciplines to reach the outcome (grey boxes).

The business ecosystem modelling was required to map the market dynamics and identify CBM opportunities and limitations (paper I). Based on these findings, potential CBMs could be identified and ranked (paper II). The techno-economic assessment was required to understand a used battery's technical capabilities and its related practical limitations due to technical and economic factors. If a business model is unsuitable for the intended market or is not economically viable, the business will not endure. That is why economic viability is assessed as part of the thesis work (paper III): to make realistic predictions about suitable CBMs for EVBs. Simultaneously, the environmentally sustainable management of the eventually large numbers of EVBs (paper IV) must be prioritized to secure a future supply of raw materials and the availability of high-capacity batteries to store renewable energies. The urgent need to mitigate climate change and protect the natural environment is increasingly acknowledged and globally shared interests. Without environmental gain, no incentive would exist to promote this CBM over a linear business model.

Interdisciplinarity means different disciplines are used to address a system problem. Perspectives of one discipline are then applied in another discipline, ultimately aiming to contribute to solving the system problem (Stock and Burton, 2011). The interconnected factors of the economy and environment require an interdisciplinary approach to reach relevant sustainability recommendations (Martini et al., 2021) for the EOL of EVBs. The interdisciplinarity approach in this thesis considerably contributes to existing research as it contributes to solving a complex system problem of used EVB management. Cooperating with other researchers from different disciplines and training in the methods used were necessary strategies to adopt the different schools of thought from the engineering sciences, economics, and business. This interdisciplinary approach to identifying and assessing CBMs for EVBs is unique. Achieving environmental and economic sustainable development requires cooperating across disciplines (Hopton et al., 2010).

5 Results and discussion

The results and discussions in section 5.1 are connected to RQ 1 and chiefly related to paper I (Hellström and Wrålsen, n.d.). This paper is based on a report (Hellström and Wrålsen, 2020) from early thesis work related to the BATMAN project (Lithium-ion BATteries – Norwegian opportunities within sustainable EOL MANagement, reuse, and new material streams). The results and discussions in section 5.2 are linked to RQ 2 and largely associated with paper II (Wrålsen et al., 2021). The results and discussions in section 5.3 are connected to RQ 3 and primarily related to paper III (Wrålsen and Faessler, 2022). The results and discussions in section 5.4 are linked to RQ 4 and mainly associated with paper IV (Wrålsen and O'Born, 2023).

5.1 End-of-life opportunities and limitations

Business ecosystem modelling can help one understand the actors' roles within the system, which is crucial to identify CBM opportunities for EVBs (Chirumalla et al., 2022). The ecosystem modelling in Hellström and Wrålsen (paper I) **(**n.d.), based on Hellström and Wrålsen (2020), focused on the findings that are globally relevant to gain the knowledge needed to continue with the Delphi panel research (paper II) and the thesis's aim of globally relevant recommendations. Findings show systemic dependencies among the used EVB ecosystem actors. These dependencies potentially restrict the idealistic (i.e., the most environmentally and economically viable) CBM. One example of an ecosystem dependency is the required competence within safe battery handling and a state-of-health check before the second life – processes needing rear competence and human skills (Faessler, 2021). Several of these remanufacturing processes require human labor, but ongoing research exists for increased automatization by, for example, Choux et al. (2021). The ecosystem model reveals that three actors have more power than the others in the used EVB ecosystem: 1) the EV manufacturer, due to the battery management system control, which is crucial for repurposing; 2) car dismantlers, who channel the used batteries; and 3) the extended producer responsibility contractor, assuring secure EOL treatment aligns with the law on extended producer responsibility on a mission from the producer who is placing the battery on the market (Batteriretur, 2021; Ekvall et al., 2016). The battery's

CBM opportunities potentially depend on the car- and battery dismantlers, who are responsible for distributing the batteries for safe EOL treatment. The car and battery dismantlers are the collectors in Norway, who are crucial to managing a CE (Urbinati et al., 2017). Cooperating with these central actors to achieve the ecosystem goal (e.g., sustainable repurposing EVBs) is currently crucial for the EVBs from Norway. In other countries, car manufacturers are in some cases more directly involved in the EOL management and can be an alternative key partner. Cooperation among key actors enhances a CE for EVBs (Albertsen et al., 2021; Schulz-Mönninghoff et al., 2023).

In battery business ecosystems there is a growing trend of vertical integration in various areas, specifically to 1) secure a steady supply of raw materials for primary production and 2) manage production scrap and EOL waste as sustainably as possible. The original equipment manufacturer will have more control of operations in cases of vertical integration (Hellström and Wrålsen, 2020; n.d.). If one actor runs several of the repurpose processes, enabling CBMs because they control the operations can be easier. Vertical integration was recently considered a success factor for battery manufacturers (Bechberger et al., 2022). Thus, the ecosystem dependencies can be reduced. Nevertheless, having systemic changes and collaboration among stakeholders is essential to overcome the challenges of implementing CBMs (Hellström and Wrålsen, 2020; n.d.).

Traceability along the supply chain becomes easier in cases of high vertical integration. Traceability is an incentive to enhance a CE for EVBs (IEA, 2022c). Europe is making efforts to implement a digital passport for each battery produced that collects information throughout the battery lifetime at a cloud platform that can be accessed through a quick response (QR) code. Relevant information includes materials and their origin and user history. When the batteries reach EOL, they can more efficiently be collected and sorted with artificial intelligence (AI) based on the passport information (Plociennik et al., 2022). The batteries with remaining capacity can be reused in a suitable application before optimizing the recycling of the materials based on available recycling technology (Koppelaar et al., 2023).

Hellström and Wrålsen (2020; n.d.) show that repurposing the used battery modules or packs and recycling the materials are possible CBMs. Business models that include remanufacturing, will improve material circularity (Schulz-Mönninghoff et al., 2023). However, findings show that the battery ownership model has a crucial role in the business model of EV manufacturers and will significantly impact the business ecosystem. Batteries can be owned by the EV manufacturer, EV owner, or a third party, such as a car distributor, that offers leasing agreements (Martinez-Laserna et al., 2018a). Despite a trend towards vertical integration, most ownership models will likely retain the EV owner or a third party as the battery's owner, according to the sources interviewed (paper I). Thus, the used EVB ecosystem modelling showed that the ownership model would affect the opportunities and limitations for repurposing.

5.2 Circular business models for electric vehicle batteries

The findings from the EVB ecosystem modelling (Hellström and Wrålsen, n.d.) relevant outside Norway were used to conceptualize the Delphi panel study. In this study, Wrålsen et al. (2021) adopted a holistic and problem-solving approach when establishing a Delphi panel to rank and elaborated on the most appropriate CBMs for batteries (Okoli and Pawlowski, 2004). The battery experts were from different countries in Europe, North America, and South America. Thus, the findings from paper II are particularly relevant for these parts of the world.

Findings suggest that implementing CBMs can help organizations recover economic value from used EVBs while potentially decreasing their environmental impact. The CBM with the highest potential to recover value, according to the battery experts, are 1) "Remanufacture + reuse + recycle + waste management (disposal)"; 2) "Product life extension by durable design, update services, remanufacture"; and 3) "Resource recovery of discarded materials". Thus, the CBM for used EVBs ranking the highest was repurposing before recycling, proposing an extended lifetime (Wrålsen et al., 2021). The expert panel suggests that using multiple circular strategies in one CBM can be beneficial. Earlier case studies confirm the high interest in repurposing EVBs and that this is a CE strategy EV manufacturers pursue (Jiao and Evans, 2016; Olsson et al., 2018; Reinhardt et al., 2020). However, the level of manufacturer involvement varies, shaping the opportunity and choice of appropriate CBM (Albertsen et al., 2021). The most effective CBMs will depend on factors such as market conditions, available infrastructure, and the ecosystem actors' dependencies (Hellström and Wrålsen, n.d.).

According to the Delphi panel experts, the main barrier to CBM success was financial (Wrålsen et al., 2021). This aligns with findings from Guldmann and Huulgaard (2020), who detected barriers at the market, institutional, and value chain level as the most critical for CBM innovation. The financial barrier can be addressed regarding cost and income potential. The battery investment cost is highlighted as a challenge (Xu et al., 2016), although the market price for a second-life battery is lower. Different energy management strategies, such as electricity arbitrage, can improve the income potential (Wrålsen and Faessler, 2022). In 2018, Olsson et al. identified that resistance to allocating resources to the CBM was a barrier to success. However, this may have evolved in just a few years, along with market battery second-life efforts (Albertsen et al., 2021).

The Delphi expert panel ranked governments, then car manufacturers, as the most important stakeholder (Wrålsen et al., 2021). The main drivers for a CBM's success that was recognized was national and international regulations and policies. As the battery industry continues evolving, the importance and necessity of regulations have become increasingly apparent. These regulations not only influence research and development efforts but shape business decisions. One example is the EU's battery regulation, which proposes stricter guidelines for the minimum use of recycled materials in battery manufacturing. For second-life batteries, agreement exists among stakeholders and the European Commission that market forces should determine the future of battery reuse and repurpose (European Commission, 2020). Wrålsen et al. (2021) illustrate the study's relevance for policy-makers and several actors in the EVB ecosystem to promote a CE by enabling an international Delphi panel to rank and comment on CBMs for EVBs.

5.3 Economic viability

Wrålsen et al. (2021) did not consider the economic viability of the recommended CBM (repurposing before recycling), yet this was identified as the most crucial component for CBM success. Therefore, Wrålsen and Faessler (2022) identified critical factors for the economic viability of battery repurposing. This techno-economic assessment revealed factors to achieve the highest economic potential with the CBM. The factors were identified through a multiple-scenario analysis with different European countries. The findings are relevant globally as correlations between variables are discussed instead of only providing country-specific factors. For example, the results showed that the locations with high solar irradiation had the highest economic income with increased self-consumption of solar energy.

The multiple scenarios simulated included several energy management strategies. For the electricity arbitrage scenario, the regional electricity price and fluctuations in price were important factors identified. As other researchers mentioned, energy management strategies should be chosen based on location and context (Madlener and Kirmas, 2017; Neubauer et al., 2015). Also, combining several energy management strategies can increase the economic viability of the CBM (Wrålsen and Faessler, 2022). The power usage profile of a manufacturer should align with the most suitable strategies (Braeuer et al., 2019).

Wrålsen and Faessler (2022) simulated the number of charge cycles during battery operation, which previous research recognized as important (Metz and Saraiva, 2018). Results show the expected lifespan of a new battery was 5 to 15 years and 3 to 10 for used. For the CBM to be economically viable, the expected second-life battery lifetime must be greater than the expected payback time on investment. Furthermore, Wrålsen and Faessler (2022) showed that the shortest payback time on the investment of all scenarios assessed was 7 years in Spain with increased self-consumption of solar energy. A newer study considering used EVBs found that the lowest payback time was also 7 years (Al-Wreikat et al., 2022). The study was of a United Kingdom household – a different context than the one studied in this thesis. Wrålsen and Faessler (2022) showed that the most financially advantageous scenarios had the highest number of charge cycles, suggesting that a battery lifetime under 7 years will result in no economic gain. Choosing a healthy second-life battery can decrease the payback time from 0.5 to 2 years due to a lower initial investment cost.

Wrålsen and Faessler (2022) and previous thesis work (papers I, II, and III) identified factors important for economic viability of the battery repurpose CBM. Table 2 shows a summary and discussion of the main factors. The factors are particularly relevant to consider for manufacturers considering investing in energy storage and for energy management policymakers. For companies responsible for managing and developing electrical grids, investing in battery energy storage systems can replace the need for other expenses like power plants, as they help balance energy supply and demand. This could financially motivate providing incentives for businesses investing in battery energy storage systems connected to the grid.

Table 2: Summary of the main factors affecting the economic viability of battery repurposing.

Prices. Hellström and Wrålsen (2020; n.d.) identified the battery selling price as a factor for who purchases the battery and whether the battery is repurposed before the materials are recycled. Zink and Geyer (2017) also recognized that used product prices affect the market dynamics. For example, if the used EVB with the same quality as the new is cheaper, the demand for second-life batteries will increase.
Ownership. According to Martinez-Laserna et al. (2018a), a battery can be owned by the EV manufacturer, EV owner, or a third party (e.g., a car distributor). Jiao and Evans (2016) identified the battery ownership models for their studied case companies and found that the ownership models vary. Depending on the regional EV collection system, the ownership model should be an integrated and strategic part of the CBM (Hellström and Wrålsen, 2020; n.d.). For example, the battery owner can often decide who it is sold to after use, and different owners have different interests.
Ageing. In the techno-economic assessment of second-life applications, Wrålsen and Faessler (2022) simulated the number of charge cycles for the different scenarios. Based on the findings, the lifetimes were estimated,

illustrating how important operation incentives are for ageing and economic viability. For example, if the payback time of investment is longer than the expected battery lifetime, the investment is discouraged. Braco et al. (2020) studied parameters affecting ageing and found that the batteries from EVs cycled 2033 times (5 years in the studied application) before reaching the “ageing knee”, where ageing speeds up dramatically. A general recommendation has been that the battery pack should be replaced when 20% of the original remaining capacity is lost. However, this is increasingly questionable as EV battery pack sizes increase and performance and monitoring technology improve (Zhu et al., 2021).
Location. Repurposing applications for used EVBs can include energy management strategies such as storage of renewable energies with increased self-consumption, arbitrage electricity price trading, and peak-shaving to balance the electricity demand over time (Braeuer et al., 2019; Rallo et al., 2020). Wrålsen and Faessler (2022) compared economic performance based on different energy management strategies and locations. Findings reveal that country-specific characteristics such as electricity prices and solar irradiation are crucial when choosing the appropriate CBM. For example, low electricity price fluctuations in Norway lead to poorer economic gain for energy arbitrage (storing electricity from the grid when the price is low and consuming from the battery when the market price is high).

5.4 Environmental sustainability

The CBM must be economically viable to be realistic (except for incentivized or pilot projects) (Wrålsen et al., 2021). As a CBM is a type of sustainable business model, it also aims to reduce environmental burden. A CBM causing problem shifts between economic and environmental sustainability is insufficient. Previous research has shown that the actual environmental impacts of CBMs are not explicit (Manninen et al., 2018; Saidani et al., 2019). Therefore, after identifying the recommended CBM for EVBs (Wrålsen et al., 2021) and the potential for economic viability (Wrålsen and Faessler, 2022), Wrålsen and O’Born (2023) investigated the environmental consequences of the CBM. LCA methodology was applied to calculate environmental impacts as it can enhance a CE (Peña et al., 2021). LCA results can indicate potential problem shifting between environmental impact categories. The resulting thesis paper (IV) compares the impacts of second-life EVBs with new batteries to support future decision-making (Yang and Heijungs, 2018). The findings are globally relevant because the data used for the new battery hold a global perspective. The electricity used to remanufacture the used EVBs is modelled with the Norwegian market mix, but the electricity consumption is small. Therefore, if the remanufacturing is performed with another electricity market mix, the results will only change marginally and should not change the study's recommendations (for similar system dimensions).

Findings show that investing in a remanufactured battery instead of a new one is recommended if 1) the battery still has enough capacity for the intended use (technical quality) and 2) the used battery is not chosen only because it is cheaper than a new one but is the preferred option over a new battery (market value of remanufactured batteries versus new). If these two points are fulfilled, one can assume the used battery, to some extent, replaces a new one, reducing demand for new batteries and avoiding future production. This can eventually lead to avoided emissions in the environmental impact calculation, implying a real contribution to a CE for batteries. A used EVB's ability to replace a new one is key for the LCA impact results, highlighted by too few studies (Vadenbo et al., 2017; Vandepaer et al., 2019). If the used EVB is able to replace a new and therefore decrease demand of a new battery by >16%, it is recommended in a climate change mitigation perspective (Wrålsen and O'Born, 2023). This recommendation aligns with Schulz-Mönninghoff et al. (2021), who found that repurposing is the most environmentally beneficial CBM for vehicle manufacturers. Most LCA studies examining reusing or repurposing batteries found this can reduce product environmental footprint; however, the lack of primary data and inclusion of the substitution coefficient calculation left a research gap for EVBs before Wrålsen and O'Born (2023). For batteries, the substitution coefficient is significant for repurposing assessments as the potential for reducing demand can be higher than for recycling the materials.

The substitution coefficient implies the specific expected reduction in demand due to a decision (e.g., choosing the repurposed CBM for a battery). For example, if the second-life EVB with 80% remaining capacity is assumed to replace 80% of a new battery, the calculation (depending on the scope) could subtract 80% of total emissions from a new EVB. Figure 3 illustrates this substitution concept in LCA methodology. In the example, the box with the stippled line would represent 80% avoided production that would be subtracted from the calculation.

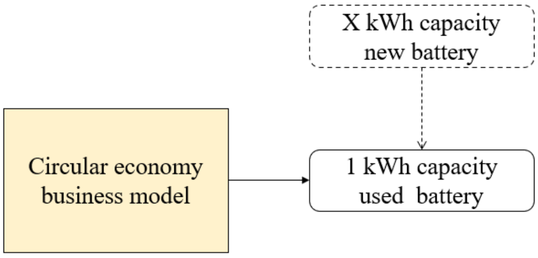

Figure 3 illustrates the substitution concept. The stippled line represents the potential for avoided production.

LCA was used to quantify the future environmental consequences of the CBM choice in Wrålsen and O'Born (2023) to advance the LCA methodology for substitution calculation in the battery context. The methodology from Rigamonti et al. (2020) and Zink et al. (2016) was applied and adjusted for the battery context. Insight into the EOL market is required to determine how much a used battery can replace a new one (Rigamonti et al., 2020) (e.g., through business ecosystem modelling), which is why Hellström and Wrålsen's (n.d.) work was crucial for Wrålsen and O'Born's (2023) environmental assessment. Findings show that the remaining battery capacity was the main technical factor in determining the coefficient. The price of new versus used EVBs was an equally important market factor. Combining these factors with equal weighting identified the substitution coefficient (Wrålsen and O'Born, 2023).

As expectations of transparency and the reporting of carbon and other environmental footprints are increasingly emphasized and already existing, the assumptions made for avoided production are increasingly important. Calculating the substitution coefficient is challenging as it is partly based on future predictions of avoided production (Chalmers et al., 2015). Nevertheless, the potential for avoided production should be identified through a substitution coefficient for each particular study, ideally by including technical and market factors. Wrålsen and O'Born's (2023) approach can be applied to other products or product components by LCA practitioners. Understanding how business model characteristics affect market prices can clarify the dynamics and improve assumptions of the substitution coefficient applied.

6 Conclusion

CE efforts for batteries can lower environmental impacts by reducing the total consumption of non-renewable resources. Mapping the EVB ecosystem allowed for an understanding of market opportunities and limitations for CE efforts of used EVBs (paper I). The EOL treatment operations must be economically sustainable to be realistic. Therefore, a business model perspective is appropriate in this context as it aims to generate a plan for how operations can secure higher income than costs. A CBM is a type of sustainable business model relevant to CE efforts such as repurposing and recycling. Using the Delphi panel method, a battery expert panel ranked the CBMs (paper II) proposed to them based on the ecosystem modelling (paper I). Findings showed that repurposing before recycling was recommended globally, but economic viability might be challenging. Despite the goal of a CBM to be both economically and environmentally sustainable, potential problem shifting can disrupt the sustainability. Also within environmental sustainability conflicts appear between impact categories. Such conflicts can cause problem shifts in a CE. CBMs must be quantitively assessed to avoid problem shifts and make as realistic recommendations as possible. Techno-economic assessment with multiple scenarios is an appropriate approach to examine how the recommended repurposing business model (paper II) can be economically viable (paper III). LCA methodology is appropriate to examine how the recommended repurposing activity (paper II) can be environmentally sustainable (paper IV).

In conclusion, batteries used in EVs can reduce their environmental footprint by being repurposed in a second-life application to extend their lifetime. This CBM's main potential environmental benefit is if the battery repurposing activity reduces the demand for new batteries and displaces primary production, causing avoided environmental impacts. However, there is a risk for poor economic viability for the CBM, although several factors can enhance the required profitability: battery state-of-health after first life, ageing and lifetime, price of a used battery, ownership of battery, and location and electricity profile of the battery system. For maximum financial income of battery repurposing, a combination of different energy management strategies should be considered suitable for the second-life application.

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Appendix: Papers

Paper I

Towards a circular business ecosystem of used electric vehicle batteries – A modelling approach

Magnus Hellström and Benedikte Wrålsen

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Paper II

Circular business models for lithium-ion batteries - Stakeholders, barriers, and drivers

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Circular business models for lithium-ion batteries - Stakeholders, barriers, and drivers

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ABSTRACT

Business models for the circular economy, or circular business models, is a growing field of research applied in various industries. Global sustainability trends, such as electrification of the transport sector and increased energy consumption from renewable sources, have led to rapid growth in the number of batteries produced, especially lithium-ion based batteries. Sustainable lifetime management, including end-of-life, needs development to avoid social and environmental harm and potentially to recapture economic value as the use of these batteries increases. Current research primarily focuses on technical and economic issues based on recycling and the second use of batteries rather than circular business models. This study's purpose is to explore the circular business models, drivers, barriers, and stakeholders required to enable value recapturing. The Delphi panel method was applied to communicate with battery experts from various disciplines. The study's findings reveal that the favored circular business model includes several circular strategies. According to the expert panel, the most critical driver is national and international regulations and policies; the most critical barrier is financial viability; the most critical stakeholders are governments and vehicle manufacturers.

1. Introduction

Governments, institutions, businesses, and consumers need to join forces as the global society moves towards increased sustainability to achieve meaningful targets such as the United Nation's (UN) Sustainable Development Goals (SDG) (United Nations, 2015). Working towards achieving these goals represents an opportunity to implement the Circular Economy (CE) and transition towards low-carbon societies. This transition relies on increasing renewable energy production on the supply side and electrification on the demand side, especially within the transport sector. Electrifying the transport sector inevitably requires an increase in battery energy storage systems' production capacity to supply an increasing share of electric vehicles (EV) (Winslow et al., 2018; Zhang et al., 2018). In 2019, the total global electric vehicle (excluding two- and three-wheelers) stock was already above 7 million vehicles and is estimated to increase to nearly 140 million by 2030, which implies 7% of the total vehicle fleet (IEA, 2020). Lithium-ion batteries (LIB) are the most-used energy storage system in EVs due to their high energy and power densities (Opitz et al., 2017). The EV demand is largely expected to continue contributing to growth in LIB production (Winslow et al., 2018). However, the increased use of LIBs comes with several challenges. They are hazardous, and their projected demand will increase the need for raw materials that may not be sustainably available. Hence, their increased use can cause environmental and social damage, and be economically challenging if not handled responsibly. CE implementation is critical to establish practicable, commercially viable, or financially profitable solutions in this field (Yang et al., 2021). Within a CE framework, for example, the second use of batteries can potentially reduce battery waste and contribute to future (renewable) energy storage needs (Ahmadi et al., 2014; European Commission, 2019; Kamath et al., 2020a). Implementing second use batteries and improving recycling rates will require overcoming economic and technical barriers. Companies can overcome these barriers by adopting Circular Business Models (CBM) and implementing circular strategies, such as second use, as part of their core business activities.

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Abbreviations

CBM	Circular Business Model (–)
CE	Circular Economy (–)
EOL	End-of-Life (–)
EV	Electric Vehicle (–)
LIB	Lithium-ion Battery (–)
RQ	Research Question (–)
SDG	Sustainable Development Goal (–)
UN	United Nations

Recent academic literature focuses on economic and technical studies of second use LIBs (Beverungen et al., 2017; Heymans et al., 2014; Martinez-Laserna et al., 2018) rather than on CBMs. Adopting a business model perspective would help us better understand how to enable an economically viable, circular use of batteries. Research on CBMs for LIBs is scarce and has relied on literature reviews and multiple-case studies (Jiao and Evans, 2016; Olsson et al., 2018; Reinhardt et al., 2020). As second use and recycling of EV LIBs have not reached industrial scale, these studies typically report from pilot studies or simulations based on available information. For example, Swain (2018) developed a theoretical analysis that suggests combining two cost-effective and environmentally sustainable processes, such as reverse osmosis and lithium carbonate precipitation, to recover lithium from wastewater that derives from the LIB recycling industry. While these studies provide us with an idea of what the alternative CBMs may be (and their key characteristics), we know little about which CBMs are likely to succeed, for what reasons, and which stakeholders will play a role in that. The value chains of LIBs are complex, consisting of several activities and stakeholders. To enhance CBMs for LIBs, it is necessary to consider several aspects as most activities are interconnected (e.g., LIB design affect dismantling complexity and costs in EOL). Research mapping LIB experts' opinions on CBMs and three additional vital aspects to enhance circular economy practice is currently lacking despite the large volumes of batteries that will be retired from EVs.

Appropriate CBMs will be essential for battery second use and recycling to become economically feasible. Simultaneously, to enhance, drivers for CBMs need to be empowered. Currently, there are several barriers for CBMs (Guldmann and Huulgaard, 2020) that need to be solved to proceed. Several stakeholders need to cooperate to enhance the drivers and overcome the barriers to recover value from spent LIBs. Therefore, the following Research Questions (RQ):

RQ1: What are the circular business models that have the highest potential in the context of lithium-ion battery lifetime management?

RQ2: What are the main drivers to develop circular business models in the lithium-ion battery market?

RQ3: What are the main barriers to develop circular business models in the lithium-ion battery market?

RQ4: Which stakeholders are crucial in empowering the drivers and overcoming the barriers?

A novel Delphi study was performed to answer the research questions; several assessment options were ranked by an expert panel based on their potential. This study has unveiled the applicable circular business models, drivers, barriers, and stakeholders needed for sustainable LIB lifetime management.

2. Lithium-ion battery value chain

A battery pack used in an EV comprises several components: the casing, electrical components (e.g., battery management system, converters, switches, wires, and sensors), and individual battery modules and cells. The battery pack is disassembled and processed by a battery handler when an EV battery reaches 70–80% of its initial capacity (Faessler et al., 2019; Keeli and Sharma, 2012). The battery handler can assess if the battery is suitable for second use applications or if the battery should be sent for recycling. The second use case batteries are repurposed on the battery pack, module, or cell level in an energy storage system. Typical second use applications are stationary energy storage applications that are usually less demanding than mobile energy storage applications (Reinhardt et al., 2017). A second use battery can be used until it reaches 60% of its initial capacity before it is finally sent for recycling (Cicconi et al., 2012).

If LIBs are consumed in a second application before recycling, the product and associated resources are further exploited over time compared to direct recycling materials after first use. Such circular practice may reduce the production of new LIBs (Rallo et al., 2020) and be environmentally beneficial (Kamath et al., 2020b). Spent batteries may also be more economically viable for stationary energy storage systems; however, they depend on several factors such as battery degradation mechanisms (Casals et al., 2017) and future market characteristics. Fig. 1 illustrates the LIB value chain, including the second use.

In 2018, recycling businesses estimated that 97 000 tons of LIBs would need to be recycled globally; however, the forecast for 2025 already predicts four times this amount (Melin, 2018). LIB recycling typically involves separating the casing and electrical components, and decommissioning the battery pack to modules and/or cells (Gaines, 2014). Many of these fractions are exported to Asia for further processing (Brandslet, 2019). Industrial LIB recycling processes are generally inefficient because not all materials are currently recovered (Heelan et al., 2016).

Exposure and release of battery materials such as nickel and cobalt into the environment should be avoided due to their carcinogenic and mutagenic nature (Banza et al., 2009; Chagnes and Pospiech, 2013). Environmental mitigation through material EOL management is thus the main incentive for developing circular battery value chains at the moment (Pagliaro and Meneguzzo, 2019). Fortunately, the 2020 EU Circular Economy Action Plan has a stated goal of "boosting the circular potential of all batteries" (European Commission, 2020). Asian countries like Japan, South Korea, and especially China have designed regulatory frameworks for materials recovery, such as the Chinese Policy on recycling technology of electric vehicle power battery (Yang et al., 2021). These efforts illustrate the importance of evaluating battery value chains from a sustainability and transparency perspective to strive for circularity. The EU Action Plan encourages CBM designs for battery second

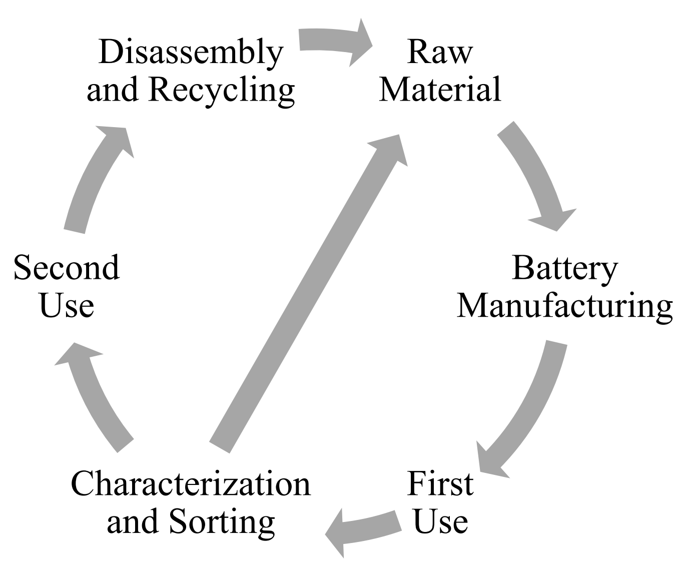

Fig. 1. Lithium-ion battery value chain of an electric vehicle including second use.

use, improved recycling practices, and ways to eliminate waste, emissions, and pollution in the value chain. Therefore, it is critical for the European and global battery markets to ensure that environmental and economic sustainability issues will be dealt with to push the battery market towards circularity (Bobba et al., 2018; Gaines, 2014; Melin, 2018).

3. Circular business models

The business model is an old concept (Drucker, 1954) revitalized during the last twenty years, catalyzed by the emergence of new technologies. Many authors have contributed to enriching this concept and have concluded that a business model's focus is on value creation, delivery, and value capture (Amit and Zott, 2001; Magretta, 2002; Shafer et al., 2005). From another perspective, BMs are links between new technologies and the market, being key to the diffusion and success of a technology (Chesbrough and Rosenbloom, 2002). Embedded in sustainable development, the discourse on CE adopted the business model concept. The CE aims to close the loops of materials and energy in biological and technical cycles to avoid exploiting raw materials, keeping the value of goods during their life cycle (Prieto-Sandoval et al., 2018). According to Salvador et al. (2020, p. 3) review, the CBMs are circular systems, economically viable (Bocken et al., 2016), regenerative in nature, which offer immediate solutions to immediate problems rather than sell products of permanent ownership (Antikainen and Valkokari, 2016). They intend to maintain resource value to the maximum, eliminating or reducing their leakage by closing, slowing, or narrowing their flows. Also, they argue that CBMs help reconcile resource efficiency with the creation of commercial value, capitalizing on both the environmental and economic value embedded in products (Bocken et al., 2016).

The innovation paths for CBMs have been presented through different typologies. Vermunt et al. (2019) identified four types of CBMs in terms of the 4Rs (reduce, reuse, recycle and recover) framework proposed in the EU Waste Framework Directive (European Commission, 2008; Kirchherr et al., 2018). These four models are 1) product-as-a-service, 2) product life extension, 3) resource recovery, and 4) circular supplies. Vermunt et al. (2019) reported that each model faces some barriers. The product-as-a-service model that focuses on leasing or performance models mainly faces organizational, financial, and market barriers. The product life extension model struggles with supply chain and market challenges, while the resource recovery model faces supply chain, market, and institutional barriers. The business models for circular supplies are mainly threatened by knowledge and technology, supply chain, and market barriers. A CBM can promote different loops: "closing loops, slowing loops, intensifying loops, narrowing loops and dematerializing loops" (Geissdoerfer et al., 2017). All contribute to a CE from an organizational level, and such a business model that creates value from waste is identified as a sustainable business model archetype (Bocken et al., 2014).

Olsson et al. (2018) proposed two types in the particular case of CBMs for electric vehicle batteries: 1) refurbishment after the first use, followed by second use in an EV in another market before final recycling, or 2) repackaging followed by second use in another application, followed by recycling. The study categorizes barriers to facilitating CBMs as technical, organizational, and cognitive. Several stakeholders in the battery value chain see the potential of second use for LIBs; however, a need exists to overcome the current challenges (Linder and Williander, 2017; Martinez-Laserna et al., 2018; Olsson et al., 2018). Three significant factors encourage businesses to seize these opportunities: battery ownership, inter-industry partnership, and policy support (Jiao and Evans, 2016).

4. Research methodology

The Delphi method is a systematic, anonymous, and iterative process for structuring a group communication process to obtain consensus between experts about a complex problem (Dalkey, 1969; Landeta, 1999; Linstone, Harold A. Turoff, 1975; Okoli and Pawlowski, 2004). It provides controlled feedback and a statistical response from the experts (Landeta, 1999). The response received guarantees the presence of each viewpoint in the result and reduces the pressure toward conformity. Several rounds (iterations) enable the experts to review their preliminary idea and understand the questions. Achieving a representative result by dynamic discussions requires 10 to 18 experts to respond (Okoli and Pawlowski, 2004).

The Delphi method comprised two online rounds. The second round was enhanced with opinions and consensus from multiple academics, practitioners, and CBM experts from different European and American countries. The panel was asked after the two rounds to provide additional comments regarding the responses in round two. The two online survey rounds were completed from March to April 2020, and the additional comments were collected in August 2020. The Delphi technique was chosen for three reasons. Firstly, this fast development phenomenon implies a high amount of knowledge exchange within the business ecosystems, which requires managerial resources. Secondly, the academic literature about CBMs for LIB EOL management is scarce; for example, a combined search in Web of Science about the topics "circular economy" AND "lithium" AND "business model*" yields only five papers, published from 2018 to (September) 2020. Finally, the Delphi panel method is suitable for research on framework development (Okoli and Pawlowski, 2004) to identify particular CBMs for the battery industry.

4.1. Expert recruitment and Delphi process

The Delphi panel was formed by contacting experts with profound knowledge via various channels and professional networks. The experts hold various professional backgrounds working in academia and businesses, with experience within sustainable transportation technologies, lithium- and traditional-batteries management, CBMs, and smart cities. The panel is also diverse in terms of demography, culture, and gender.

45 experts were invited to participate in the online Delphi panel. 21 participated in the first round, including men and women from different countries (Colombia, Finland, Italy, Mexico, Norway, Spain, and the USA). 9% were aged between 21 and 30 years, 30% between 31 and 40, 26% between 41 and 50, and 35% above 51 years. 44% had a master's degree and 38% a doctorate. 20 out of 21 experts confirmed they have more than five years of experience in LIBs and batteries, and nine have more than 20 years. 52% in the panel work in academies, research centers, and universities, 26% in business, 9% in governments and international institutions, 9% in non-governmental organizations, and 9% in other. In terms of profession, 44% identified as researchers, 26% managers, 18% consultants, 4% advisors, 4% engineers, and 4% professors. 12 of the experts finished the second round. The experts that responded to both rounds (12) have experience from Europe (11), South America (3), and North America (1). When establishing the expert list, the authors wanted a representative number to provide feedback. The surveys were sent to all experts listed and did not systematically exclude experts based on continent of origin to achieve equal share from Europe and America. The majority represents European expert opinions, as detailed in Table 1. The panel was additionally asked to provide comments completed by eight experts to justify some of the statistical responses. The Delphi process of this study is illustrated in Fig. 2.

LimeSurvey software was used to collect data in the two statistical rounds, and SurveyXact software was applied to gather the additional comments. These survey platforms were chosen because they allow for anonymous data collection, offer different question formats, provide automatic reports, and offer data security. After all, experts finished round one and two; a statistical report was provided showing the panel results, i.e., the mean of the group's ranking (Skulmoski et al., 2007).

Table 1
Second round experts' profile.

Expertise	Experience in Organizations	Experience in Countries	Level of Studies
Remanufacturing and recovery of lead and lithium-ion batteries, sustainable mobility	Rebattery, ULMA, MUISU	Spain, France, Latin America	Master/ postgraduate
Circular economy expert, sustainable development, and life cycle assessment consultant in electronics, mining, and oil industries	Consultancy firms, Apple	Mexico, Ecuador	PhD
Environmental health scientist	Public environmental protection agencies and research centers	USA	PhD
Business models and technological innovation expert, senior researcher	Industrial research centers	Multiple countries in Europe	PhD
Chemistry and materials sciences, including research on low CO_2 battery recycling	Universities	Finland	PhD
Battery and renewable energy expert	Hitachi ABB Power Grids, Nissan Energy engineering team, Saft	Spain, France	Master/ postgraduate
Energy and water technologies, including research on autonomous demand side management of electric vehicles in a distribution grid	Universities and research centers	Germany, Austria	Master/ postgraduate
Energy management algorithms for thermal and electrical systems and components	Universities and research centers	Austria	PhD
Smart cities and sustainable mobility	Universities and public organizations	Norway	Master/ postgraduate
Battery and power electronics (UPS) technologies, applications, and business	Consultancy firms	Finland, Ireland	Master/ postgraduate
Sustainable supply chain development in the renewable energy sector, and high-end technology solutions	Universities	Spain	PhD
Strategy, business models design, digital transformation	Universities, research centers and consultancy firms	Spain and Colombia	PhD

4.2. Data collection structure and performance

In the first round, the panel chose between options based on existing literature and were encouraged to add options if the given ones were not sufficient. In the second round, the panel observed the results of the scores from the first round prior to choosing between the options for the second time – this time including the experts' added options. Information of the overall results and remarks was presented in the second round and for the additional comments to promote the consensus or encourage personal reflection about the group answer. However, a potential barrier to reaching consensus is if individuals are influenced by self-interest (Hussler et al., 2011).

The Delphi was structured into four assessment categories with the options presented in 2. The first assessment category is dedicated to evaluating the potential viability of four CBM proposals and investigating other business models that allow the recovery of LIBs. This category's options are based on the CBMs (product-as-a-service model, product life extension, resource recovery, and circular supplies) proposed by Vermunt et al. (2019). The second category focuses on identifying the drivers that will enhance the recovery of LIBs. For the third category, the panel was asked about the importance of barriers that hinder the recovery of LIBs. The fourth category evaluated the influence of stakeholders who can facilitate or hinder the development of CBMs in the context of LIBs. The structure presented to the expert panel in the first round is illustrated in Table 2.

The degree of importance of these categories was assessed on a Likert scale from one to six. Other questions were designed to obtain an extended explanation and justification of the experts' ranking (Tapio et al., 2011), which allows for equality of all answers (Okoli and Pawlowski, 2004).

5. Results and discussion

This chapter presents the Delphi panel study results from the two rounds and the additional expert comments. The results are sorted and presented according to the four assessment categories described in Section 4.2. The results show the average value of each component within these categories. The panel used additional terms interchangeably with "second use" and "second life". This Section uses "reuse" to describe the process of repurposing spent EV batteries in stationary applications to avoid replacing the experts' words. The term "remanufacture" refers to the process of restoring a discarded EV battery and is used to describe the reuse of batteries in the same application for both first and second use. The experts also used the term "electric car" interchangeably with EV.

5.1. Circular business models for lithium-ion batteries

The experts were asked to assess the potential of four CBMs in the first round based on the business model typology (product-as-a-service model, product life extension, resource recovery, and circular supplies) proposed by Vermunt et al. (2019). They were also asked to propose

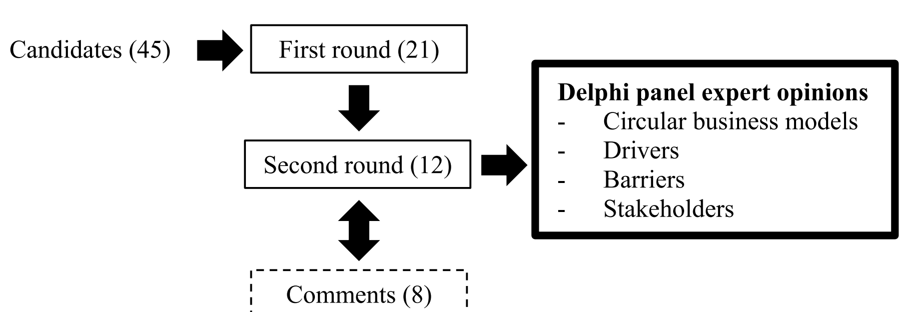

Fig. 2. The Delphi process including the number of experts participating in the surveys.

Table 2
Original Delphi panel structure prior to inputs from the expert panel.

Assessment category	Description and options	References
Circular business models for lithium-ion batteries	Potential of CBM to extend the use or recover the value from used lithium-ion batteries that have been discarded from EVs: • Product-as-a-service model • Product life extension by durable design, update services, remanufacture • Resource recovery of discarded materials • Circular supplies by using recyclable or biodegradable materials • Current circular practices for LIBs recovery in organizations and businesses (invitation for the panel to add)	(Merli and Preziosi, 2018; Nußholz, 2018; Vermunt et al., 2019)
Drivers for circular business models for lithium-ion batteries	Assessment and prioritization of drivers that encourage more efficient waste management of lithium-ion batteries: • National and international regulation and policies • Global difficulties in exploiting raw materials • Pollutant risk • Raw material availability • Second-hand material availability • Raw material production costs • Production and recovery technologies • Logistic and infrastructure development • Waste management costs • Potential applications of recycled products • Potential profits from repurposing or remanufacturing • Consumer behavior	(Balbuena and Wang, 2004; EYDE; NCE, 2019; Speirs and Contestabile, 2018; Yang et al., 2021)
Barriers for circular business models for lithium-ion batteries	Assessment and prioritization of barriers for recovering materials from lithium-ion batteries considering infrastructure, financial, legislation, technology, human talent, socio-cultural, and market barriers.	(Garcés-Ayerbe et al., 2019; Kirchherr et al., 2018; Ormazabal et al., 2018; Rizos et al., 2015; Vermunt et al., 2019; Yang et al., 2021)
Stakeholders for end-of-life management of lithium-ion batteries	Assessment and prioritization of stakeholders who may encourage the management of lithium-ion battery wastes: • Governments • Institutions • Research centers and universities • Car users and shoppers • Car producers • Public transport companies • Suppliers • Waste managers and recyclers	(Bocken et al., 2014; Del Río et al., 2016; Ellen MacArthur Foundation, 2015)

additional business models, which were added and ranked based on their potential in the second round. The majority of the proposed CBMs consisted of several EOL value chain activities, which indicate that a broader approach may be beneficial. Table 3 shows the average ranking rated by the experts from one to six based on the potential of each of the CBMs (1 means "no potential", 6 means "very high potential") and the associated standard deviations of the ranking.

More than half of the experts in the first round declared knowledge of organizations developing CBMs or technical applications to recover value from used LIBs. 13 experts out of 21 answered that they knew businesses reusing LIBs from EVs. Second use of LIBs and EV batteries is increasingly emphasized in research and at a regulatory level (European Commission, 2020b). 13 experts also responded that they are familiar with businesses, research centers, or any other organizations that improve the material sustainability of LIB components. Eight out of 21 confirmed that they are familiar with a business that offers battery performance as a service instead of battery ownership. Some experts indicate that ownership models should be designed for each application, dependent on, e.g., infrastructure and market characteristics. Martinez-Laserna et al. (2018) highlighted three potential EV battery ownership models: EV owner, EV manufacturer, or a third party. If one of the two latter owns the battery, there is likely a leasing agreement with the EV owner. Thus, contextual factors determine the ownership model.

As a result of the ranking, the most suitable business model, according to the experts, is "Remanufacture + reuse + recycle + waste management", comparable to a combined, flexible version of the two recognized CBMs by Olsson et al. (2018). The second was the "Product life extension by durable design, update services, remanufacture". These CBMs include several CE strategies (Blomsma et al., 2019) involving updating services and remanufacturing. Design for remanufacturing is recognized as an important effort and can include, for example, modular design, standard parts, and complexity reduction (Prendeville and Bocken, 2017).

The low standard deviation of the "Product life extension by durable design, update services, remanufacture" indicates a consensus among the experts on the importance of this CBM. However, the highest-ranked CBM shows more conflicting opinions regarding remanufacturing and reuse, which led to a higher standard deviation. The discrepancy is emphasized in the additional comments concerning the safety aspects of remanufacturing and reuse and the potential for economic viability. "Resource recovery of discarded materials" was ranked as the third-highest CBM, indicating that direct recycling is the most appropriate EOL path in some cases. However, new LIB recycling processes need to be commercialized to upscale the recovery of valuable materials more

Table 3
Circular business model potential to recapture value from spent lithium-ion batteries from electric vehicles.

Circular Business Model	Proposed by the Panel	Average Ranking	Standard Deviation
Remanufacture + reuse + recycle + waste management	X	5.08	1.11
Product life extension by durable design, update services, remanufacture		4.83	0.80
Resource recovery of discarded materials		4.67	0.94
Vertical integration of lithium-ion battery production + recycling	X	4.67	1.31
Product life extension + product as-a-service model to ensure that the product can be remanufactured after use	X	4.33	1.11
Product-as-a-service model		4.08	0.86
Circular supplies by using recyclable or biodegradable materials		4.00	1.00
Reuse without any upgrading process	X	4.00	1.47

efficiently to enhance the recycling system's economic viability (Heelan et al., 2016).

Two out of the four CBMs proposed by the expert panel were a combination of existing CBMs (Merli and Preziosi, 2018; Nuβholz, 2018; Vermunt et al., 2019). The other two proposed are new to the LIB context, although the "reuse without any upgrading process" did not receive high ranking. Similarly, Olsson et al. (2018) included refurbishment or repackaging for both CBMs for spent EV batteries. "Vertical integration of LIB production (+recycling)", however, is identified as a CBM with potential. This finding correlates with Jiao and Evans (2016) significant factor inter-industry partnership to encourage businesses to reuse EV batteries.

Answering the first research question, "*What are the circular business models that have the highest potential in the context of lithium-ion battery lifetime management?",* the circular business models with the highest potential are "Remanufacture + reuse + recycle + disposal", followed by "Product life extension by durable design, update services, remanufacture". Both include product life extension and reuse; however, the share of LIBs that will be reused or repurposed before recycling is uncertain. There are a few assumptions but no consensus. The following sections discuss the drivers and barriers that will affect this.

As a reaction to the need for knowledge concerning the global COVID-19 pandemic, the experts were additionally asked to consider the usefulness of LIBs during crisis and isolation scenarios. Table 4 shows the average ranking based on a rating scale from one to six based on the level of agreement (1 means "completely disagree", 6 means "completely agree").

Most experts agreed with the statement that "Reuse of lithium-ion batteries is an excellent choice in crisis and isolation scenarios". Back-up power systems for the hospital, telecom and military uses, and solar energy accumulation were suggested as potential applications. The panel further emphasized that the COVID-19 pandemic has slowed down public and shared transportation development and adoption. Public and shared transportation is generally seen to reduce the number of passenger vehicles and hence, as a possible counterforce to the growing demand for EVs.

5.2. Drivers for circular business models for lithium-ion batteries

Based on current research, twelve drivers for upscaling CBMs for LIBs were suggested to the panel. The experts were asked to assess the importance of each driver on a Likert scale from 1 to 6 (1 means "not important at all", 6 means "very important"). The experts proposed two additional drivers (Environmental values: saving this planet for next generations and Economic benefits). Table 5 shows the resulting average rankings and associated standard deviations.

The average rating and the standard deviation varied for some drivers. For example, most experts agreed on the importance of the driver "Raw material availability", whereas they disagreed on "Consumer behavior", reflected in the corresponding standard deviations. The significant variation can be explained by the different backgrounds and interests of the individual experts. Both organizational and individual values may affect responses (Hussler et al., 2011). The panel stressed that regulations, policies, and economic factors are the main drivers for all circular practices, such as reuse and recycling. Experts are concerned about LIB-appropriate waste management systems because they are in different development stages in different countries. However, if partnerships abroad are established, spent batteries can be exported to countries with appropriate waste management systems, although costs will increase. The panel agreed that it is challenging to rank the most important driver because several are critical to successfully establishing CBMs.

Table 4
Reuse of lithium-ion batteries in crisis and isolation scenarios.

The relevance of reuse in crisis scenarios	Average Ranking	Standard Deviation
Reuse of lithium-ion batteries is an excellent choice in crisis and isolation scenarios	4.67	0.94

Table 5
Drivers for circular business models of lithium-ion batteries.

Drivers for Circular Business Models	Proposed by the Panel	Average Ranking	Standard Deviation
National and international regulation and policies		5.58	0.76
Economic benefits	X	5.25	0.60
Potential profits from reuse or remanufacturing		5.17	0.55
Raw material availability		5.08	0.49
Raw material production costs		5.08	0.64
Production and recovery technologies		5.08	1.32
Global difficulties in exploiting raw materials		5.00	0.41
Second-hand material availability		4.75	1.09
Logistic and infrastructure development		4.75	1.23
Waste management costs		4.58	0.86
Potential applications of recycled products		4.58	1.11
Environmental Values: saving this planet for next generations	X	4.00	1.35
Pollutant risk		3.92	1.04
Consumer behavior		3.83	1.46

A strong consensus agreed that the most important driver is "National and international regulation and policies". This implies that governments and institutions can incentivize businesses and consumers to adapt to CBMs. The panel emphasized that appropriate regulations and policies are required at national and international levels to commercialize the reuse of LIBs (Jiao and Evans, 2016). Furthermore, the experts proposed the following policymaking focus: obligatory recycling with clear responsibilities across the value chain, targets for collection, research on potential economic benefits, and logistics and infrastructure development.

One expert proposed the "Economic benefits" driver in the first round, and it gained prominence in the following round as the second most important driver. Economic drivers for CBMs are internal drivers such as revenue growth from recovering value, and additional opportunities for innovation in the organization (Mont et al., 2017). An interesting comment was made regarding reuse practice by the automotive industry. The expert argued that reuse is currently driven by the lack of alternative EOL treatments, not by economic viability. The driver "Consumer behavior" was ranked the lowest, which implies that consumers have limited power and knowledge to drive CBMs. Consumer preferences is a part of external market pressures on businesses (Mont et al., 2017).

In comparison with drivers identified in CE research in general,de Jesus (2018) found that the drivers most frequently mentioned in academic literature is 1) economic/financial/market; 2) institutional/regulatory; 3) social/cultural; and 4) technical. Applying these categories in our context, the authors found that for CBM for LIBs, the following is ranked as the most important: 1) institutional/regulatory; 2) economic/financial/market; 3) technical; and 4) social/cultural. The difference points at the importance of the context when choosing CBM and the special context of the LIB as a technology and as an application.

Answering the second research question, "*What are the main drivers to develop circular business models in the lithium-ion battery market?",* "National and international regulation and policies" followed by "Economic benefits" are considered the main drivers for developing CBMs in the LIB market. However, several drivers were highly ranked based on their importance. The findings imply that a high uncertainty exists about which CBM(s) will be upscaled because several factors will affect future success. Battery price was raised as something that could determine if a battery is remanufactured, reused, or recycled. The issue concerns a second use LIBs potential to compete with the continually decreased price of a new battery (Martinez-Laserna et al., 2018; Zhang et al., 2020). Raw material availability and production costs will be cooperating factors, as the expert panel proposed. Nevertheless, retired LIBs require circular business models to outcompete primary-produced batteries.

5.3. Barriers for circular business models for lithium-ion batteries

Some barriers prevent a circular practice, such as enabling commercial repurposing of spent EV batteries. Seven barriers were proposed to the panel, based on current research. They were subsequently assessed for their significance on a Likert scale from 1 to 6 (1 means "not important at all", 6 means "very important"). One additional barrier, proposed by the experts in the first round, was added (Transportation cost of hazardous materials) to the second-round ranking. Table 6 shows the resulting average rankings and associated standard deviations.

The experts stress that similar to the drivers' findings, most barriers are linked; therefore, identifying a sole dominant barrier is not expected to occur. The highest-rated barrier was "Financial", reflecting challenges such as incentives and financial viability. The uncertainty of the profitability is also recognized by existing research, illustrating sensitivity to second use LIB price, battery aging (lifetime), discount rate, and efficiency (Kamath et al., 2020a; Rallo et al., 2020). "Technology" was ranked as the second most important and includes safety concerns, indicated in the additional comments. The experts additionally expressed that a legal framework would support a transparent and predictable market. Barriers related to "Socio-cultural" and "Human talent" are rated lower. No consensus exists regarding "Human talent" - if the people's skills and knowledge on circular practice on batteries are already available today. One expert pointed out that this talent will be available when needed; in contrast, another argued that it should be developed today.

Guldmann and Huulgaard (2020) found that most CBM innovation barriers were at the organizational level in their multiple-case study. In contrast, the barriers ranked the highest by the Delphi panel experts are at the market and institutional- or value chain levels. The barriers at the employee and organizational level (human talent and socio-cultural) are ranked the lowest. "Financial", however, is related to several levels. This comparison indicates that circular practice of LIBs mainly requires system-level innovation and change to overcome current barriers.

Answering the third research question, "*What are the main barriers to develop circular business models in the lithium-ion battery market?",* "Financial" followed by "Technology" are considered the main barriers to developing CBMs in the LIB market. The experts highlighted the importance of considering remanufacturing or refurbishing processes to technically enable the LIB to meet customer needs in the second use application (e.g., establish a new battery management system). This is also reflected in the "remanufacture" activity included in the preferred CBM.

Table 6
Barriers importance for circular business models of lithium-ion batteries.

Barriers for Circular Business Models	Proposed by the Panel	Average Ranking	Standard Deviation
Financial		5.42	0.65
Technology		4.92	1.19
Lack of technical standards		4.58	0.86
Infrastructure		4.58	1.11
Transportation cost of hazardous materials	X	4.50	0.87
Market		4.42	1.38
Legislation		4.33	1.03
Human talent		3.42	1.32
Socio-cultural		2.83	0.69

5.4. Stakeholders for end-of-life management of lithium-ion batteries

Several stakeholders must cooperate to recover value from spent lithium-ion batteries, a practice that is applicable in a broader circular economy context (Parida et al., 2019). The experts assessed and ranked the relevant stakeholders on a Likert scale from 1 to 6 (1 means "not important at all", 6 means "very important") in this section. The panel suggested two additional stakeholders during the first round (Battery cell manufacturers and raw material producers, and Renewable energy companies).

Table 7 shows the resulting average rankings and associated standard deviations.

The ranking showed that the most important stakeholders for LIB EOL management are governments and battery-related businesses because they develop applicable standards and regulations and have crucial knowledge for optimal battery waste management.

Overall, "Governments" are considered the most important stakeholder, followed by "Car producers". The panel argues that these two stakeholders must collaborate to steer EOL management by introducing appropriate regulations. One comment was related to the EU Battery Directive regarding its importance for incorporating circular economy principles, eco-design, the economic impact on companies, and potential job creation. The following regulative tools were suggested: standardization with strict requirements, taxes, tax reduction in the initial phase, binding collection, recycling targets with sanctions, legislation for reuse of LIBs, and innovation support. One expert argued that the focus should be on studying the economic potential to reduce governmental efforts. "Waste managers and recyclers", as well as "Battery cell manufacturers and raw material producers", are highly ranked due to their knowledge that is needed to develop battery standards for practices such as improved recycling. "Car users and shoppers" was the lowest-ranked stakeholder and was not considered critical to EOL management. The experts stated that most consumers focus on the market battery price rather than on the quality or potentially hazardous materials a battery contains. According to one expert, some consumers are likely to purchase a battery for reuse or remanufacturing if the technical standard is guaranteed.

The panel agreed that cooperation among the different stakeholders is required. Earlier research illustrates that existing partnerships and dependencies can hinder new (circular) practice (Boons and Lüdeke-Freund, 2013) if a traditional, linear approach exists within the stakeholder network. Several stakeholders need to collaborate to manage a circular practice (Mont et al., 2017).

The panel was asked for final comments about who should be managing the LIB collection; the experts suggested professional logistics companies, recyclers, and manufacturers because they have the

Table 7
Stakeholders' importance for lithium-ion batteries' end-of-life management.

Stakeholders	Proposed by the Panel	Average Ranking	Standard Deviation
Governments		5.77	0.42
Car producers		5.17	0.80
Battery cell manufacturers and raw material producers	X	5.08	1.04
Waste managers and recyclers		5.08	1.04
Research centers and universities		4.42	0.95
Suppliers		4.33	0.85
Industrial/business associations and clusters		3.92	1.26
Institutions		3.75	1.09
Renewable energy companies	X	3.58	1.38
Public transport companies		3.50	1.04
Car users and shoppers		3.00	1.15

appropriate knowledge and can meet high environmental standards. Furthermore, these stakeholders are more capable of generating economically viable businesses due to high battery volumes.

Answering the fourth research question, "*Which stakeholders are crucial in empowering the drivers and overcoming the barriers?",* "Governments" followed by "Car producers" are interpreted as the most important stakeholders to empower the drivers and overcome the barriers mainly due to the regulative tools' importance to upscaling circular business models.

6. Conclusion

The Delphi study method was used to identify circular business models for spent lithium-ion batteries, along with the key drivers, barriers, and stakeholders to consider. The invited expert panel shared valuable experience and knowledge. Findings map vital aspects to better cope with the complexity of circular economy for lithium-ion batteries. This rapidly changing phenomenon requires clarity, supporting policies, and context-sensitive business activities. Appropriate waste management systems, including logistics and infrastructure development, must be adapted to recover the valuable materials incorporated in batteries as their volume increases.

6.1. Theoretical contributions

Circular business models are vital parts of the circular economy framework to enable economically viable recapturing of value. This study proposes context-adapted, circular business models and ranks them based on their potential for feasible lifetime management of spent lithium-ion batteries. Previously, Olsson et al. (2018) identified two circular business models for spent electric vehicle batteries (such as lithium-ion batteries) through interviews. This study ranks several circular business models and unveil the most important drivers, barriers, and stakeholders for upscaling circular business models through the Delphi panel method. The results support Jiao and Evans (2016) three important factors to encourage businesses to invest in second use battery practice: inter-industry partnership, battery ownership, and policy support.

Circular business model research (Merli and Preziosi, 2018; Nuβholz, 2018; Vermunt et al., 2019) was applied to structure this Delphi panel study. Findings reveal, however, that it is beneficial to combine circular business models for spent lithium-ion batteries. Furthermore, which circular business model(s) will have the most success depends on market characteristics, infrastructure, involved stakeholders, and regulatory involvement.

Drivers and barriers identified in earlier work were appropriate to apply in the context of this study. Applying Guldmann and Huulgaard (2020) categories of barriers for circular business models innovation, the market and institutional- and value chain level barriers are currently ranked the most important for spent lithium-ion batteries. Additionally, Guldmann and Huulgaard's (2020) other two categories, organizational and employee barriers, heavily depend on the market and institutional- and value chain level barriers. Hence the importance of system-level change and stakeholder cooperation is crucial to overcome the barriers of CBMs for LIBs.

6.2. Managerial and policy implications

Circular business models can facilitate organizations to recapture economic value from spent lithium-ion batteries while potentially reducing environmental impacts. The three with the highest potential to recover economic value from lithium-ion batteries found are 1) Remanufacture + reuse + recycle + waste management (disposal), 2) Product life extension by durable design, update services, remanufacture, and 3) Resource recovery of discarded materials. It may be interesting for managers to compare their existing business models with these findings and to consider these options when they are about to start innovating their business models in a circular direction. Together with the panel, we found that it may be beneficial to hold a broader view of the circular business models, often involving several end-of-life value chain activities. Nevertheless, the most appropriate circular business model depends on the context. Our study still gives a better understanding of which contextual factors to look at (e.g., in terms of drivers and barriers). The results also indicated that raw material prices and availability may accelerate interest in applying particular circular business models, which is a crucial matter to consider for companies that have not yet seen an incentive to implement CBMs.

Results related to the drivers showed that national and international regulations and policies and economic benefits are the most critical to upscale circular business models. The most critical barriers are related to the financial aspects, technologies, and lack of technical standards. However, the panel commented that technological solutions for a lithium-ion battery circular economy could be found if the financial barriers are solved. Regarding stakeholders, governments and institutions were ranked the highest by the experts. Nevertheless, it is emphasized that managers who bring battery-containing products to the market should closely cooperate with them to develop regulations with clear responsibilities.

As regulations and economic factors are ranked the highest by the expert panel, this is a clear indication that currently, the circular economy practice of spent lithium-ion batteries needs development at a system level in parallel with the growth of spent battery volumes.

6.3. Limitations and further research

The presented study is a baseline study for circular business models for sustainable end-of-life management of spent lithium-ion batteries. Future research should focus on more in-depth analyses of the assessment categories presented, for example, by studying the value creation and capture in circular business models to upscale the remanufacturing and second use practices of lithium-ion batteries, including empirical data analysis. The rated results additionally require further investigations, such as specifying the regulations needed and assessing environmental sustainability.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author, [BW]. The data are not publicly available due to their containing information that could compromise the privacy of research participants.

CRediT authorship contribution statement

Benedikte Wrålsen: Investigation, Writing – original draft, Writing – review & editing, Project administration, Conceptualization. **Vanessa Prieto-Sandoval:** Methodology, Formal analysis, Writing – original draft, Conceptualization. **Andres Mejia-Villa:** Resources, Writing – review & editing, Visualization, Conceptualization. **Reyn O'Born:** Term, Project administration, Conceptualization. **Magnus Hellström:** Validation, Writing – review & editing, Conceptualization. **Bernhard Faessler:** Resources, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Paper III

Multiple Scenario Analysis of Battery Energy Storage System Investment: Measuring Economic and Circular Viability

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Multiple Scenario Analysis of Battery Energy Storage System Investment: Measuring Economic and Circular Viability

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Abstract: Circular business models for batteries have been revealed in earlier research to achieve economic viability while reducing total resource consumption of raw materials. The objective of this study is to measure the economic performance of the preferred business model by creating different scenarios comparing second life (spent) and new battery investment for seven different European regions and four energy management strategies. Findings reveal levels of economic ability for a total of 34 scenarios simulated, including direct savings per kWh, a total change in energy costs per year, battery charge/discharge cycles, and comparative breakeven analyses. Regional effects are also measured based on day-ahead electricity prices and solar irradiation. The minimum payback time is 7 years before battery system investment costs are covered. The most viable energy management strategies also had the highest number of charge/discharge cycles, which decreases battery lifetime. Investment in a second life battery compared to a new battery reduced the payback time by 0.5 to 2 years due to lower investment costs. However, the estimated lifetime range (3 to 10 years) is lower compared to a new battery (5 to 15 years), which questions the circular business model viability for the scenarios studied. Energy management strategies should be combined and customized to increase economic benefits.

Keywords: battery energy storage system; simulation study; multiple scenario analysis; circular economy; circular business models; techno-economic assessment

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1. Introduction

Grid connected battery energy storage systems (BESSs) linked to transient renewable energy sources, such as solar photovoltaic (PV) generation, contribute to the integration of renewable energy to the grid [1,2], which is important to Sustainable Development Goals (SDGs) [3]. By enabling to replace fossil fuels with renewable energy, also in mobile applications, political agendas are driving battery demand [4]. Batteries are an increasingly used storage technology due to their flexibility in placement, scalability, and maintenance-free operation [5,6]. Combined with energy management (EM) strategies, such as peak-shaving, load shifting, electricity arbitrage, and solar PV generation with self-consumption, BESSs also benefit the power system by contributing to sophistically balancing the demand and supply of electricity on the demand side [7]. BESSs can provide various services that achieve economic savings [5] and are currently becoming an increasingly profitable investment [6]. However, the potential economic benefits of BESS investment rely on several parameters connected to costs of investment, savings achieved through EM strategies, and end-of-life (EOL) management.

Research and industrial interest of repurposing batteries from electric vehicles (EVs) for, e.g., stationary energy storage [8–11] has recently increased. Such circular economy (CE) practice can benefit both the environment and economic viability of BESS investment [12]. Repurposing a battery can reduce investment costs when the battery price is lower and the quality is assured [9,13–15]. Circular business models (CBMs) map how to enable the commercial success of a product or service with an underlying CE strategy [16,17], e.g., by enabling a second life for batteries that will extend the lifetime before recycling and contribute to a CE for batteries by slowing the materials loop [18]. Wrålsen et al. [19] identified CBMs for lithium-ion batteries (LIBs), particularly those stemming from EVs, and found that the most critical barrier for these CBMs is financial. Thus, it is crucial to develop economically viable business models for the CE of batteries. To enhance economic savings, Braeuer et al. [20] explored BESS investment with peak-shaving, primary reserve control, and electricity arbitrage in Germany and found that the latter strategy led to the least income of the three. The reason for this could be a too low price spread in the German day-ahead and intraday continuous market used for electricity arbitrage. In contrast, Rallo et al. [11] found, by studying two real cases (a furniture factory and a hotel) in Spain, that arbitrage was the best strategy to obtain profitability as it indirectly also performed peak shaving. There is potential for profitable CBMs, however, BESS costs, and lack of awareness and use of EM strategies to enhance savings are barriers for businesses to invest [21,22]. Furthermore, battery ageing is a recognized important characteristic and depends on operation incentives, climate conditions, and other contextual factors.

Current research shows diverging profitability results from case-specific analyses and does not cover the role of regional conditions or assessments comparing investments in new and second life batteries. There is a research gap of measuring these crucial factors for successful battery system investment, which also can benefit environmental sustainability through circularity. CBMs aim to achieve both economic and environmental sustainability; however, these can experience trade-offs [23]. Therefore, it is important to measure CBMs in terms of both approaches [24,25]. CBMs for batteries and factors that are important to achieve economic viability need to be measured. EM strategies can contribute to enhance economic viability of CBMs while contributing to delicately balance the supply and demand of electricity. However, value generated from EM strategies can be challenging to quantify and such investments are complex to evaluate. Country specific characteristics, such as electricity prices and solar irradiation, are also important factors to consider, but studies simulating battery behavior and assessing economic viability in different European countries do not exist.

This paper develops multiple scenarios consisting of different combinations of the factors identified as important for economic viability of battery system investment: battery behavior (when it charges/discharges and how many cycles); EM strategies (including PV); different European regions; and investing in a second life versus a new battery. The objective of this study is to measure economic performance of the battery repurposing CBM [19] and assess other opportunities to lower BESS investment costs. Simulations were based on a battery optimization method [26] and performed for seven European countries investigating the economic potential of the battery storage to generate profit: (1) making use of energy price arbitrage; (2) using it to harvest photovoltaic energy; (3) performing load shifting from peak to low demand times; and (4) improving self-consumption by balancing demand and self-generated photovoltaic energy. Based on the different countries and strategies, 28 scenarios were designed. These scenarios have been applied in a simulation study to a case manufacturer (where real energy data was available) using a generic BESS. The case manufacturer operates in the food industry in southern Norway. Additionally, to test the CBM, six of the scenarios applied a second life battery. Thus, in total, 34 scenarios were designed and investigated. Based on the identified research gaps, this paper aims to answer the following research questions (RQs) through the multiple-scenario analysis:

RQ 1 What is the potential of the four energy management strategies to enhance economic viability of battery investment?

RQ 2 How does location affect economic viability in terms of electricity prices and solar irradiation?

RQ 3 How does the repurposing circular business model compare economically with investment in a new battery?

This study is particularly relevant for manufacturers and others considering BESS investment; the battery industry, both with CBMs (seeking profit while promoting a circular economy) and traditional business models (seeking profit) and policy makers working with regional, national, or international CE strategies. In addition, the work is relevant for researchers in the field of CE and CBMs as the performance of a recognized CBM [19] is measured quantitatively.

2. Economic and Environmental Sustainability

In addition to the increasing demand for stationary energy storage, the electrification of the transport sector enhances the use of battery-dependent mobile applications, such as EVs [27]. As production and consumption of batteries are expected to continue growing significantly [5,27–29], the European Union (EU) launched its battery regulation in late 2020 to motivate a CE for batteries. One of the encouragements is to repurpose batteries from EVs for stationary energy storage. LIBs are expected to reach EOL technically when the battery has 60% of the original capacity [15] and should then be ready for recycling the materials. However, depending on application, consumers may bring the battery to waste management earlier when, for example, reduced EV driving distance reaches an unsatisfactory level, when an accident occurs, or a vehicle swap is desired. In these cases, through CBMs, a second life can be enabled prior to recycling the materials by recapturing their remaining economic value after use in the EV [8,9]. CBMs are based on sustainable development principles and are recognized as a type of sustainable business model [30]. The aim is to retrieve the economic value of resources and intentionally reduce extraction of virgin materials (e.g., nickel for batteries). The principal techniques are to close, slow, or narrow material flows [16]. Several researchers have recently considered this opportunity and some particularly framed the research in a CBM context [8,19]. By applying the Delphi method, Wrålsen et al. [19] identified and ranked CBMs for LIBs based on their potential for success. An expert panel within the field constructed the results together. The highest ranked CBM included repurposing of a spent battery. Such CE efforts can also benefit environmental sustainability through reduced virgin battery material consumption [31] if the second life battery replaces a new. Adopting a pragmatic approach to the CBM, it should furthermore be measured in terms of economic performance, particularly as economic and environmental sustainability do not necessarily concur despite CBMs' intention [32]. The cost and revenue models are vital elements of all business models [33] and can be quantitatively measured with business cases.

The prices of new batteries decrease; however, exact investment costs of BESS vary in existing literature [11,34]. What the prices consist of also differs, for example, between LIB technologies and applications (such as for stationary energy storage or electric vehicles) and when the price reflects the battery at a cell, module, or pack level. Additional costs from cell to pack can be 21% of total costs [35]. Mathews et al. [15] assumed the cost of a new battery module is 176 EUR/kWh based on research from 2018 concerning LIBs for utility-scale energy storage. Prices decrease rapidly, and the worldwide average battery pack prices for LIB technologies for e-buses, passenger, commercial electric vehicles, and stationary storage were 115 EUR/kWh in 2020, according to Bloomberg NEF's annual battery price survey. This price is without taxes and includes multiple cells, modules, the battery management system, wiring, thermal management system, pack housing, and holding the cells and modules in place [36]. The price is expected to decrease to 84 EUR/kWh by 2023 and to 49 EUR/kWh in 2030 [35]. Upscaled mass production of battery packs leads to an expected battery price reduction of 50% by 2030 from 2018 prices, according to Tsiropoulos et al. [37]. Fundamental improvements to battery chemistry is another factor causing cost reductions and performance improvements (e.g., power and energy density and higher charge/discharge cycle stability) [38]. The new battery price could decrease by 70% from 2019 to 2040 [6].

The cost of the battery pack is one element of BESS initial investment costs; additionally, there is an 80 EUR/kW cost of power electronics, including inverter, 30 EUR/kW for electric materials, and 30 EUR/kW for labor, according to Rallo et al. [11]. Tools, such as identifying the breakeven points, can contribute to considering whether an investment is advisable [39]. The decreasing battery prices also enhance the investment interests as BESS investment costs are considerable [6,35]. Based on a number of studies, Rallo et al. [11] found that the expected price of a second life battery pack that has reached 80% of its original capacity is currently 50 EUR/kWh, about half the price of a new battery [35].

The transition from fossil fuel power to renewable energy sources is a global strategy driven by sustainability to reduce greenhouse gas emissions. Solar PV generation is expected to grow by 15% each year from 2021 to 2030 [40]. Due to natural fluctuations in intermittent energy sources, such as solar and wind, the need for energy storage is growing [41]. This trend is desired in terms of reaching several of the SDGs, particularly goal 7 (affordable and clean energy) and goal 13 (climate action) [3]. When integrating local solar PV generation to a BESS, solar irradiance (which naturally depends on location) largely determines the extent of power generation. Hence, it is an important factor to examine for potential economic benefits [42]. A solar PV system generates economic value throughout its lifetime due to either selling the power generated through the grid [15] or self-consumption and therefore reduction of electricity purchase. When PV is integrated in the BESS, one needs to consider the additional initial investment costs related to PV modules. Prices have decreased notably in the last 40 years. From 2010 to 2020, there was a price reduction of 89% [43]. Improved efficiency of modules, government incentives, research and development, and economics of scale have contributed to the cost reduction [44]. A common PV module with 60 multicrystalline cells cost 230 EUR/kWp in March 2021, according to pvXchange [45]. To complete an installation, additional initial investment costs include the inverter (110 EUR/kWp), electrical parts (110 EUR/kWp), and installation (120 EUR/kWp) [46].

Whether investing a new or a second life battery, its lifetime is important to account for, both in terms of environmental and economic sustainability. There are two common measures applied to estimate battery lifetime due to degradation (ageing): Cycle and calendar lifetime [9]. Battery cycle lifetime is the number of full charge/discharge cycles before it reaches EOL. The number depends on the characteristics of the battery and contextual factors. Jo et al. [47] estimated, for example, that a new 1000 kWh LIB with a depth of discharge of 95% can charge/discharge 3000 times. A second life battery study by Braco et al. [48] found that at least 2033 cycles should be expected before the battery reached a sudden nonlinear loss (ageing knee). The researchers tested different second life LIBs from Nissan Leaf EVs with an unknown user history. To grasp this important parameter, a multiple scenario analysis can account for both the number of cycles based on the specific operation and the potential economic benefits during the lifetime of the battery.

3. Research Methods

3.1. Study Scope

The multiple scenario analysis performed in this study consisted of 34 scenarios in total. These include four different EM strategies in seven countries located in different regions in Europe and investment in a new or second life battery. The purpose was to measure and compare the potential for economic viability with the battery repurpose CBM compared to new battery investment and examine the importance of different factors. To define a realistic scope of study, modelling choices were based on a case manufacturer in Europe. Both direct economic savings per kWh and annual change in energy costs were simulated. In addition, the number of full charge/discharge cycles were identified for the different scenarios as this is highly relevant for the results. These findings were combined with additional data and applied in comparative breakeven analyses. The scope of the study is illustrated in Figure 1 and is further detailed in this chapter.

Each EM strategy studied had an incentive for when the battery charges/discharges. These were simulated for seven European countries to consider country-specific and regional characteristics that can influence economic savings. The strategies applied are described and illustrated in Table 1.

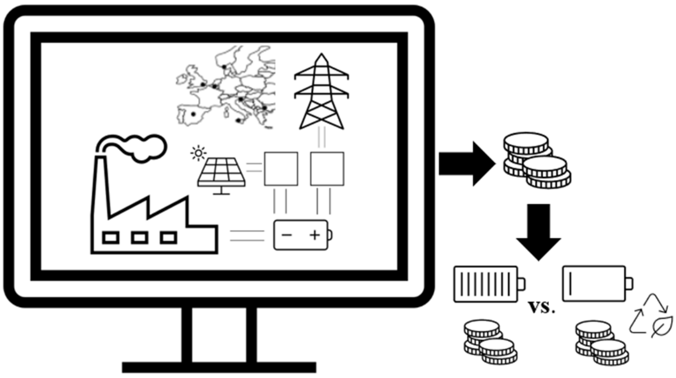
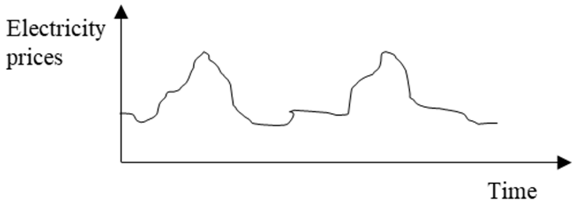
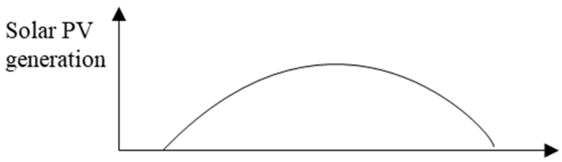
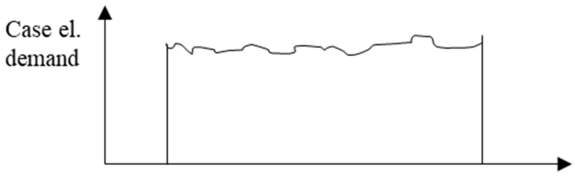
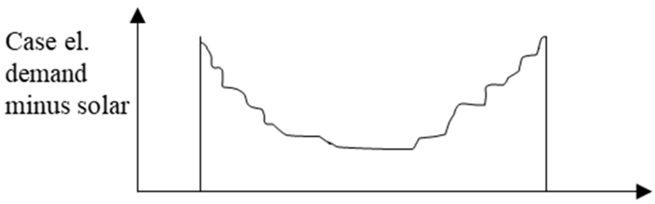


Figure 1. Illustrated study scope.

Table 1. The four energy management strategies and the European countries and regions covered in the multiple scenario analysis.

Energy Management Strategy	Illustration (Daily Profiles)
1. Electricity arbitrage The battery stores energy when electricity prices are low and consumes when prices are high [6]	
2. Solar photovoltaic generation Rooftop solar PV generation is connected to the BESS. Both self-consumption and selling surplus to grid are possibilities [15]	
3. Load shifting Attempts to balance the case electricity use profile by shifting use in time to flatten own demand curve, particularly at the times of day when electricity is most expensive [49]	
4. Solar self-consumption Stores energy and converts to electricity for own use instead of feeding it into the grid, and thus become more self-sufficient [50], reducing the daily grid draw [51]	
Country—European region	Norway—Northern Slovenia—Central Eastern Bulgaria—South Eastern Italy—Apennine Peninsula Spain—Iberian Peninsula Belgium—Central Western United Kingdom—British Isles 

3.2. Research Process and Data

Firstly, an analysis of the electricity demand of the case manufacturer was performed. In this research stage, modelling choices, such as battery and solar PV sizes, started to form based on the typical daily demand profile. The maximum electricity consumption peak of the real case manufacturer within 2018 and 2019 was 185 kWh. Based on this, to compensate this demand with PV, the planned power for the solar PV system was 185 kWp. The battery capacity was chosen accordingly and was 185 kWh. Secondly, investment costs were investigated. Thirdly, the countries were selected based on the European Commission's classification of regions. One country per region (seven in total) was chosen based on the highest average relative standard deviation of day-ahead electricity price for 2019 [4]. Due to incomplete day-ahead electricity price data for Romania and Ireland, these were replaced with United Kingdom and Slovenia, the next countries listed in the ranking in these regions. Because this study included several countries, the most profitable average capacity-to-power ratio for stationary battery storage system was applied (2.32) [26]. Thus, the battery power was assumed to be 79.7 kW. Furthermore, the solar PV power generated for the seven geographical locations was identified with PVSYST software [52] based on requested weather and solar irradiation data from Solargis [53]. The real day-ahead prices were accessed for the countries selected for 2018 and 2019. These historic prices do not show any clear price trend for two years [4]. All sources with specifications and modelling characteristics are collected in Table 2. When all data were collected and investigated, the scenarios were simulated. Lastly, simulation results and investment costs were applied in breakeven calculations.

Table 2. Data specification and sources.

Data	Specification	Source
Electricity demand profiles from 2018 and 2019	One fraction of the production plant	Case manufacturer [54]
Battery system	Capacity: 185 kWh Power: 79.7 kW State of charge: 10% to 90% Capacity-to-power ratio: 2.32	The real case manufacturer's maximum kWh in the electricity demand profiles from 2018 and 2019
Solar PV system	Planned power: 185 kWp	The real case manufacturer's maximum kWh in the electricity demand profiles from 2018 and 2019 (to cover demand)
New battery price	Price: 115 EUR/kWh Technology: Average of different lithium-ion battery chemistries Includes: Multiple cells, modules, the battery management system, wiring, thermal management system, and pack housing. Without taxes Year: 2020	BloombergNEF [35] BloombergNEF [55]
Predicted new battery price	Price: 49 EUR/kWh Technology: Same as above Includes: Same as above Year: 2030	BloombergNEF [35]
Second life battery price	Price: 50 EUR/kWh Technology: Average lithium-ion battery (that has reached 80% of its original capacity) based on a number of studies Includes: Battery pack Year: 2020 (study published)	Rallo et al. [11]

Table 2. *Cont.*

Data	Specification	Source
Other battery system costs	Power electronics: 80 EUR/kW Materials: 30 EUR/kW Labor: 30 EUR/kW Operation and maintenance: 3% annually Region: Spain Year: 2020 (study published)	Rallo et al. [11]
Solar PV system investment costs	Technology: Generic PV modules: 230 EUR/kWp Inverter: 110 EUR/kWp Electrical parts: 110 EUR/kWp Installation: 120 EUR/kWp Operation and maintenance: 1% annually Region: Global Year: 2021 (PV module price)	Abu-Rumman et al. [46] BloombergNEF [43] pvXchange [45]
Annual loss in terms of time value of money in the breakeven analyses	6.2%	Annual average value of highest and lowest discount rate in Lugo-Laguna et al. [56]
Climate conditions, hourly, 2018 and 2019	For seven European countries: Norway, Slovenia, Bulgaria, Italy, Spain, Belgium, United Kingdom	Solargis [53]
Local solar PV generation, hourly, 2018 and 2019	Technology: Generic For the seven European countries	PVSYST software [52]
Historic day-ahead stock market electricity prices for 2018 and 2019	For the seven European countries	Entsoe transparency platform [57]
Optimization method	The four energy management strategies were used as incentive in the optimization method to assess the economic savings	Faessler and Bogunović Jakobsen [26]
Currency converter	Currency per 15 March 2021	Morningstar [58]

3.3. Calculations

An optimization method [26] developed in MATLAB [59] was applied in the simulations. The direct economic savings for the different scenarios were calculated by multiplying the total power consumed for each hour (minus for positive power and plus for negative power) with the day-ahead price at that time from the respective country. The specific power consumed in the different scenarios was based on the EM strategy and country. For example, with strategy number four (Table 1), the total power consumed and generated (from solar PV) in that country for each hour was multiplied with the day-ahead price at that time. This included the battery, solar PV generation, and the self-consumption. The direct savings showed the saving per kWh per year and did not account for the reduced grid draw. The change in energy costs showed total cost change per year and accounted for the reduced grid draw. The day-ahead price analysis was also performed using MATLAB [59].

The number of battery cycles were calculated based on the energy flowing in and out of the battery. One full charge/discharge cycle was done at any time the in- and output energy equaled 185 kWh, reflecting that the battery was once completely charged and discharged. The number of cycles was calculated for each year. Degradation was not included as this layer would only have minor effects on the results since a limited number of years were assessed. Based on these findings, new and second life lifetimes were calculated based on the number of charge/discharge cycles identified in this study (Figure 2) and cycle lifetimes of a new [47] and second life battery [48] (results in Section 4.4).

The estimated battery lifetimes were applied in breakeven analyses (Equation (1)) to measure the economic potential of the CBM. The analyses identify points in future time (e.g., in years) when the expense of a financial investment is covered by the economic value generated, i.e., when costs = revenue. Using Excel [60], initial investment costs were summarized and the change in energy cost was then subtracted each year.

$$\text{total costs of investment} - ((\text{yearly revenue}) - (\text{yearly value loss})) = \text{years before breakeven} \quad (1)$$

Interest rates and costs associated with EOL were outside the scope of this research. Taxes and costs that may occur due to power fed to the grid from solar PV generation at the plant rooftop were not included as regulations and practice vary by country. To compare new and second life battery investments, the battery pack cost parameter was adjusted as the price was estimated to be lower for the latter battery [11]. The following parameters are not expected to change significantly over the next years: Electricity demand profile of the case manufacturer, day-ahead price fluctuations, and the weather and solar irradiation in the different countries. The parameters and values applied are specified in Table 2.

The results and discussion of this study represent findings based on the day-ahead electricity prices, which were central in the calculations. Hence, the results indicate participation in the day-ahead stock market. Additionally, the authors want to highlight the significant influence that the algorithm applied and the modelling choices (e.g., battery price) had on the results.

4. Results and Discussion

The results reveal battery performance, energy cost savings, and the number of charge/discharge cycles to estimate battery lifetime. These results were applied in an economic model, including investment costs to estimate breakeven points and lifetime range for the different scenarios of a new or second life battery system. The following chapters answer in detail the three RQs: Sections 4.1–4.3. answers RQ 1 and RQ 2 and Section 4.4. answers RQ 3. The simulation results are presented in Figure 2.

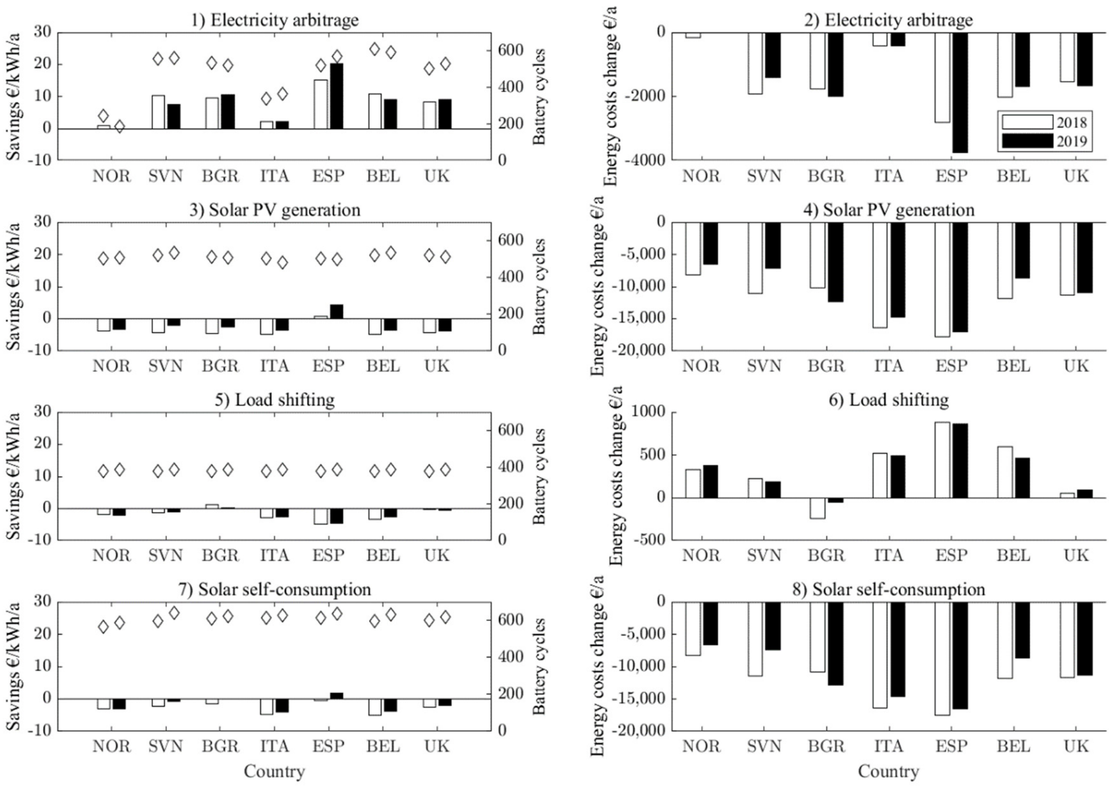


Figure 2. Direct economic savings due to the battery system and number of battery cycles (diamond shape) to the left, and the total changes in energy costs per year to the right for each scenario for year 2018 (white) and 2019 (black).

The changes in energy costs on the right side in Figure 2 were multiplied by minus one to visualize the costs saved. Results reveal that the case manufacturer would gain the most economic benefit in Spain for all four EM strategies. Overall, the manufacturing company gains the least if located in Norway, except for load shifting.

Figure 2 shows that each strategy contributes to energy cost reductions. This illustrates potential benefits for businesses to operate several strategies for the investment to become economically viable. However, more EM strategies lead to more frequent consumption of the battery in the system, resulting in a shorter lifetime.

4.1. Electricity Arbitrage

The incentive for the electricity arbitrage strategy is the day-ahead price, which reflects the results of trading hourly electricity prices for the day ahead per region. During the trading, the generators' offers are matched with the bid from consumers, based on the supply and demand balance in the market. The day-ahead market is part of a larger system that determines the final price. The different regional wholesale markets in Europe experience different electricity prices and fluctuations. These prices are, for example, affected by the share of renewable and carbon-intensive sources. The latter must pay fees due to CO_2 emissions released. Markets relying on imports or experiencing limited capacity to transfer electricity across borders also face higher prices [4]. Thus, electricity prices are influenced by several factors, including climate and weather, generation costs, market competition and integration, regulatory costs, and consumer patterns [61].

Zhang et al. [13] found that regional electricity prices are important when considering the value of battery energy storages. Table 3 presents characteristics of the day-ahead electricity prices in euros per MWh and year for the seven countries studied to consider correlation between prices, fluctuations, and economic savings. The mean value of the daily standard deviations considers fluctuations in prices and shows large variations among the European countries. Electricity prices are expected to fluctuate more in the future due to renewable sources, and energy storage technology will be used to manage this change in the electricity market [4]. Electricity prices reaching zero or below, also observed in Table 3, occur more frequently due to renewable energy growth, which causes a destabilizing effect. This phenomenon can occur when the supply is greater than the demand, or in case of link malfunction [62,63].

Table 3. Maximum, minimum, average value, and mean value of the daily standard deviations of historic day-ahead electricity prices in euros per MWh and year for each country in 2018 and 2019.

Day-Ahead Electricity Prices 2018 and 2019	Norway	Slovenia	Bulgaria	Italy	Spain	Belgium	United Kingdom
Average price 2018	43	51	40	69	57	55	65
Average price 2019	39	49	47	63	48	39	49
Max. price 2018	105	141	143	196	84	499	216
Max. price 2019	109	200	466	155	75	121	312
Min. price 2018	2	−76	0	0	2	−32	10
Min. price 2019	6	−20	0	0	0	−500	−3
Mean value of the daily standard deviations for 2018	3	11	11	18	6	12	12
Mean value of the daily standard deviations for 2019	2	11	13	22	5	8	10

For some strategies, including arbitrage, high fluctuations in electricity prices can potentially benefit economic earnings because of the greater opportunities for activity in trading electricity with larger variations in price. For example, the United Kingdom had more fluctuations in electricity prices compared to Norway, with a standard deviation of

3 and 2 in 2018 and 2019 for Norway and 12 and 10 in the United Kingdom, identified in the day-ahead electricity price analysis (Table 3). The United Kingdom battery was therefore more active in electricity arbitrage where power from the battery was used when prices from the grid were high. While in the Norwegian case, the battery was not used as frequently, as prices have a flatter curve.

Figure 2(1,2) shows results with electricity arbitrage. With this EM strategy, all countries except for Norway in 2019 show direct savings per kWh with a battery. If the case manufacturer has a higher demand when the battery discharges, the demand is reduced in that hour and economic savings are achieved. The inferior economic results for electricity arbitrage in Norway can at least partly be explained with the low energy prices, and fluctuations in these prices leads to a less active battery, reflected in the diamond shaped marks in Figure 2. Nevertheless, the battery cycle lifetime in Norway will be longer. Furthermore, it is not intuitive why Spain is the location with the most economic benefits as this country does not have the highest fluctuations in electricity prices. This example illustrates the complexity of such techno-economic assessments.

4.2. Load Shifting

The electricity demand profile of the case manufacturer contributed to defining the research scope and is integrated in the scenarios. Figure 3 presents the typical case's daily current profile. There are no distinct peaks in the demand pattern. The demand is lower during the night and is higher from 04:00 until 22:00 As a result, the battery has limited time to charge during these hours and limited opportunities to generate direct economic savings with a battery system for this case. Load shifting is a relevant EM strategy to shift the demand from one time to another, from times of high demand during the day to valleys during the night, thus reducing the energy costs since the energy is mostly cheaper during the night when demand is lower. This will flatten the demand curve. Findings reveal that load shifting is not considered an appropriate strategy for the case manufacturer electricity profile due to the low demand fluctuations (illustrated in Figure 3).

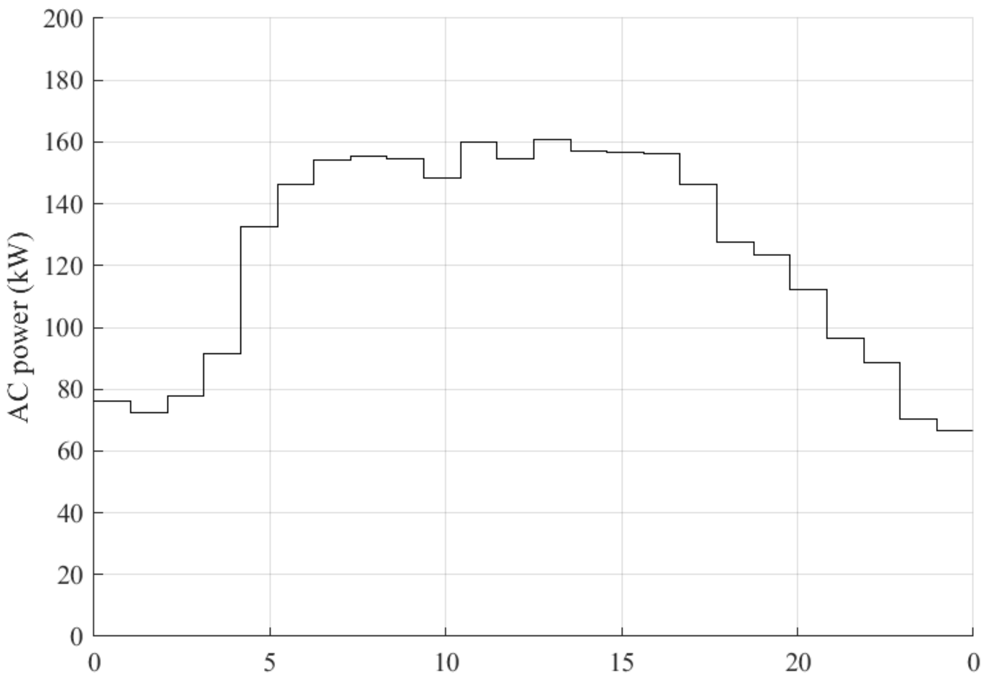


Figure 3. Typical daily case manufacturer electricity demand profile.

4.3. Solar Photovoltaic Generation and Self-Consumption

Findings reveal that Spain and Italy achieve the most economic benefits in the EM strategies involving solar PV generation. The data Solargis [53] provided show that these countries also have the highest solar irradiation of the seven countries. For solar PV generation and self-consumption, Norway has the lowest solar irradiation of the countries assessed and the least change in energy costs (Figure 2). These results illustrate the correlation between economic benefits and solar irradiation, which confirms Kamath et al.'s [42] finding. Businesses planning EM operations should consider this in decision-making processes.

The results for Figure 2(4,8) show the same values because the electricity produced from the local solar power generated is multiplied with the day-ahead prices in both cases. Nevertheless, Figure 2(8) does not reflect the reduced grid draw. Furthermore, this strategy includes the option to sell surplus electricity to the grid instead of self-consumption. To consider this alternative, the business firstly must be located with access to the applicable grid infrastructure. Secondly, businesses must pay a fee to feed into the grid, which can challenge profitability depending on regional regulations. Thirdly, savings may be lost compared to self-consumption where the battery can, in combination with electricity arbitrage, exploit fluctuations in electricity prices to a greater extent.

4.4. Breakeven Analyses

Breakeven point analyses were performed comparing the best-case scenarios in terms of EM strategies (electricity arbitrage and local solar PV generation with self-consumption) and years within the study scope (either 2018 or 2019). Thus, the best-case scenarios for the three countries with the lowest (Norway), mid (Belgium), and highest (Spain) profitability potential are illustrated in Figure 4. Furthermore, the analyses compare investments in a new battery versus a second life battery and the range of estimated battery cycle lifetimes. The parameters are specified in Table 2.

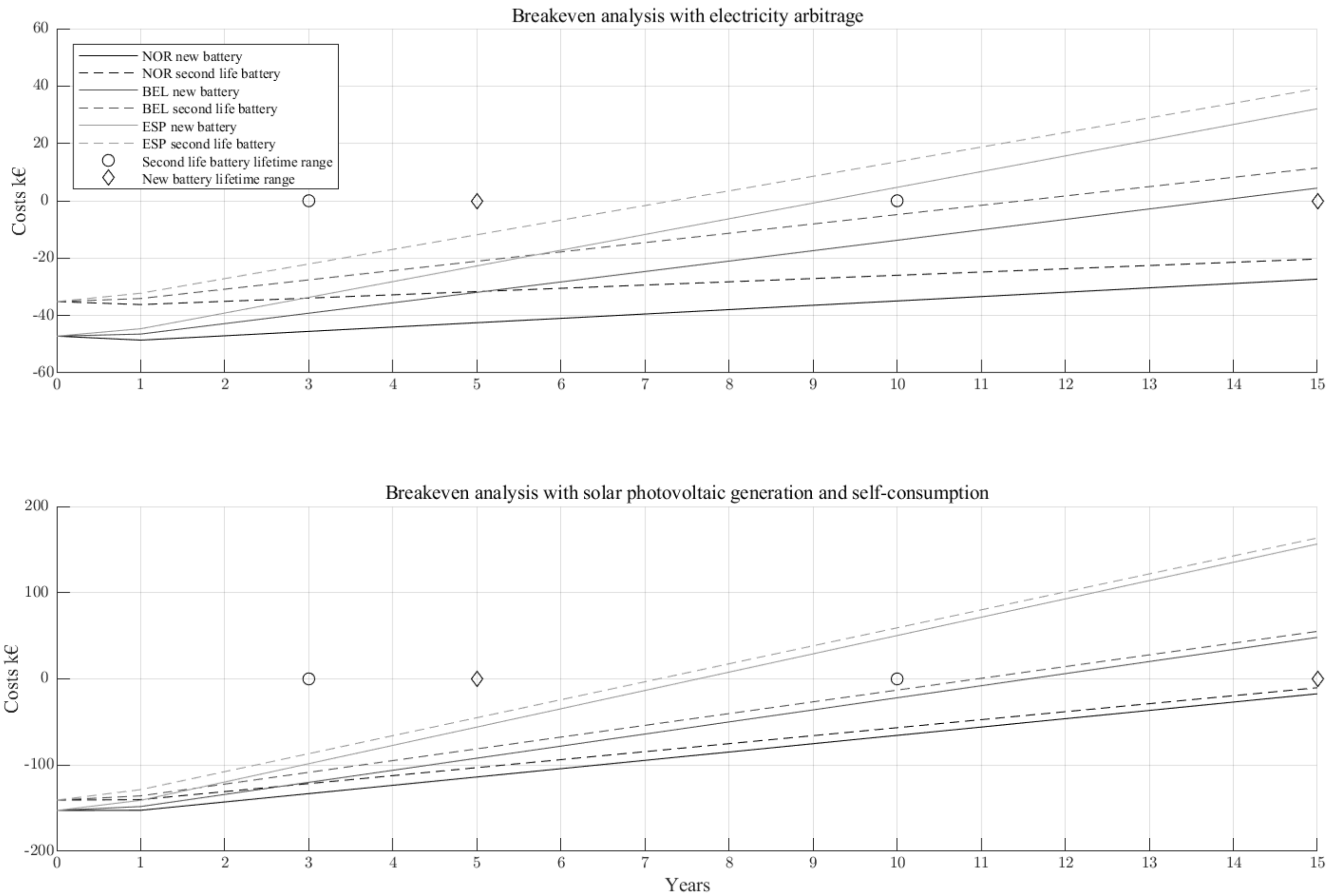


Figure 4. Breakeven points for battery investment scenarios for Norway (NOR), Belgium (BEL), and Spain (ESP), and estimated cycle lifetime range for a new and second life battery.

Figure 4 shows how the battery CBM was measured in terms of practicality and economic viability. These findings reveal that applying the repurpose CBM (i.e., the second life battery) reduces the price, which results in a decreased payback time of 0.5 to 2 years. However, the second life battery lifetime range is estimated to be lower (3 to 10 years) for second life batteries than for new batteries (5 to 15 years). Table 4 presents the calculations for the estimated battery cycle lifetime ranges.

Table 4. Calculation for expected battery cycle lifetime ranges.

	Cycle Lifetime	Reference
New	3000	Braco et al., 2020 [48]
Second life	2033	Jo et al., 2019 [47]
	Estimated cycles	
Min.	200	This study
Max.	600	This study
	Battery lifetimes based on cycles	
New min.	3000/600 = 5	
New max.	3000/200 = 15	
Second life min.	2033/600 = 3	
Second life max.	2033/200 = 10	

The lowest payback time on BESS investment for EM strategy purposes is 7 years. This was found for solar PV generation with self-consumption with a second life or a new battery (lower graph in Figure 4) and electricity arbitrage with a second life battery (upper graph) in Spain. The most viable scenarios also showed the highest number of charge/discharge cycles and thus the shortest battery lifetime. These findings indicate that the battery lifetime of the most profitable scenarios can be less than 7 years. In such a case, a battery system investment is not recommended as costs will not be covered before the battery reaches EOL. Thus, the number of years before the manufacturer reaches profit of the BESS investment is high in relation to the estimated battery lifetime range.

As part of the breakeven analyses, the 2020 battery price parameter was exchanged with the future predicted 2030 price. The calculation model revealed that the number of years before reaching breakeven was not reduced. This indicates that the annual revenue is insignificant compared to the battery investment costs. Thus, the battery price reduction is not necessarily crucial for businesses when deciding whether to invest in a BESS. However, firstly, the minimum payback time may be reduced in scenarios with a larger battery. Secondly, the battery price reduction does reduce the payback years in some scenarios in this study, but not for the most economic viable shown in Figure 4.

As indicated, the larger battery equates to a higher price. Therefore, the battery size should not exceed the BESS's needs. Size and capacity-to-power ratio should be thoroughly optimized for the BESS. If the battery does not have a sufficient capacity for the system, there will not be enough time to charge before the battery is in use again. For example, in an electricity arbitrage scenario when electricity prices are low over a certain period and the battery cannot store the available energy, economic savings might be hindered. Similarly, with local solar PV generation, the battery should have sufficient capacity to store the on-site generated energy.

Whether or not businesses invest in new or second life batteries can be determined by price [64], and this parameter can be crucial to outcompete new batteries [15]. Mathews et al. [15] found that the cost of a second life battery must be <60% of new batteries to achieve profitability. Despite that second life batteries are estimated to cost about half the price of a new battery [11], they do not ensure a profit, as illustrated in this study. Furthermore, future prices are uncertain and rely on several factors within technology, policy (societal and environmental), and economy. Technologically, it depends on (1) the primary consumption patterns (cycle lifetime), (2) requirements for the second life consumption, and (3) the number of years before the application (for example, EV) reaches EOL (calendar lifetime) [9].

Legislative incentives can stimulate a second life market [13]; however, the most recent EU battery regulation implies that market mechanisms shall determine commercial activities for second life batteries [65]. Large volumes of spent batteries from mobile applications due to strategic electrification of the transport sector are expected to reduce battery prices [66] and boost competitiveness for batteries for stationary storage [7]. Hence, the processed volumes will grow, and prices can decrease [11] due to reduced costs of refurbishing, as an example. However, the large volumes of LIBs in EVs are still in use on the road and it is currently challenging to predict future prices and the size of the second life market [9]. Additionally, affecting timing, there is a frequent assumption that a battery reaches first EOL when an EV battery reaches 80%; however, a remainder of 60% to 80% capacity is sufficient for most drivers [67,68]. Nevertheless, for second life batteries to outcompete new batteries, there needs to be an efficient quality system, including a regional collection system [69,70]. This is crucial for all CBMs for batteries [19]. Although such practice increases the selling price, it is vital to assure predictable, secure, and operational second life batteries.

5. Conclusions

In this work, the repurpose circular business model based on previous work is measured in terms of economic performance through a multiple scenario analysis with a case manufacturer as the basis for comparison. The battery simulation and economic analysis measured factors related to economic and circular viability of battery system investments for the business case. The simulation study was limited to seven European countries using four different strategies for the years 2018 and 2019. A breakeven-point assessment was chosen as a data analysis method to evaluate economic viability. Findings reveal diverging results for the different scenarios, and many are not economically viable. The results vary depending on if a new or second life battery is purchased, the battery system location, and the energy management strategies applied.

The breakeven analyses revealed that the shortest payback time among all scenarios is 7 years. This was revealed for solar PV generation with self-consumption (same for second life or new battery investment) and electricity arbitrage (with a second life battery) in Spain. The lifetime range based on estimated charge/discharge cycles was 5 to 15 years for a new battery and 3 to 10 years for a second life battery. The most profitable scenarios also showed the highest number of cycles, which indicates a lifetime potentially less than 7 years, thus no economic benefits, especially for the second life battery scenarios. The results reflect 2020 battery prices, but for comparison, the estimated 2030 battery prices did not reduce the minimum years of payback time. However, for other circumstances, this will be dependent on the battery size as total investment costs increase with size. For system operators and grid developers, some energy management strategies with battery energy storage system investments can potentially displace other costs, such as power plants, given that the systems contribute to balance demand and supply. This can economically encourage offering of incentives for businesses investing in battery energy storage systems connected to the grid but requires further investigation. The battery industry applying circular business models should be aware of the customer market connected to energy management strategies, such as the case manufacturer in this study.

To maximize economic benefits, it is recommended to combine several energy management strategies, and a manufacturer's electricity profile should be matched with the appropriate strategies. For example, load shifting is not considered valuable for manufacturers with low demand fluctuations during operation hours. Both load shifting and electricity arbitrage can be more beneficial for profiles experiencing peaks. With electricity arbitrage, lower regional electricity prices and fluctuations decreased battery activity and economic benefits. For businesses in regions with lower prices and fluctuations, there is not as much economic value to trade compared to regions with large variations during a day. For solar photovoltaic generation with self-consumption, a correlation between solar irradiation and economic savings was found. Thus, location is crucial for economic viability: High solar irradiation is beneficial for solar PV generation with self-consumption, and high electricity price and fluctuations is beneficial for the arbitrage strategy. Nevertheless, unidentifiable factors also affected the results for the different regions, illustrating the complexity of such techno-economic assessments.

The battery lifetime is an important parameter that will be shorter when the battery is more active per year. As illustrated in the breakeven analyses, the years of payback time must be lower than battery lifetime to reach economic viability, which this study shows is not always the case. It is therefore important to account for potential trade-offs between an active battery and its lifetime and years before reaching profit on the investment.

Investing in a second life battery reduced the payback time from 0.5 to 2 years due to lower investment cost. However, the battery needs quality assurance that includes a minimum battery lifetime that is longer than the years of payback time on the investment. This was not evident in all scenarios, and circular business models for batteries are not considered particularly more economic viable compared to new battery investment. Furthermore, most of the batteries stemming from electric vehicles are still in use on the road, the future second life battery market size is uncertain, and the price must be lower than for a new battery. The recent EU battery regulation did not allocate resources to enhance this market. Despite that, it may be environmentally preferable if second life batteries displace new batteries. Nevertheless, relevant policy makers should notice the potential of circular economy practice for batteries combined with energy management strategies. Through comparing a second life and a new battery investment, this study illustrates how a circular business model can be measured in terms of economic potential and compared to a traditional business model. Having assessed the economic potential, the environmental impact and consequences will be assessed next. Future research will use appropriate methodology to quantify and compare environmental consequences of the circular business model in multiple scenarios.

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Paper IV

Use of life cycle assessment to evaluate circular economy business models in the case of Li-ion battery remanufacturing

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LCA OF WASTE MANAGEMENT SYSTEMS

Use of life cycle assessment to evaluate circular economy business models in the case of Li-ion battery remanufacturing

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Abstract

Purpose The purpose of this study is to advance and illustrate how life cycle assessment (LCA) can assess circular economy business models for lithium-ion batteries to verify potential environmental benefits compared to linear business models. Scenarios for battery repurpose are assessed to support future decision-makers regarding the choice of new versus second life batteries for stationary energy storage. A procedure to determine the substitution coefficient for repurpose and reuse of batteries is proposed.

Methods Two different circular economy business models are assessed by applying primary data from two Norwegian companies for the development of a new life cycle inventory. With this new data, the authors compare second life battery (from first life in electric vehicle) scenarios and avoided production potential by performing a complete consequential LCA. Building on earlier work, a procedure to identify the substitution coefficient (i.e., potential for avoided production) for battery life cycle assessments is proposed. Interviews during factory visits were performed to identify a technical and a market factor affecting the substitution coefficient.

Results and discussion This study illustrates how life cycle assessment methodology can detect and thus enhance the potential environmental benefits and trade-offs of circular economy business models. Results show that the CBMs which use second life batteries correspond to 16% (for global warming potential) of manufacturing a new battery. This means that a second life battery must avoid > 16% production of a new battery to become the preferred alternative. Hence, circular economy business models with second life batteries can generate net environmental benefits while the remaining battery capacity and market price are identified factors that can alter the potential environmental benefits. The findings suggest that assumptions concerning the avoided production emissions are crucial for understanding the overall impacts of battery value chains.

Conclusions Circular economy business models which enable second life batteries show lower environmental impacts compared to a new battery when it can partly avoid production of a new battery. Based on the identified technical and market factor affecting this potential, a key message to industry and other organizations is that second life batteries should be chosen over new batteries. This depends on the remaining capacity being satisfactory for the new application, and the investment is not performed *because* of a low price compared to a new battery. Consequential LCA practitioners adopting a market approach while evaluating battery reuse and repurpose should model and account for the avoided production potential.

Keywords Circular economy · Life cycle assessment · Batteries · Substitution · Circular economy business models · Remanufacture

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1 Introduction

Demand for stationary energy storage such as high-capacity batteries to support grids and store renewable energies is increasing (IEA 2020). Simultaneously, the electric vehicle (EV) market, powered by Li (lithium)-ion batteries (LIBs) is growing continuously (IEA 2021). This development in LIB demand increases the consumption of metals and other valuable materials used in battery production (BloombergNEF

2022) while used LIBs are increasingly seen as a future waste problem (Pehlken et al. 2017). These trends require intelligent management of used batteries and battery materials to ensure that EVs (and their LIBs) are sustainable in a life cycle perspective. Circular economy business models (CBMs) can contribute to tackle the upcoming wave of used batteries (Jiao and Evans 2016; Olsson et al. 2018). A CBM is a plan for how a business can operate profitably while ensuring decreased environmental impacts through closed-loop supply chains and reduced resource consumption (e.g., sharing models, energy efficiency, and applying recyclable materials in primary production) (Bocken et al. 2019; Geissdoerfer et al. 2020; Lüdeke-Freund et al. 2019). CBMs can be used to implement sustainable strategies to manage a product after its first life, such as repurposing in a second life application prior to recycling of the materials. However, current research questions the real advantages of such circular economy (CE) efforts and recognize trade-offs where further assessment is needed to understand how these CBMs affect the life cycle environmental impacts of product systems (Manninen et al. 2018; Rigamonti et al. 2017; Saidani et al. 2019; Zink and Geyer 2017). Life cycle assessment (LCA) is a useful methodology to assess CE efforts, where consequential LCA methods can be used to determine if CBMs should be implemented (Haupt and Hellweg 2019; Ncube et al. 2022; Peña et al. 2021; Rigamonti and Mancini 2021; Stucki et al. 2021; van Loon et al. 2021). Consequential LCA aims to detect environmental consequences of future decisions (Frischknecht et al. 2017; Schulz-Mönninghoff et al. 2021), such as a choice between new business models (Løkke et al. 2020). LCA can thus be a valuable tool to support sustainable, circular business opportunities (Murakami et al. 2019).

Earlier LCA studies (Ahmadi et al. 2017, 2014; Bobba et al. 2018; Commission et al. 2018; Cusenza et al. 2019; Ioakimidis et al. 2019; Kamath et al. 2020a, b; Philippot et al. 2022; Richa et al. 2017; Wang et al. 2022; Wilson et al. 2021; Xiong et al. 2020) found that second life batteries have lower environmental impacts compared to new batteries. However, these studies did not include primary, new inventory data for the remanufacturing processes required to form a second life battery from an EV battery pack to a larger battery for a stationary energy storage applications as most LCA studies of LIBs rely on secondary data (Aichberger and Jungmeier 2020). Schulz-Mönninghoff and colleagues (2021) assessed repurposing of a battery pack, however, only included testing, calibration, software updates, and shipment to assembly site for the reassembly life stage in Germany. The study included new inventory data for the installation, however, not from battery module level (i.e., not dismantling the battery pack and reassembly the module parts for a second life battery pack). Current research on LCA of second life batteries does not currently have focus on the disassembly and remanufacturing processes.

In consequential LCA (cLCA), determining a precise substitution coefficient (i.e., the amount of avoided production due to use of a second life product or material) is crucial for life cycle impact assessment results (Chalmers et al. 2015). Despite this, several consequential LCA studies on waste management assume one hundred percent avoided production (causing negative emissions) for second life products and recycled materials, which is seldom the case (Heijungs and Guinée 2007; Rigamonti et al. 2020; Zink et al. 2016; Zink and Geyer 2017). There is an ongoing discussion on how to determine the substitution coefficient in LCA studies (Vadenbo et al. 2017). Rigamonti and colleagues (2020) suggest a guideline to develop the technical substitution coefficient, representing degree of technical replacement potential. The researchers encourage LCA practitioners to develop coefficients for other secondary materials or products to advance and harmonize their work. Market-related factors also affect the substitution coefficient, such as price mechanisms (Zink et al. 2016). Increased emphasis is needed on considering market characteristics such as substitution, rebound, and price effects in cLCA (Yang and Heijungs 2018). The authors are not familiar with other LCA studies that propose a technique to combine a technical and market factor to identify the substitution coefficient for batteries.

This study assesses the consequential environmental impacts between two different circular economy business model alternatives for second life LIBs based on two companies in Norway. These two CBMs utilizing used EV batteries for energy storage are compared to the existing linear business model using new LIBs. The first CBM enables repurposing of used EV battery packs for a second life in stationary energy storage systems to obtain increased self-sufficiency (i.e., reduced grid dependence by local renewable energy generation). The second CBM enables repurposing by dismantling the pack into modules and thereafter reassembly of the modules to a second life battery pack. The origin of the batteries and the second life application for both CBMs are identical but differ in how these used batteries are dismantled and reassembled. A new life cycle inventory is introduced for the two CBM cases including the remanufacturing and installation processes required. Applying consequential LCA, this research investigates real environmental effects of CBMs where batteries are repurposed in a stationary energy system as identified in earlier work (Wrålsen et al. 2021). As part of the complete assessment, a procedure for practitioners to identify the substitution coefficient in battery reuse and repurpose cases is proposed, implementing both a market and a technical factor. The methodological advancements are illustrated within the two cases described in Sect. 3.

2 Li-ion battery repurpose

Previous research shows that remanufacturing and repurposing is identified as the CBM with the highest potential for LIBs (Wrålsen et al. 2021). Battery repurpose is when a used battery is applied in a different application than it was originally designed and manufactured for, for example, if a battery has a first life in an EV and a second life in a stationary energy storage system. LIBs have high energy density compared to other batteries and are recognized as interesting for repurpose when there is remaining capacity left after first life (Melin et al. 2021; Neubauer et al. 2015; Wind et al. 2021). If there is remaining capacity left depends on the case-specific use and application. Thus, the lifetime of second life batteries will vary (Wrålsen and Faessler 2022). A study testing the cycle lifetime of a used EV battery with unknown user history found that the battery could be charged and discharged 2033 cycles (Braco et al. 2020). In cases where repurposing is considered, the used batteries can be tested through characterization to assess remaining capacity and suitability for repurpose (Harper et al. 2019).

Current CBMs which enable a second life remanufacture EV batteries at different levels, primarily (1) remanufacturing of the complete battery pack or (2) remanufacturing by first dismantling the pack to several modules and then reassembling a new pack based on these modules. This is possible as an EV battery pack consists of several connected battery modules. These modules consist of several battery cells. Since the commercialization of LIBs in 1991, researchers have worked to increase the energy density of the battery cells by testing different materials and compositions (Zhao et al. 2021). Several LIB chemistries are now in use in EVs. The longest (real) driving range in a commercialized EV is currently (in 2023) almost 700 km, according to EVDB (EV database 2023).

Remanufacturing enabling repurpose will extend the battery lifetime before the materials are recycled at the final end-of-life. Recycling technologies for LIBs are underdeveloped and repurpose will enable more time for LIB recycling technologies to improve (Kotak et al. 2021). These technologies must be improved as battery packs consist of several valuable materials, for example, aluminum, steel, copper, nickel, cobalt, and lithium. The two latter are the most critical in terms of reserves and supply risks (to some extent also nickel) (Xu et al. 2020). High-nickel batteries such as the lithium nickel manganese cobalt oxide (NMC)811 chemistry is a growing trend, reducing market share of lower nickel content chemistries such as NMC 111. Chemistries without cobalt is also a growing trend (Wind et al. 2021).

Recognized battery repurpose applications can be grouped into (1) in-front-of-the-meter applications (i.e., the power passes through the meter before reaching the end-user), (2) behind-the-meter (i.e., the power can be used on-site), and (3) off-grid (i.e., battery systems not connected to the electricity grid). A second life battery can for example be used for energy arbitrage where the battery stores electrical energy when the electricity from the grid is cheap to purchase and uses this when the electricity price is high. This is an example of a repurpose application in-front-of-the-meter. The used battery with remaining capacity can alternatively be used for peak shaving to reduce the demand peaks which often cost more. This is an example of a repurpose application behind-the-meter (Faessler 2021). A disadvantage of second life batteries, and a potential challenge with repurpose practice, is that the batteries are designed for their first use application (e.g., an EV) and are therefore not technically optimal for the second life application (Rallo et al. 2020; Reinhardt et al. 2019).

3 Case studies

The life cycle inventory list in this study is based on two existing projects from two Norwegian companies working with different circular economy business models. Both projects apply used EV batteries for stationary energy storage systems for storing solar energy to increase self-sufficiency of electricity and decrease grid dependence.

3.1 Circular economy business model 1: Eco Stor

Eco Stor AS was established in 2018 in Norway to commercialize stationary energy storage solutions based on second life batteries from electric vehicles (Eco Stor AS 2022). The company offers solutions for applications such as solar energy storage (increased self-consumption), peak shaving, grid infrastructure support, and demand side grid trading. Their subsidiary company in Germany uses new batteries in large-scale systems for grid support applications (linear business model), and in Norway, second life battery packs from electric vehicles are used (circular economy business model). The used battery packs are sent from central Europe to Eco Stor in Norway by their vehicle manufacture business partners. This car manufacturer characterizes and sorts the used batteries to ensure only quality battery packs with sufficient remaining battery capacity are repurposed. Repurposing used battery packs from EVs can be challenging due to the lack of data sharing from the battery management system (BMS). The BMS programming code and historic consumer data is currently protected by the owner to hinder hacking and to secure business value. This hinders third-party firms like Eco Stor from having a history of battery cycling and battery state of health, which is critical to understanding how the used batteries can be repurposed (Faessler 2021). Therefore, cooperation with an electric vehicle manufacturer and

BMS owner is key to success for this CBM. The life cycle inventory list built for CBM 1 (repurposing battery packs) in this study reflects the required resources to build generic racks with battery packs applied for stationary energy storage projects. For this case, the energy storage system consisted of a 280 kWh battery system.

3.2 Circular economy business model 2: Batteriretur

Batteriretur is a Norwegian company approved to collect all types of used batteries in Norway, including high-capacity batteries such as lithium-ion batteries from EVs (Batteriretur 2022). The company is owned by several vehicle manufacturers and is responsible to treat the used batteries sustainably according to the European Union's Battery Directive from 2006 (European Union 2006). This directive states that the actors distributing the battery on the market are responsible for providing a collection (take-back) system and to recycle it to the full extent possible. The end-of-life collection, discharge of pack, characterization, dismantling of pack, and further distribution are Batteriretur's responsibility, and they do this on behalf of the battery market distributors. There are two options for the final distribution stage, as the batteries can either be sold to second life distributors or battery recyclers. Currently, most used batteries are sent for treatment and recycling in Europe. To analyze potential economic and environmental gains, Batteriretur developed a pilot project using second life battery modules (the main pack components) from EVs to store solar energy at their plant to reduce their dependency on the grid. The inventory built for CBM 2 (battery modules) in this study reflects the required resources for this pilot project. The case energy storage consisted of a 500 kWh battery system.

4 Material and methods

4.1 Goal and scope

The goal of this LCA study is to assess the environmental consequences of two CBMs which utilize used EV battery packs (CBM 1) and modules (CBM 2) for battery energy storage systems. A secondary goal of this study is to compare these two CBMs with a new NMC 811 battery pack used for the same purpose. The two CBMs are assessed as part of three different scenarios where avoided production (potential for a second life battery to replace new production) is included. The scope includes the resources required to remanufacture a used EV LIB for a new life in a stationary energy storage system and installation in this new application. The functional unit of this study is 1 kWh capacity (second life) NMC 811 battery pack. The inventory is modelled in mass, where 1 kWh capacity NMC 811 battery pack weights 6.7 kg (Crenna et al. 2021).

This study uses a consequential modeling approach that aims to achieve relevant information about environmental consequences to support prospective decisions and considers the consequences of decisions within the market (Ekvall and Weidema 2004; Yang and Heijungs 2018). The decision considered in this study is choosing a traditional, linear business model with a new LIB for stationary energy storage versus second life batteries based on two different CBMs. To account for the potential avoided production, substitution is included in the modelling. This method is preferred by the ISO 14044:2006 (ISO 2006) standard for LCA, where "negative" impacts from avoided production can be included (ISO 2006). CBM 1, CBM 2, and the new battery have the same function: 1 kWh of battery capacity ready for use in a stationary energy storage system application. It is crucial that these product systems are comparable to examine effects of substitution (Weidema 2000). Figure 1 shows the required processes for the two CBMs. Recycling of the materials is outside the scope of this study.

The complete, unmodified battery pack is used in CBM 1, and thus, dismantling, characterization, sorting, and reassembly are not part of the scope for CBM 1. Dismantling and reassembly are not necessary because the complete battery pack from the EV is used in the second life battery pack. Characterization and sorting, checking the state-of-health of the battery packs, and sorting them are done before the battery packs are received by the case company. CBM 2 requires characterization and sorting which are assessed within the scope. As this CBM builds second life battery packs based on battery modules from EVs, the dismantling of the battery packs and reassembly of the modules are required processes. The manufacturing of the machinery and tools at the remanufacturing plant are not included within the scope of either CBMs.

4.2 Life cycle inventory data

The inventory data for each CBM was collected from the two case companies. Both companies were visited following a digital interview. The company visits and the digital interviews followed the same semi-structured interview guide to secure the most crucial information for the inventory while being open to additional relevant information. Before and after the interview, the authors had e-mail correspondences with the case companies discussing relevant processes and developed a basic data collection procedure for collecting the inventory data at each company. Background data is from the consequential Ecoinvent database v.3.8 (Wernet et al. 2016) where a global approach on material production was adapted, except for production of new LIBs, which was assumed to come from China. The major upstream supply for new batteries comes from China; although Europe and the USA are expected to increase their market share (IEA

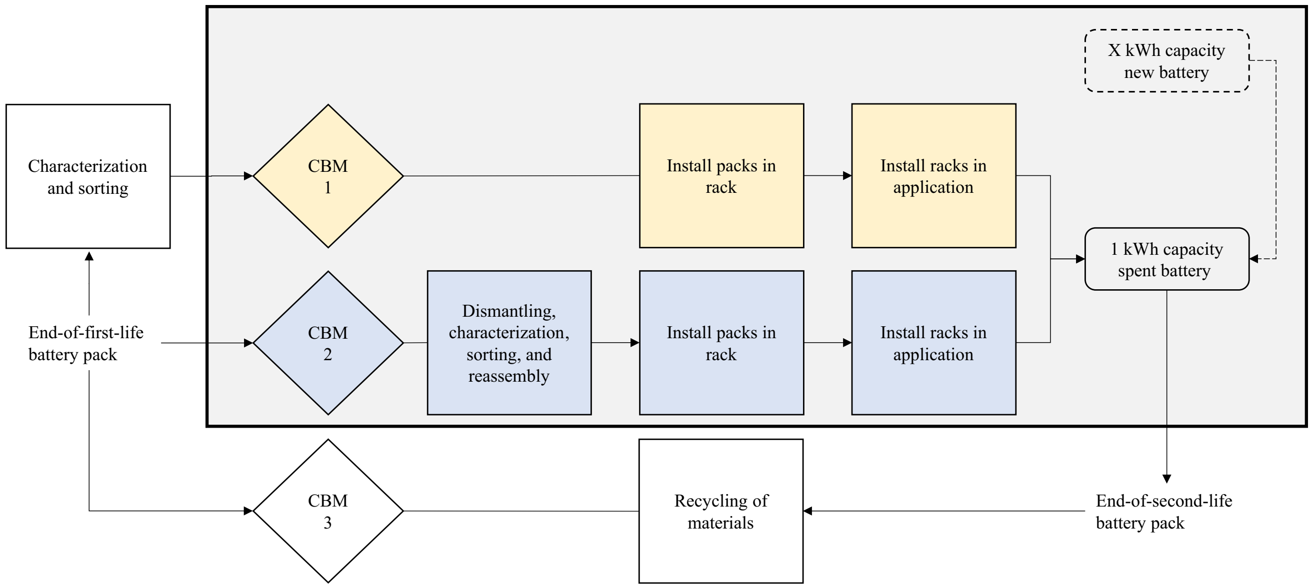

Fig. 1 Bold border and gray area represent system boundaries: the scope includes circular economy business model (CBM) 1 and 2 for lithium-ion batteries (LIBs). Stippled lines represent substitution potential

2022; Melin et al. 2021), it is assumed in this study that most new batteries will continue to be produced in the near future in China. When a new NMC 811 battery is displaced, it is therefore expected that the change in production (avoided) will occur in China as they are considered the main marginal supplier of batteries. All data sources for the inventory are listed in Table 1.

4.3 Impact assessment

SimaPro 9.3.0.2 (PRé Sustainability 2021) was used to build the inventory model and perform the impact assessment. ReCiPe 2016 Midpoint, Hierarchist (H) perspective, version 1.06 (Huijbregts et al. 2016) is the characterization method used in this analysis. It includes 18 impact categories which are assessed to avoid problem shifting between different environmental areas of protection. Global warming, mineral resource scarcity, and water consumption are the main impact categories highlighted in the "5.3" section as they have been identified as being important in previous battery assessments (Ahmadi et al. 2017).

4.4 Scenario analysis

In a market perspective, repurposing batteries can decrease the demand for new batteries and potentially avoid production of these (i.e., avoid impacts from the cradle-to-gate life stage: extraction of raw materials required for new batteries, the processing of the materials, and the battery cell manufacturing). To examine such consequences, three scenarios are assessed based on different substitution coefficients (i.e., degree of decreasing demand of battery due to repurpose of a used LIB). Rigamonti et al. (2020) proposed a procedure based on technical properties for practitioners applying consequential LCA modelling, which is applied in this study. According to the case companies in this study, the remaining battery capacity appears as a crucial technical factor for battery repurposing and is considered as the main

Table 1 Data and source

Data	Source	Specification
Circular economy business model 1 inventory	Case company 1	Resources required for the (foreground) processes
Circular economy business model 2 inventory	Case company 2	Resources required for the (foreground) processes
Background processes	Ecoinvent v3.8	Norwegian electricity mix for remanufacturing and testing
New battery inventory	Ecoinvent v3.8	Lithium-ion battery with chemistry NMC811
Technical factor determining substitution coefficient	Both case companies	Interview during visit, May 2022
Market factor determining substitution coefficient	Both case companies	Interview during visit, May 2022
Factors affecting battery market price	Both case companies	Illustrated in Fig. 2

factor for determining the technical substitution coefficient for second life LIBs. Battery charge–discharge cycles and calendar aging lead to reduced capacity (measured in kWh) while the second life LIB capacity can also be hindered if the battery was optimized for another application in the first life. Regardless, a battery should have > 60% of the original capacity remaining after end-of-first-life to be used in second life applications (Faessler 2021; Martinez-Laserna et al. 2018). Thus, if an EV battery has aged from 100 to 80% of its original capacity, roughly 50% of the total lifetime is used in its first life and 50% remains for second life. Equation 1 illustrates how to calculate the technical substitution coefficient and exemplifies a 50% capacity remaining. The procedure is based on Rigamonti et al. (2020).

$$\begin{aligned} TSC &= \frac{TP(SecP)}{TP(SubP)} \\ TSC &= \frac{kWh(SecP)}{kWh(SubP)} \\ TSC &= \frac{0.50(SecP)}{1(SubP)} = 50\% \end{aligned} \tag{1}$$

Equation 1 presents the proposed technical property for lithium-ion batteries and example of how the technical substitution coefficient is calculated (TSC, technical substitution coefficient; TP, technical property; SecP, secondary product; SubP, substituted product).

Market factors also affect the potential for avoided production as the flow of products and materials are integrated in market structures and mechanisms. A consequence of remanufacturing LIBs and selling these as second life batteries is increased supply of batteries. As a result, the price can be affected through price elasticity of demand. This price effect is present in the circular economy rebound concept by Zink and Geyer (2017) and frames the main market factor affecting the substitution coefficient for this study. If the second life LIB price is lower than a new LIB (often the case currently), the battery may be purchased *because* of the low price. The three business model characteristics affecting the LIB price illustrated in Fig. 2 were revealed during case company dialogues. Through identifying these characteristics, the assumed LIB price effect on the substitution coefficient becomes more robust.

Table 2 shows how the substitution coefficient is identified for the LCA based on the technical and market factors.

Equation 2 illustrates the final step to combine the technical and market factor to find the combined coefficient applied in this LCA study.

$$\begin{aligned} \frac{(TC + MC)}{2} &= CC \\ \frac{(0.5 + 0.5)}{2} &= 0.5 \end{aligned} \tag{2}$$

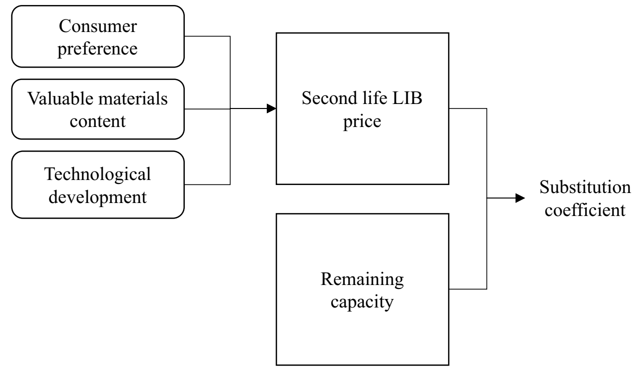

Fig. 2 Key market and technical factor affecting avoided production in battery reuse and repurpose cases. To the left, three business model characteristics affect the dynamic market price

Equation 2 presents the final step to calculate the combined coefficient to apply in the LCA (TC, technical coefficient; MC, market coefficient; CC, combined coefficient).

5 Results and discussion

5.1 Life cycle inventory

The inventory for CBM 1 represents the required resources to remanufacture and install second life battery *packs* in a 280 kWh stationary energy storage system. The inventory for CBM 2 represents the required resources to remanufacture and install second life battery *modules* in a 500 kWh stationary energy storage system. Porzio and Scown (2021) suggest phasing out use of battery mass as functional units in LCAs due to a large variation of chemistries and pack design. Hence, the inventory list in Table 3 is normalized to 1 kWh.

5.2 Life cycle impact assessment

The two CBMs are in different substitution scenarios compared with a new battery. The CBMs represent two different second life batteries remanufactured for stationary energy storage.

Table 2 How the remaining capacity and the second life battery price affect the substitution coefficient

Remaining capacity (%)	LIB price	Coefficient (%)
≤ 60	Second life < new	0
80	Second life < new	0.5
100	Second life ≥ new	1

Table 3 The resources required for circular economy business model (CBM 1 (Eco Stor); CBM 2 (Batteriretur); and a new battery, ready for (second life) stationary storage use per functional unit (1 kWh battery capacity))

Resource	CBM 1 (pack)	CBM 2 (module)	New (pack)	Unit
Steel rack (reusable one time)	1.250	0.700	1.250	kg
Battery interface unit	0.005	-	0.005	kg
Cables	0.288	0.288	0.288	kg
Circuit breakers and junction boxes	0.050	-	0.050	kg
Electricity, Norwegian	1.019	13.780	-	kWh
Inverter	0.058	0.058	0.058	p
Inverter rack	0.357	-	0.714	kg
Router	0.001	-	0.001	p
Electricity losses during startup test, Norwegian	0.014	0.008	0.014	kWh
Switch, power supply, e-stop, energy management system, extra controller	0.012	0.007	0.012	kg
New mini-BMS for modules	-	0.003	-	kg
Copper rail	-	0.083	-	kg
Electronics	-	0.050	-	kg
Main BMS (laptop)	-	0.02	-	p
Production of NMC811 (Ecoinvent)	−6.7	−6.7	6.7	kg

Table 4 shows the complete life cycle impact assessment (LCIA) results for all 18 categories. The two CBMs are in different substitution scenarios compared with a new battery. The CBMs represent two different second life batteries remanufactured for stationary energy storage.

The scenarios with 0% substitution show only impacts from the remanufacturing and installation processes required to transform a used EV battery to a functional second life battery. The scenarios with 50% substitution include negative impacts caused by 50% of the impacts from production of a new battery (−24.6 * 0.50). The scenarios with 100% substitution include negative impacts caused by 100% of the impacts from production of a new battery (−24.6 * 1). Thus, the two latter scenario groups show negative impacts in some of the categories. Mineral resource scarcity and terrestrial acidification show negative impacts, also for scenario i. with 0% substitution. This is mainly due to two by-products from copper processing for the inverter: firstly, the rare-earth metal palladium from electronics scrap in anode slime, and secondly, the rare-earth mineral molybdenite. As impacts associated with by-products are subtracted from the total in consequential LCA methodology, the net impacts can become negative. Smelting of copper concentrate is responsible for the majority of the terrestrial ecotoxicity impacts (553.1 kg 1,4-DCB with 0% substitution). The contribution analysis for the highlighted categories is shown in the supplementary information document.

The results show that the difference between the two CBMs is small (≤ 0.1) for all categories. As the CBM 1 case consisted of a 280 kWh sized system and CBM 2 was a 500 kWh system, the impacts from CBM 1 can be marginally lower as the resources required (Table 3) is divided by the total size of the system to obtain the functional unit of 1 kWh. Some, e.g., electronics are equal independent of this size range. Figure 3 compares the CBMs with a new battery for stationary energy storage and highlights three impact categories. The results are illustrated with three substitution scenarios (i. 0%, ii. 50%, and iii. 100%).

5.3 Discussion

The main results of this study show that the repurposing of used EV batteries for energy storage systems at both the pack and module level is environmentally advantageous compared to using new batteries. This confirms the findings in literature related to battery reuse and repurposing. The three substitution coefficient scenarios in Fig. 3 illustrate the significant effect assumptions on avoided production potential have on impact assessment results. Consequentially, if using the second life battery cannot avoid any production of new batteries, the resulting impacts are higher for choosing one of the battery solutions from the CBMs compared to a new battery. Thus, CBMs utilizing second life LIBs can lower environmental impacts in all categories if some production of a new battery is avoided.

This study developed a procedure for assessing the impacts of battery reuse and repurposing and emphasizes the importance of not neglecting substitution coefficients in LCA studies. In scenario iii., the second life batteries from the CBMs fully replace (substitute) a new battery and avoid production and thus environmental impacts, while in scenario i., where 0% substitution is assumed, the second life battery is consumed *in addition* to a new battery due to market expansion. The consumption of a second life battery will in this scenario not reduce the use of new batteries but increase the total number of batteries on the global market.

Table 4 LCIA results for CBM 1 (second life battery packs) and CMB 2 (second life battery modules) for all impact categories in three substitution scenarios and a new battery. Values per kilowatt-hour battery capacity

Impact category	Unit	CBM 1, 0% substitution	CBM 1, 50% substitution	CBM 1, 100% substitution	CBM 2, 0% substitution	CBM 2, 50% substitution	CBM 2, 100% substitution	New
Global warming	kg CO2 eq	4.04E+00	−6.26E+00	−1.66E+01	3.97E+00	−6.33E+00	−1.66E+01	2.46E+01
Stratospheric ozone depletion	kg CFC11 eq	2.76E-06	1.04E-07	−2.55E-06	3.03E-06	3.69E-07	−2.29E-06	8.07E-06
Ionizing radiation	kBq Co-60 eq	1.91E-01	−1.94E+00	−4.08E+00	1.91E-01	−1.95E+00	−4.08E+00	4.46E+00
Ozone formation, human health	kg NOx eq	2.11E-02	3.96E-02	5.81E-02	2.21E-02	4.07E-02	5.92E-02	−1.60E-02
Fine particulate matter formation	kg PM2.5 eq	−4.32E-02	−3.87E-02	−3.43E-02	−4.16E-02	−3.71E-02	−3.27E-02	−5.20E-02
Ozone formation, terrestrial ecosystems	kg NOx eq	2.18E-02	4.01E-02	5.84E-02	2.29E-02	4.12E-02	5.95E-02	−1.48E-02
Terrestrial acidification	kg SO2 eq	−1.60E-01	−8.86E-02	−1.76E-02	−1.53E-01	−8.21E-02	−1.11E-02	−3.02E-01
Freshwater eutrophication	kg P eq	5.22E-03	−4.25E-03	−1.37E-02	5.01E-03	−4.46E-03	−1.39E-02	2.41E-02
Marine eutrophication	kg N eq	1.69E-04	−2.09E-03	−4.36E-03	1.46E-04	−2.12E-03	−4.38E-03	4.70E-03
Terrestrial ecotoxicity	kg 1,4-DCB	5.53E+02	1.47E+03	2.38E+03	6.27E+02	1.54E+03	2.46E+03	−1.28E+03
Freshwater ecotoxicity	kg 1,4-DCB	2.26E+00	−1.45E+00	−5.17E+00	2.19E+00	−1.52E+00	−5.24E+00	9.69E+00
Marine ecotoxicity	kg 1,4-DCB	2.99E+00	−1.25E+00	−5.48E+00	2.93E+00	−1.30E+00	−5.54E+00	1.15E+01
Human carcinogenic toxicity	kg 1,4-DCB	7.82E-01	9.42E-01	1.10E+00	8.27E-01	9.87E-01	1.15E+00	4.63E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	5.69E+01	4.49E+01	3.28E+01	6.05E+01	4.84E+01	3.63E+01	8.10E+01
Land use	m2a crop eq	5.11E-01	1.95E+00	3.38E+00	5.85E-01	2.02E+00	3.45E+00	−2.36E+00
Mineral resource scarcity	kg Cu eq	−1.80E-01	−3.66E+00	−7.15E+00	−2.24E-01	−3.71E+00	−7.19E+00	6.79E+00
Fossil resource scarcity	kg oil eq	1.07E+00	−2.91E+00	−6.88E+00	1.05E+00	−2.93E+00	−6.91E+00	9.02E+00
Water consumption	m^3	5.25E-02	−1.85E+00	−3.76E+00	7.29E-02	−1.83E+00	−3.74E+00	3.86E+00

A lower battery price leads to a higher number of consumers willing to purchase a battery, which means more batteries in total according to the circular economy rebound concept (Zink and Geyer 2017).

The remaining battery capacity (technical factor) and battery price (market factor) were identified as important for the substitution coefficient for LCAs assessing reuse and repurpose of batteries. Building on work by Rigamonti and colleagues (2020) and Zink and colleagues (2016), the procedure for calculating the substitution coefficient proposes to account for both factors by combining them in the calculation. Although battery price is recognized as important, it is dynamic and regionally based and thus challenging to use as a parameter in LCA models. To increase predictability, three business model characteristics affecting the LIB price are identified (illustrated in Fig. 2):

1. Demand for second life batteries based on consumer preference (e.g., perception of quality and security).
2. Valuable materials affect economic value (e.g., older batteries can contain more cobalt).
3. Technological development integrated in new batteries can lower value of the older batteries (e.g., improved battery energy density).

These business model characteristics affect the battery price and thus the substitution potential of the second life batteries. By understanding the CBMs assessed, more realistic assumptions were made during the LCA modelling. Hence, CBM insights are valuable when calculating the substitution coefficient to understand the factors affecting the potential for avoided production.

By assessing the CBM for batteries proposed in Wrålsen et al. (2021), this study found the potential environmental benefits from this CBM compared to a linear business model. In percentage, the comparison shows that the remanufacturing process of the used batteries corresponds to 16% of the global warming impact of producing a new battery. A

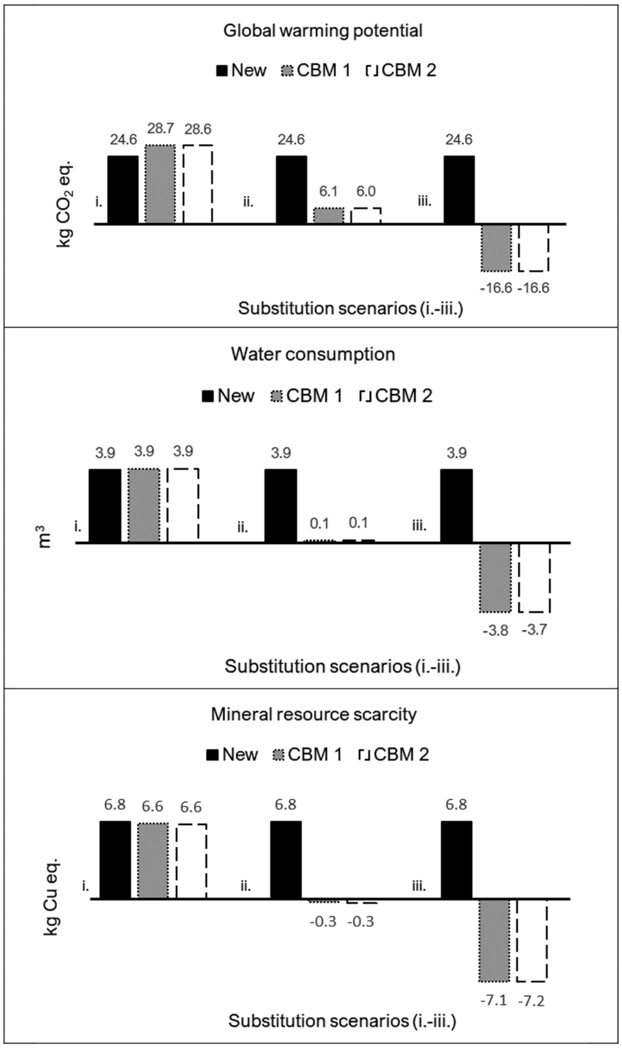

Fig. 3 Impacts of a second life battery from two different CBMs with no (scenario i.), 50% (ii. dotted line), and 100% (iii. stippled line) avoided production of a new NMC811 battery

minimum of 16% production needs to be avoided for second life batteries to contribute to climate change mitigation. For water consumption, this is valid when a used battery can replace 3% of a new battery. For mineral resource scarcity, this is valid even with 0% substitution. CBMs (which aim to gain environmental benefits) should be assessed for different environmental impact categories to quantify potential benefits and avoid problem shifting between different environmental areas of protection.

6 Conclusion

This study illustrates the possibilities and advantages of applying life cycle assessment to assess circular economy business models with the case of used lithium-ion batteries from electric vehicles. When comparing the impact of second life batteries facilitated by the circular economy business models with new batteries, results show that the latter has generally higher environmental impacts. Global warming potential results show that the remanufacturing of used batteries corresponded to 16% of emissions from manufacturing. The water consumption corresponded to 3% and mineral resource scarcity to 0%. Despite the relatively low impacts from the battery remanufacturing process, the results indicate that there is a relatively low threshold for environmental benefits by utilizing second life batteries to replace and avoid production of new batteries.

For organizations and individuals choosing between new and second life batteries, an investment in the latter is proposed if (1) the remaining technical capacity is sufficient for the new application and (2) the second life battery investment is not performed *because* of a lower price compared to a new battery but is acquired instead of a new battery. Hence, it should be able to replace a new battery with second life batteries to some extent. If these two technical and market factors are considered, the environmental advantages of the circular economy business models are validated through the results of this study.

For LCA practitioners working with consequential modelling, and particularly in circular economy contexts, the substitution coefficient is essential for improving the precision of the life cycle impact assessment results. It is recommended that the potential for avoided production should be identified for each specific study, preferably based on both technical and market factors. The proposed procedure can be applied to other products or product components. Furthermore, business model characteristics affecting market prices can be useful to understand the dynamics and thus improve the substitution coefficient in the model.

This study shows that life cycle assessment is valuable to examine if circular economy business models gain net environmental gain as pledged and to evaluate problem shifting to support decision-making. The substitution coefficient appears crucial for impact results, and future research should advance methodology for practitioners to calculate the avoided production potential, also for other second life products.

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Data availability All data generated or analyzed during this study are included in this published article and its supplementary information file.

Declarations

Conflicts of interests The authors declare no competing interests.

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