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Published in:
Sustainable Production and Consumption

DOI (link to publication from Publisher):
10.1016/j.spc.2022.11.025

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Sustainable Production and Consumption 35 (2023) 559–575

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Key tasks for ensuring economic viability of circular projects: Learnings from a real-world project on repurposing electric vehicle batteries

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ARTICLE INFO

Article history:
Received 18 August 2022
Received in revised form 27 November 2022
Accepted 29 November 2022
Available online 5 December 2022

Editor: Prof. Konstantinos Tsagarakis

Keywords:
Circular economy
Circular business models
Battery energy storage system
Second life
Net present value
Life cycle cost

ABSTRACT

In order to reach sustainable consumption and production patterns at scale, the implementation of a circular economy (CE) and the corresponding circular business models (CBM) increasingly need to become competitive with linear alternatives. This is inhibited by a lack of customer focus when implementing circular projects today. To address this challenge, this study presents an in-depth study of a real-world project on repurposing electric vehicle batteries in stationary battery energy storage systems in Germany, which serves to investigate the role of market- and customer requirements in implementing CBM. By combining quantitative analysis based on secondary sources with primary qualitative data collected at different stages of the project, the study offers unique insights into the practical key tasks for ensuring economic viability of circular projects from a multi-stakeholder perspective. These are identified as: i) Develop the product platform, ii) assess multiple value streams, iii) leverage on resource value, iv) provide risk assurances on product quality, v) observe trends in targeted downstream markets, vi) acquire access to suitable financial capital and vii) carry out pilot projects under market conditions. By addressing these tasks, the value captured in terms of the contribution of repurposing to the reduction of battery life cycle cost is found to be 109€/kWh in the case investigated. Based on the findings, the study concludes that implementing circular projects requires companies to provide resource, time and technical expertise for coordinating the identified key tasks and achieve competitiveness with linear alternatives. For future research, we hence suggest further investigation of the use of customer-oriented methods for assessing and developing CBM, as well as required policy-action to ensure commercial viability of CE strategies in industry.

1. Introduction

In order to achieve sustainable production and consumption of resources in accordance with sustainable development goals (SDG) defined in the Paris Agreement (United Nations, 2015), the introduction of a Circular Economy (CE) is seen as a way forward (Geissdoerfer et al., 2017; Ghisellini et al., 2016). Besides policy-action towards a CE adoption, one way for businesses is to engage in so-called circular business models (CBM), which are identified as one specific category of sustainable business models in research (de Angelis, 2018; Ferasso et al., 2020; Geissdoerfer et al., 2020). Hence, the key challenge for businesses is to establish CBM as a competitive alternative to linear ones, taking into account environmental and economic profitability for both customers and manufacturers. However, such transition towards a widespread adoption of CBM is currently lacking behind (Calisto Friant et al., 2021).

One possible explanation is provided in literature on implementing CBM, stating that “currently, the characteristics of customers and users targeted by specific [CBMs] are only weakly defined, when these are defined at all […]” (Lüdeke-Freund et al., 2019). The authors further state that this issue of a manufacturer-centric view on CBM “translates into revenue models that barely account for, or completely disregard, user heterogeneity” (Lüdeke-Freund et al., 2019), thereby indicating that economic success of CBM relies on thorough consideration of customer requirements.

In the mobility sector, this challenge is particularly relevant for the case of electric vehicle (EV) batteries, which are responsible for a large share of the future resource consumption of personal mobility (European Commission, 2020a). As the vehicle market is still quantity-driven and the number of vehicles still increases globally (European Environment Agency, 2010), implementing sustainable management of resources used for mobility and batteries in particular is seen as a key

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https://doi.org/10.1016/j.spc.2022.11.025

challenge (Bonsu, 2020). Among the available options for CBM for batteries, Battery Second Use (B2U) describes the possibility of repurposing EV batteries after their use in the EV in stationary battery energy storage systems (BESS) (Martinez-Laserna et al., 2018a). From a sustainability perspective, B2U on the one hand addresses SDG 12.5, i.e. "reduce substantially waste generation through prevention, reduction, recycling and reuse by 2030" (United Nations, 2015), through increasing material circularity of battery resources. At the same time, B2U contributes to SDG target 7.2, i.e. to "increase substantially the share of renewable energy (RE) in the global energy mix by 2030" (United Nations, 2015), by supporting the deployment of BESS as key component in future electricity grids (Reinhardt et al., 2020; United Nations, 2015).

The rational for repurposing EV batteries is that it creates value in energy systems, which can be captured by manufacturers (Bowler, 2014). However and despite some analysis of the economic implications of B2U (Madlener and Kirmas, 2017; World Economic Forum, 2019), the mechanisms and success factors for capturing economic value from B2U projects are still not well understood. This resonates with the findings of (Reinhardt et al., 2019) who investigate the role of different stakeholders in implementing B2U. The authors state how „it appears that multi-stakeholder business models are preferred over integrated business models", and suggest that "further practical rich case studies that take a multi-stakeholder perspective must be carried out to evaluate how [original equipment manufacturers] are forming such collaborative agreements to capture the full value of [B2U]" (Reinhardt et al., 2019).

Based on these findings, we identify a research gap on how manufacturers can focus on customer value and ensure economic viability of CBM. Hence, we investigate this gap based on the case of B2U and focus on the practical tasks required to ensure value creation for the targeted customers, i.e. the users of stationary battery energy storage systems from repurposed batteries in the context of an energy systems. For that, the research question is formulated as follows:

Research question: What are the key tasks for ensuring economic viability when implementing battery storage projects based on repurposed electric vehicle batteries?

To address this question, this paper presents an in-depth case study of a real-world project on implementing B2U in Germany, which has been followed over a time span of more than 2 years. The study documents the process of defining customer requirements based on qualitative data collected from project stakeholders, thereby offering unique insights into the challenges and required tasks when implementing business models based on repurposed products. Furthermore, it provides a detailed representation of the resulting business case for using repurposed batteries from the perspective of the storage customer in the case study. By linking customer-related findings to economic benefits of battery repurposing for manufacturers, this study presents, to our knowledge, one of the first comprehensive case studies on the CBM implementation process, which takes a multi-stakeholder approach.

For that, the study is structured as follows: firstly, we review recent literature to lay the foundation on how to analyze B2U as a CBM in Section 2. Afterwards, we present the research approach and the conceptual framework applied to the case study in Section 3. The results on identified customer requirements, the economic feasibility study of the B2U project and the resulting contribution to the reduction of battery Life Cycle Cost (LCC) are presented in Section 4. We then discuss the results in terms of the relationship to existing theory, the practical lessons learned for CBM implementation in general and the implications for policy-making in Section 5. Lastly, we summarize the findings and conclude directions for future research in Section 6.

2. Literature review

This section introduces relevant literature to the research question. In Section 2.1, the concept of CBM is described in relation to existing business model literature. Section 2.2 afterwards summarizes existing research on the challenges for implementing CBM. These are then further detailed for the case of EV batteries in Section 2.3, including a review of the value creation mechanisms of B2U and alternative CBM options.

2.1. Conceptualizing circular business models

The most common framework for conceptualizing business models is the business model canvas, which evolves around how a company creates, delivers and captures value (Osterwalder et al., 2010). As such, the original understanding of a business model evolves around value capture as describing customer value and economic returns (Richardson, 2008). Furthermore, the business model perspective adds considerations of the means through which value is created and captured (Demil et al., 2015). This view is extended by the concept of so-called sustainable business models, in which economic value captured is combined value and environmental and social benefits in a stakeholder network (Geissdoerfer et al., 2018).

In this context, CBM can be viewed as one case of sustainable business models (Bocken et al., 2014; Geissdoerfer et al., 2018), which are characterized by a creating competitive advantage through superior customer value and contributing to a sustainable development of the company and society (Lüdeke-Freund, 2010). Generally, CBM are presented as the concept in literature, which links a CE to different theoretical lenses of strategic management for companies and thus facilitates the adoption of CE in current business practices (De Angelis, 2018; Urbinati et al., 2017). The concept of CBM thus holds the potential to help companies analyzing and further developing current business models towards integrating CE strategies of narrowing, slowing and closing (Bocken et al., 2016). In this regard, different patterns of how companies can achieve CBM innovation are identified in literature, which include CBM diversification, CBM acquisition, CBM transformation and through Circular Start-ups (Geissdoerfer et al., 2020).

In term of characteristics of CBM, six major CBM patterns have been identified in the literature, each connected to specific business model elements (Lüdeke-Freund et al., 2019). Notably, the authors emphasize the importance of stakeholder involvement in CBM development and state how "*most CEBMs obviously rely on partnerships and cooperation with other companies, but also with customers and civil society organizations. Nevertheless, details about the roles and importance of partners are often absent, including the roles of manufacturers and complementary service providers in [CEBM]...*" (Lüdeke-Freund et al., 2019). This statement is supported by others, stating that CBM archetypes, meaning specific business model configurations in a CE, usually pay limited attention to the downstream value logic, i.e. the customer value proposition and interface (Pieroni et al., 2020). This confirms that CBM are, from a conceptual perspective, mostly interpreted as commercial or revenue model configurations, but usually lack considerations of value creation in an ecosystem or collaborative view (Antikainen et al., 2016; Galvão et al., 2020; M. P. P. Pieroni et al., 2019). Other authors here refer to a so-called value network perspective (Nußholz et al., 2020). This notion of a manufacturer-centric conceptualization of CBM is supported by the findings in (Geissdoerfer et al., 2020), stating that CBMs are often seen as an extension of existing value chains rather than from a value-network perspective.

2.2. Circular business model implementation

When studying the state of CBM implementation, a common approach in existing literature is to carry out multi-stakeholder interviews, mostly with small and medium sized enterprises (SME), and document existing practices (Ghisellini and Ulgiati, 2020; Kirchherr et al., 2018; Rizos et al., 2016). As a common element, findings conclude that recycling is still the most commonly used CE strategy, whereas high-value strategies such as re-use and remanufacturing, which require more focus on customer requirements (Lüdeke-Freund et al., 2019; Nußholz et al., 2020), are adopted much slower in industry.

In terms of the underlying reasons, literature points towards the existence of certain challenges for implementing the concept CE in industry. Recurring themes include inter-organizational collaboration, e.g. with third party providers dealing with product market recovery and rebound logistics, as well as establishing market dominance and competitive advantage of CBM over existing, linear approaches (Korhonen et al., 2018; Lieder and Rashid, 2016). Here, a recent survey study finds that the adoption of a CBM at scale is often seen as a business threat by managers, as it implies the replacement of the existing, linear business model (Schultz and Reinhardt, 2022). The authors conclude that CE innovation therefore requires a solid business case, which is economically sustainable for companies when implemented at scale (Schultz and Reinhardt, 2022).

Meanwhile, standardized frameworks for CBM implementation are scarce. In this regard, the framework provided by (British Standard Institution, 2017) is one of the few comprehensive guidelines for implementing CE thinking in organizations. This states that a business-model approach is required for a full CE adoption but provides little reference to specific tasks for CBM implementation or methods to assess the business case for a given CBM. Elsewhere, authors specifically differentiate between internal (organizational) and external (market) barriers for CE adoption (Hina et al., 2022; Vermunt et al., 2019), which require companies to build organizational capabilities for CE and clearly address customer segments in CBM implementation (Lewandowski, 2016). One way to better address customers is outlined by studies focusing on service-based offerings, which can increase the use intensity of products and incentivize manufacturers in efficiently managing product life cycles (Kjaer et al., 2019; Sigüenza et al., 2021; Simone and Remmen, 2019).

Based on these findings in literature, it can be stated that CBM implementation, especially for high-value CE strategies, seems to be inhibited by issues in manifesting a solid business case. Such business case needs to recognize the implications of sustainable value creation through CBM in a larger stakeholder network, and at the same time – or thereby - sustain in comparison to the linear system.

2.3. Circular business models for EV batteries

Implementing a CE is a particularly relevant for the case of EV batteries, as these accumulate a large share of the cost and environmental impacts of the EV at the production stage (World Economic Forum, 2019). In light of the limited exploitation of extraction potentials for certain key battery materials such as lithium and nickel, as well as social issues in the mining of others such as cobalt, implementing a CE for batteries is one way for companies to reduce impacts and risks in their supply chains (European Commission, 2020b; Lebedeva et al., 2016). Furthermore, and towards the use stage, evidence shows that the lifetime and available number of charging cycles of EV batteries is often underestimated (Hoekstra and Steinbuch, 2020). This underlines their ability to reduce life cycle benefits at the use stage of EVs while at the same time enabling diverse strategies for maximizing the benefits across the useful battery life. Meanwhile, the implementation of CE strategies for EV batteries do require additional transport networks for market recovery, repair and testing facilities- and infrastructures, as well as energy, water and material resources for further treatment or recycling processes, which need to be considered when assessing the improvements in battery life cycle impacts through CE strategies (Circular Economy Initiative Deutschland, 2020; Slattery et al., 2021).

Among the archetypes of CBM identified in literature (Lüdeke-Freund et al., 2019), three main options are applicable to the case of batteries at their EoL stage: “refurbishment and remanufacturing”, “repurposing & cascading”, and “recycling” (Drabik and Rizos, 2018; Kurdve et al., 2019). Each option is characterized by specific mechanisms of value creation (see Table 1).

Firstly, remanufacturing describes the refurbishment and reuse of EoL batteries in EVs. The value of remanufacturing is often stated to be additional revenues, e.g. through sales of refurbished products (Franco et al., 2021; Lüdeke-Freund et al., 2019). However and for the case of EV batteries, an open market for remanufactured batteries does not exist today. Instead, the benefit of battery remanufacturing lies at manufacturers, who use remanufactured batteries for providing field replacements during the battery warranty period or during the early phase of battery technology adoption, hence avoiding the production of new batteries and thereby reducing cost of service and maintenance (Kampker et al., 2016; Richa et al., 2017). At the same time, remanufacturing can be considered a risk for firms due to effects of cannibalization, which describes the fact that remanufacturing products and increasing their useful lifetime can reduce new product sales volumes and thereby represents a threat to existing manufacturing activities for companies (Okorie et al., 2021).

Secondly, B2U describes the process of further using EV batteries in stationary BESS (Hossain et al., 2019; E. Martinez-Laserna et al., 2018a). The concept exists in the scientific literature since 2003 (Cready et al., 2003). It is based on the assumption that batteries can be retrieved from the EV and enter B2U at around 70 % of their original capacity, which allows them to be used for another 10-15 years in a so-called “second life” depending on the BESS application (Casals et al., 2019; Egoitz Martinez-Laserna et al., 2018b; Müller and Birke, 2019). Several studies have demonstrated environmental benefits (Bobba et al., 2018; Richa et al., 2015; Schulz-Mönninghoff et al., 2021) as well as potential economic benefits of B2U (Kamath et al., 2020a; Madlener and Kirmas, 2017; Rallo et al., 2020). However and despite numerous projects implemented worldwide, a large uptake of B2U at scale is still lacking (Reinhardt et al., 2020). The value created from repurposing EV batteries is twofold: on the one hand, B2U generates additional revenues from sales of batteries for further use in BESS. This is stated to require new business relationships and partners such as retailers and collectors in order to address a new value streams (Franco et al., 2021; Jiao and Evans, 2017; Lüdeke-Freund et al., 2019; Reinhardt et al., 2019). On the other hand, it postpones costly recycling today and thereby reduces the cost of battery disposal for automotive manufacturers in their obligation to dispose batteries in accordance

Table 1
Circular business model options for batteries. Patterns based on (Lüdeke-Freund et al., 2019).

Circular business model pattern	Description for the case of EV batteries	Types of value capture	Key stakeholders	References
Refurbishment and remanufacturing	Reuse in the vehicle	Cost reduction in provision of new batteries for electric vehicles;	Automotive manufacturers; Third-party battery refurbishers	(Albertsen et al., 2021; Kampker et al., 2016; Richa et al., 2017)
Cascading and repurposing	Further use in stationary battery energy storage systems	Additional revenues from sales; Cost reduction in battery disposal due to postponement of recycling;	BESS supplier, BESS system integrator and operator; BESS customers (energy consumers, energy producers, transmission system operators)	(Albertsen et al., 2021; Jiao and Evans, 2017; Olsson et al., 2018; Reinhardt et al., 2019; Richa et al., 2017; Schulz-Mönninghoff et al., 2021)
Recycling	Mechanical and hydrometallurgical processing to recover key materials	Reduced cost compared to new materials (closed loop) Additional revenues (open loop)	Dismantlers, recyclers, battery cell producers	(Albertsen et al., 2021; Dunn et al., 2021; Neidhardt et al., 2022; Velázquez-Martínez et al., 2019)

with legal requirements (Olsson et al., 2018; Richa et al., 2017; Schulz-Mönninghoff et al., 2021). The latter aspect is, however, not included in existing studies in scientific literature today.

Lastly, recycling as a CBM for batteries offers a source of battery raw materials such as Lithium, Nickel, Manganese and Cobalt at reduced cost compared to primary materials when kept in a closed loop by manufacturers (Neidhardt et al., 2022; Velázquez-Martínez et al., 2019). Alternatively, recycling provides additional revenues when batteries are sold and secondary materials are used in an open loop (Lander et al., 2021).

Based on these descriptions, capturing the value from B2U for manufacturers depends on the ability to address customer requirements in energy systems. Key stakeholders hence include the second life BESS supplier, who is responsible for the repurposing process, as well as potential second life BESS customers, e.g. energy consumers such as households and industrial facilities, transmission and distribution system operators (TSO), or energy producers and utilities (Fischhaber et al., 2015). Depending on the use case, services provided by a BESS can include so-called behind-the-meter applications such as support of RE integration, time-of-use bill management and peak power management, as well as front-of-the-meter applications such as power quality services or frequency response (Fischhaber et al., 2015; Fitzgerald et al., 2015; Tepe et al., 2021). At the same time, more studies point towards the possibility of providing so-called "multi-use-cases", which refer to the combination of different services provided simultaneously or at different points of time towards different BESS customers in order to maximize economic value (Fitzgerald et al., 2015; Lombardi and Schwabe, 2017; Müller, 2018; Schulz-Mönninghoff et al., 2021).

For the business model of B2U, this implies that second life BESS can address a number of different customers, whose characteristics both affect the economic value created (Balducci et al., 2018). From the perspective of the second life BESS customers, implementing B2U follows the logic of planning and implementing BESS in the context of the energy system, e.g. as described in (EPRI, 2017). The role of automotive manufacturers in this process can take place in different B2U business model configurations (Jiao and Evans, 2017). Besides the BESS supplier, this involves electronic component and hardware suppliers and system integrators, as well as an energy system operator who purchases the BESS and provides system services to end customers mentioned above (Bowler, 2014; Jiao, 2017; Olsson et al., 2018). In terms of the customer value, some authors point out how repurposed batteries need to be assessed in relation to new batteries or other technologies available for the provision of grid services (Jiao and Evans, 2016; Reinhardt et al., 2016). Others state the quality- or value perception of specific customers in relation to repurposed batteries as a relevant aspect (Olsson et al., 2018), which can potentially be addressed by service-centered business models for B2U (Bräuer, 2016).

In summary, the business case for B2U as a CBM firstly results from a combination of case-specific revenues, as well as cost reductions or revenues from postponed recycling. Secondly, the characteristics of the targeted energy customer determine the corresponding BESS application and thus the B2U business model. For quantifying the value creation of B2U, this implies that a focus on customer characteristics is necessary.

3. Material and methods

The following sections describe the material and methods used in the study. Firstly, Section 3.1 describes the chosen research approach for addressing the research question. Secondly, Section 3.2. introduces the conceptual framework, which is derived from the literature review. Lastly, Section 3.3. outlines the process of data collection and analysis.

3.1. Research approach

Regarding a suitable approach for addressing the research question at hand, the literature review reveals how previous studies have investigated CBM implementation both in general and for the case of B2U. As a common element, these studies use multi-stakeholder surveys and interviews across different cases and industries in order to identify general drivers and barriers of companies to engage in CBM, with a particular focus on SMEs. Meanwhile, such approaches do not offer deeper insights into the required tasks for companies to overcome the identified barriers and capture economic value. Instead, the implications for practitioners are often limited to a list of unanswered questions (Olsson et al., 2018).

Based on these observations, we choose to use a single-case study method to carry out an in-depth assessment of a real-world project of implementing a second life battery BESS project in Germany. By combining qualitative data from stakeholder interviews at different stages of the project with quantitative analysis of economic value captured, such a research approach allows this study to provide richer analysis of the specific actions, which originate from the known drivers and barriers in a CE and together comprise what is considered an economically successful CBM implementation (Ridder, 2020).

In this sense, the present study uses an inductive research approach rooted in grounded theory (Saunders et al., 2019; Strauss and Corbin, 2008a). Based on the principles of grounded theory as explained in (Glaser and Strauss, 1967), such a research approach implies the collection of qualitative and quantitative data such as calculations, statements of stakeholders and observations, which together describe the real-world phenomena. In our case, the object of the study is the so-called "circular project", which in this context of the adoption of a CE in industry is seen as one concrete instance of the implementation of a CBM. For the present study, this is given by the implementation of a project for repurposing EV batteries in a second life BESS, which is seen as one example of implementing B2U as a CBM. As such, the researchers were involved in the project in an observing role throughout the main part of the project implementation phase, with both access to the different customers of the BESS in the energy system, i.e. the CBM customers, and the automotive manufacturer. From this unique position, it was possible to gain an understanding on the different stakeholder's roles, views and activities in implementing the circular project.

As a common element for case study research, these observations are used to develop general knowledge for a certain research field by applying techniques of sensemaking and analytical processes. The details on the specific processes of data analysis applied in this study are described in Section 3.3. In order to generalize from a single case study, the presentation of findings should acknowledge the unique character of the case and discuss implications for application to other cases (Saunders et al., 2019). Hence, the case-specific findings are presented in Section 4 before discussing general implications for CBM implementation in Section 5.

3.2. Conceptual framework

As described in the previous section, the goal of the study is to analyze the CBM implementation process by investigating the specific key tasks to ensure financial viability of the circular project in the case study. Based on the literature review, the business model canvas is the most common framework for studying business models and has also been used to study CBM in previous studies (Nußholz et al., 2020). Consequently, we structure the conceptual framework based on the three dimensions of the business model: value proposition, value creation & delivery and value capture. Furthermore, we define a key question for each dimension to structure the process of data analysis (see Fig. 1).

Firstly, and in terms of the value proposition, we investigate which customer requirements for BESS need to be addressed when using repurposed batteries. The scope of the study here focuses specifically on the BESS in general, i.e. the characteristics of BESS that determine the value for the customer. We hence imply that the customer does not draw specific value from the use of repurposed batteries, but instead

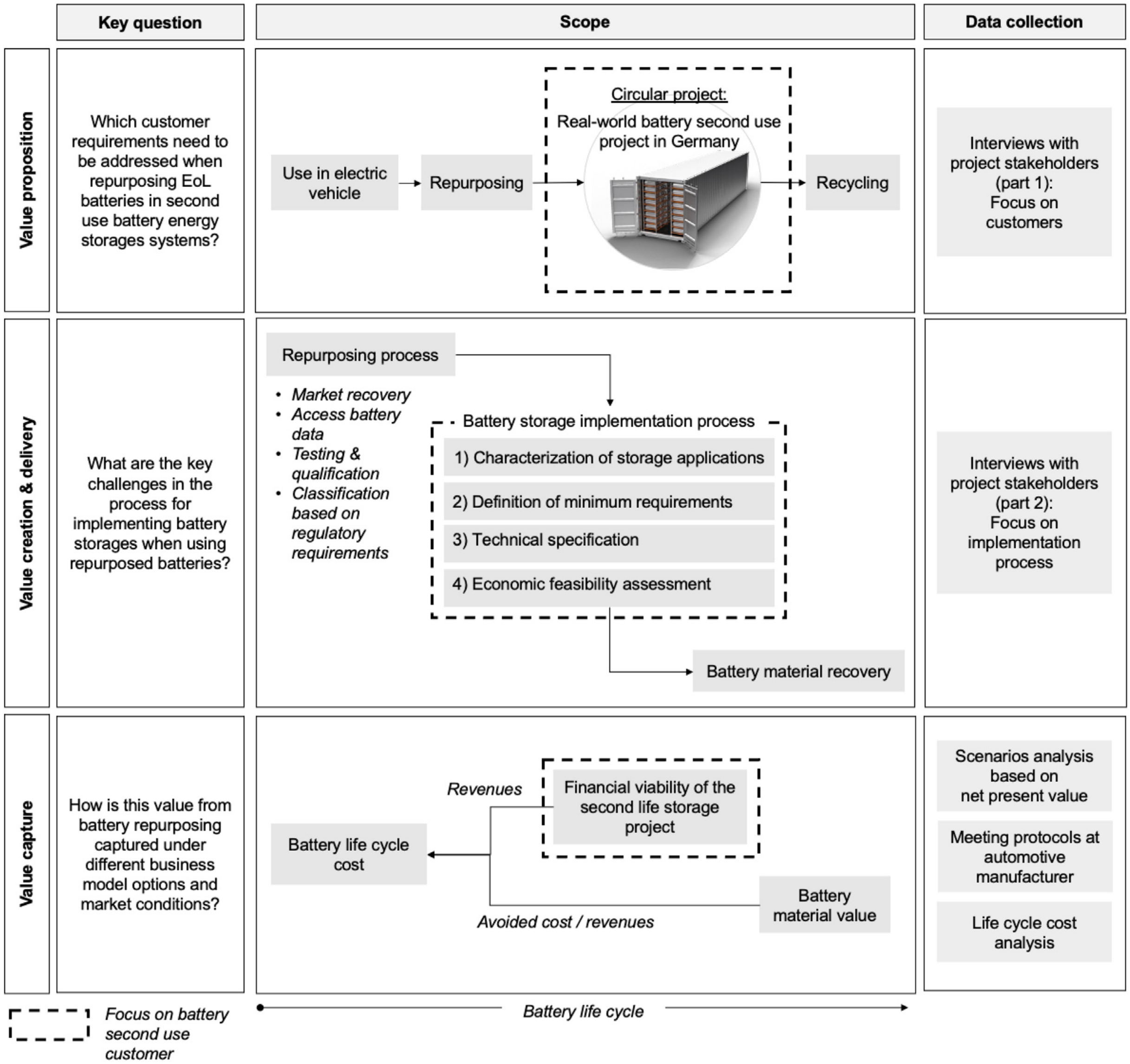

Fig. 1. Conceptual framework used to investigate the research question in the study.

applies the same performance criteria, which then need to be addressed when using re-used or repurposed materials or components.

Secondly, we revise the specific activities as part of the implementation process, which are necessary when using repurposed batteries. Here, the focus lies on the process of implementing the second life BESS from the perspective of the stakeholders, who are engaged in the value creation and delivery and enable the circular project to deliver the proposed values to customers. Based on the literature review, the EPRI standard for implementing BESS is chosen as the framework for documenting the activities. More specifically, the planning process entails the following four steps: 1) the selection and characterization of BESS applications, 2) the definition of minimum requirements, 3) the specification of technical requirements and 4) the economic feasibility assessment. As an action-oriented framework, the EPRI process supports the study in formulating the findings in the form of key tasks (EPRI, 2017). The implications of structuring the data analysis around a process are further explained in Section 3.3.

Lastly, and in terms of value capture, we assume that a circular project for B2U is economically viable when it a) provides positive economic value for the targeted customers and b) offers benefits in terms of the reduction of LCC for automotive manufacturers, as stated in e.g. (World Economic Forum, 2019). Hence, we ask for the value that can be captured from battery repurposing by automotive manufacturers, taking into account both the revenue from repurposed batteries and the changes in the cost of battery recycling due to the time delay. As the potential revenue relies on the business case at the customer, we firstly calculate the net present value of the project at the customer in order to derive the LCC contribution of repurposing.

Finally, each key task is specified in terms of how it supports value proposition towards a specific stakeholder group (see Section 2.1), value creation and delivery through certain network partners and organizational capabilities (see Section 2.2) and value capture in terms of revenue of cost reduction (see Section 2.3).

The following chapters describe in detail the process of data collection on the circular project in each step and the corresponding methods used for data analysis.

3.3. Data collection and analysis

This section introduces the process of data collection and the methods for data analysis used in the study. This includes both qualitative data analysis based on interview data, as well the quantitative data analysis of the case study based on secondary sources. An overview of the methods used is provided in Table 2.

Table 2
Description of the data analysis.

Business model dimension	Data type	Data collection	Key stakeholders	Analysis method
Value proposition	Qualitative	Interviews with project stakeholders at early project stage	Energy consumer (INT-1A, INT-1B), Energy supplier (INT-1C), Transmission system operators (INT-1D, INT-1E), BESS provider (INT-1F)	Coding of interview results based on recurring themes on the value of stationary battery energy storages (Ridder, 2020)
Value creation & delivery	Qualitative	Interviews with project stakeholders at implementation stage	Energy consumer (INT-2A, INT-2B), Energy consumer/ battery storage system integrator/ operator (INT-2C), Energy planner (INT-2D)	Coding of interview results based on key statements which link the use of repurposed batteries to the implementation process for battery storages; (Langley, 1999)
Value capture	Quantitative	Analysis of customer value in different business model configurations	Battery second use customer	Analysis of the net present value of the project
	Qualitative	Analysis of meeting protocols at automotive manufacturer	Automotive manufacturer	Analysis of meeting protocols via triangulation with life cycle cost data Focus on identification of critical factors for capturing value from battery repurposing for the company (Ridder, 2020).
	Quantitative	Analysis of resulting contribution to reduction of battery life cycle cost	Automotive manufacturer	Life cycle cost analysis

3.3.1. Qualitative data

The collection and analysis of qualitative data consists of three parts: two sets of interviews at different stages of the project, and the revision of interview protocols at an automotive manufacturer. Examples of the interview guidelines used for the interviews is provided in the supplementary materials.

The first set of interviews was conducted in the early project phase between January and February 2020 and involved different departments of the energy consumer, BESS supplier, energy producer and transmission grid operators. At this stage, the goal was to understand the market conditions for EV battery repurposing in a larger context of stationary BESS deployment. The analysis is based on content analysis, using transcripts of interview protocols to identify recurring themes regarding the value proposition of stationary battery energy storage systems. Statements on the use of repurposed batteries by the interviewees were also included in the analysis of the value creation & delivery process. As such, one characteristics of such method in grounded theory is that the expertise of the authors has shaped the identification of which aspects were deemed relevant (Strauss and Corbin, 2008).

The second set of interviews was conducted at a later stage of BESS implementation in January 2022 with specific stakeholders involved in the integration of the BESS at the final customer. Here, the process of BESS implementation was used as a guideline for the interviews in order to map key aspects for the storage project under investigation (see supplementary information for a detailed description). As such, the framework and the underlying process has shaped the interviews, which affects the way of interpreting and theorizing from the data, i.e. in terms of the underlying events which constitute the investigated process and other, overlapping processes taking place in the background (Langley, 1999). To address these aspect, the analysis firstly focused on the technical documentation of the planning process, i.e. the normative instructions for the BES project. Afterwards, we revisit interview data in terms of key statements, which link the technical properties of the project to the characteristics of the circular project, i.e. the use of repurposed batteries. Hence, the exploratory aspect was based on an existing, normative process, which already took into account temporal aspects such as changing market conditions in energy markets (see also Section 3.3.2) and the specific events which together shape the BESS planning process (Langley, 1999).

Lastly, primary data obtained includes documentation of quarterly strategy meetings on a CE for batteries held at the automotive manufacturer. When using documents, it is important to reflect on the purpose and context under which these documents are created (Ridder, 2020). In this case, the meeting setup was informal, included various and changing participants and aimed at the exchange of information across stakeholder groups involved in implementing a CE for batteries at the manufacturer. The dataset includes meeting minutes of 6 meetings held between November 2020 and April 2022. The analysis is again based on a content analysis, i.e. the identification of specific statements and recurring themes, which relate to benefits and issues for capturing value from battery repurposing for the automotive manufacturer. Given the explanations in Section 2.3, this also includes the inter-dependency between recycling and repurposing, i.e. the delay in recycling caused by B2U and the implications for recycling value and closing material loops. In this way, the qualitative data from meeting protocols was used to triangulate between the economic results and the findings on value creation and delivery in the previous step (Strauss and Corbin, 2008).

3.3.2. Quantitative data

To complement the qualitative data and study the economic feasibility of the project, this study firstly includes a comprehensive analysis of different BESS use cases, as well as an analysis of the contribution to the reduction of LCC through repurposing. For the former, primary data on the energy consumption profile was used to simulate the benefits of implementing the BESS for the energy consumer in the case study. In this case, this is given by the energy management within the production facility of the automotive manufacturer. Regarding the cost- and price data for the simulation, secondary sources are used due to restrictions for disclosure of economic battery data by the project partners. While the experience of the researchers has shaped the selection of these sources and hence the quantitative assessment in the study, it is still considered relevant to describe the case-study as described in (Ridder, 2020), given that prices and cost are chosen to reflect the actual cost of the project in Germany at the time of the study.

For the scenario analysis of the net present value for the BESS customer, a simulation of energy flows was carried out in the software tool TOP Energy (GFAI, 2017). All the technical parameters and assumptions for the energy flow model are derived from (Schulz-Mönninghoff et al., 2021) and are detailed in the supplementary materials. In order to investigate the business model in the case study, we include different variables in the analysis. Firstly, we assess and simulate different BESS applications, taking into account the possibility of multi-use cases for BESS as described in Section 2.3. In the case study, this includes different combinations of integrating locally produced RE supply (PV), peak shaving (PS), uninterrupted power supply (UPS) and primary control reserve (PCR). These are either provided by a 1.4 MWh BESS (configuration A) or by a 2.8 MWh BESS (configuration B).

Secondly, we take into account changing market conditions for using BESS in Germany. These partly result from changes in the energy markets, which have occurred at the time of the case study. Specific details on the technical assumptions for the model and the specific assumptions in each scenario are presented in the supplementary information. The scenarios are derived from public data sources and include:

- Base case: Current energy prices (2020)
- Market scenario 1: Gradual increases in energy prices to projected price for 2030
- Market scenario 2: Gradual increases in PCR revenues
- Market scenario 3: Reduction of the interest rate for battery storage projects
- Market scenario 4: A combination of all changes (best case)

Based on modelling the energy flows of that production facility when using the BESS, we calculate the net present value (NPV) of the BESS from repurposed EV batteries, i.e. the circular project under investigation.

In addition to the data obtained for the BESS customer, the study includes an analysis of the contribution of B2U to the reduction of the LCC of the battery. LCC analysis is stated as a key method to analyze product life cycles within the discipline of life cycle management in general and aims at “the assessment of all costs associated with the life cycle of a product that are directly covered by one or more actors in the product life cycle” (Sonnemann and Manuele, 2015). Similarly to life cycle assessment, the LCC follows the ISO 14040 framework and requires the definition of scope, system boundaries and functional unit (UNEP and SETAC Life Cycle Initiative, 2011). Therefore, we use the same system boundaries as the life cycle assessment of B2U provided in (Schulz-Mönninghoff et al., 2021), which includes battery production, battery repurposing process and provision of BESS system components, as well as the energy-related benefits determined in the NPV analysis. Lastly, it includes the changes in the cost of battery recycling through B2U. The cost associated with the use of the battery in the EV are excluded from the scope of the LCC analysis.

4. Results and discussion

The results are presented according to the conceptual framework, starting from the customer-focused interviews on the value proposition of BESS at an early project stage in Section 4.1. Afterwards, the findings on value creation and delivery based on the second part of the interviews conducted at the time of the BESS implementation are presented in Section 4.2. Lastly, we present the economic feasibility study and the LCC contribution analysis in Section 4.3 before summarizing the results in the form of the identified key tasks in Section 4.4.

4.1. Value proposition

The results of the interviews conducted in the early project phase (INT-1A-1F) aimed at the characterization of the value proposition of BESS in the case study, which need to be addressed when using repurposed EV batteries.

Firstly, and regarding the opportunities for using BESS, the interviewees mentioned that several target applications are identified for the BESS in the case study, which can be provided towards different customers of the energy system under investigation (1). In this regards, one interviewee suggests that two different BESS system configurations should be analyzed, namely 1.4 MWh and 2.8 MWh, since this can enable different sets of applications with different cost-benefit ratios.

Moreover, two interviewees state that multi-use cases are a precondition for achieving economic profitability of industrial BESS, i.e. to provide multiple BESS applications simultaneously (2). Here, two interviewees point out the need for supporting smart RE integration for energy producers, as well as reduction of power peaks towards the energy consumer, particularly in light of new peak-consumers such as EV charging stations. Furthermore, two interviewees point towards opportunities emerging from new regulation on offering grid services such as PCR with BESS, e.g. the provision in smaller time slots, as a chance for achieving additional revenues.

When discussing the technical requirements of the BESS, one aspect mentioned was the reduction of the battery life cycle cost (3). These represent the capacity-related cost of the BESS, i.e. the cost of purchasing battery modules and their disposal. Moreover, the specific battery technology and their characteristic lifetime and quality were mentioned as key aspects for the value of the BESS (4). Here, multiple interviewees state that reliability of the BESS service and is a key customer requirement, e.g. when ensuring supply security and power quality for the energy system. Here, one interviewee outlines the need for engaging with specialized BESS operators, who can manage different BESS applications and can use digital tools to assess the benefits in relation to the effects on the battery state-of-health and lifetime of batteries.

Among the challenges mentioned, the uncertainties in terms of revenues and costs on energy markets were mentioned most frequently, together with legal barriers for applying storage, e.g. for participation in PCR markets and energy arbitrage (5). Particularly when combining different BESS applications in multi-use cases, two interviewees mentioned the bureaucratic barriers to comply with regulations and at the same time minimize consider levies and taxes. As a consequence, different interviewees state that new collaborations between grid operators and other market participants is seen as a chance to develop new business models for BESS, e.g. for redispatch, as well as shared- and distributed storage solutions. A key aspect in this regard is to ensure suitable financial capital for investments in BESS as part of a new energy infrastructure (6).

Lastly, two interviewees mentioned that the deployment of BESS should be integrated with the achievement of other targets such as energy efficiency, e.g. through the deployment of direct current (DC) micro grids, as well as increasing digitalization and automation, which impose new challenges on power quality at industrial production sites. Such aspects require technical expertise at the implementation and operation stage in order to maximize the value from BESS (7). This links to statements of other interviewees, who also point towards the need for technical tools, e.g. for enabling forecasts on energy consumer behavior with BESS deployment at scale in order to predict the impacts on transmission grid operation.

The findings on the key characteristics of the value proposition of BESS are summarized in Fig. 2. These are used to structure the analysis of the mechanisms of value creation and delivery in the following section, i.e. the specific tasks for addressing the value proposition when using repurposed EV batteries.

4.2. Value creation and delivery

The analysis of the value creation and delivery is based on the EPRI process for planning BESS. For that, the second set of interviews aimed at understanding the requirements for the BESS to address the value proposition outlined in Section 4.1, i.e. the realization of system characteristics in each of the four steps of the process. The resulting technical documentation of the findings is presented in the supplementary information. In the analysis, we have then focused on the specific tasks and challenges, which result from the use of repurposed batteries, and their impact on the economic feasibility for the BESS customer. The resulting findings are presented in Fig. 3.

Firstly, enabling the ability to address different customer types with repurposed batteries requires a scalable BESS system architecture, which can technically accommodate the variety of different batteries recovered from the EV market (1). In the case study, this is represented by the possibility of doubling the system size to capture additional PCR revenues and thereby optimize the cost-benefit ratio of the project.

At the same time, the ability to address multi-use cases and to address multiple benefiters simultaneously requires an assessment of the degree to which repurposed batteries are suitable for such applications, e.g. for providing PCR services, UPS and RE integration jointly (2).

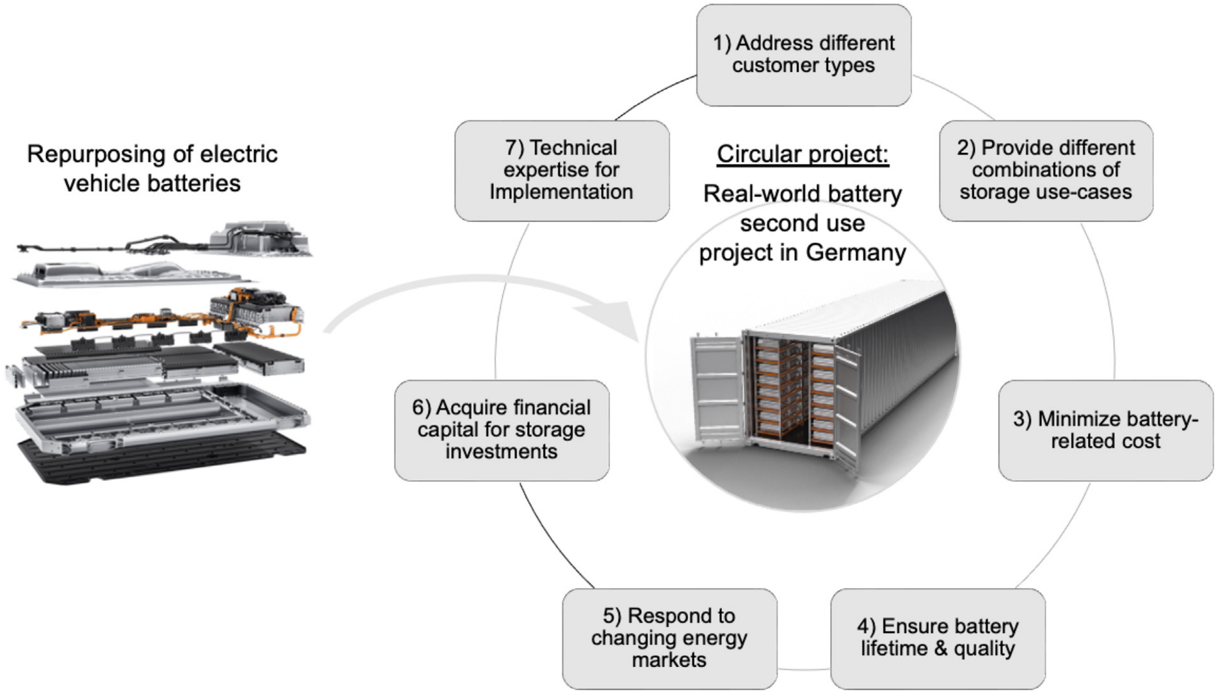

Fig. 2. Key characteristics of the value proposition for the stationary battery storage in the case study based on interviews at the early project stage.

In the case study, this was carried out via the simulation of such use-cases under the assumption of the batteries state-of-health, the maximum depth-of-discharge and the resulting number of charging cycles available. This influences the potential revenues from the BESS project. According to one of the interviewees, planned investments in additional RE production capacity now present a strong case for scaling up the implementation of stationary BESS in the production facilities.

Furthermore, the battery technology and the material value of repurposed EV batteries determine the cost of procurement of EoL batteries and the cost of disposal at the end of the use in the BESS (3). Both determine the feasibility of the BESS for the customer. In the case study, the batteries are NMC-based, which implies a high material value. In the case study, the direct agreement between automotive manufacturer and BESS supplier leads to a minimum of procurement cost. Additionally, it is mentioned that based on the high material value, the cost of disposal can potentially be reduced through efficient recycling in the future.

Another aspect which was mentioned by several interviewees is the cost of maintenance associated with the use of repurposed batteries. These are directly linked to the remaining lifetime of the batteries. Besides the state-of-health of the batteries, the characteristics of the use profile of the BESS determine whether or not the batteries need to be replaced during the 10 years period under investigation. For that, software solutions for BESS operation and optimization of battery lifetime are found as specific requirements (4).

Additionally, one aspect which was mentioned in the interviews was the development in both energy prices and possible PCR revenues. While is aspect affects the BESS project in general, the specific challenge in the circular project regarding the use of repurposed batteries is for automotive manufacturers to anticipate the growing demand and revenue potential of BESS and allocate sufficient batteries to the business model (5). In the case study, this aspect came up in the pilot project and triggered the revision of market projections and the strategic evaluation of the business model in the future. Moreover, and regarding the financial aspects of the business model, another aspect mentioned in the interviews was the development of the interest rate and the resulting cost of capital of the BESS project. Depending on the location and the risk profile of the project, interviewees mentioned that such conditions can vary and affect the NPV of the project. Consequently, the question whether the use of repurposed batteries increases the risk profile of the circular project was brought up in the interviews, and have stirred questions on the sysem safety architecture and the collaboration with suitable investors (6).

Lastly, several interviewees mentioned the technical expertise required for the integration of repurposed batteries as a potential cost driver. Examples include additional efforts for the software integration for BESS operation- and battery safety control. While these aspects were addressed together with the integration of other technologies such as bi-directional EV charging stations, a DC micro-grid, as well as digital- and automation technologies at the energy consumer in the case study, the interviewees highlighted the importance of a proof-of-concept under market conditions to reduce unforeseen cost of BESS integration (7).

A summary of the findings is presented in Fig. 3. Here, the findings are linked to the value position and positioned in relation to the corresponding stage of the BESS implementation process, including the effect on the economic feasibility at the customer in terms of the NPV.

From the findings, the following analysis of the NPV at the BESS customer needs to include several parameters relevant to the use of repurposed batteries in terms of the cost-price, revenue potentials, as well as BESS life cycle cost such as integration, maintenance and disposal. The following section investigates these aspects, starting from the perspective of the customer. The results are then further interpreted in the context of the battery LCC.

4.3. Value capture

The presentation of results on the value captured from EV battery repurposing is divided in two steps. Firstly, the analysis of the economic feasibility at the storage customer, and secondly, the analysis of the contribution to the reduction of the battery LCC for the automotive manufacturer. In each step, we include a comparison of the results with the value obtained by previous studies.

4.3.1. Economic feasibility at the customer

The results of the economic feasibility study of the BESS in the case study is presented in Fig. 4. Besides the base case, it includes different

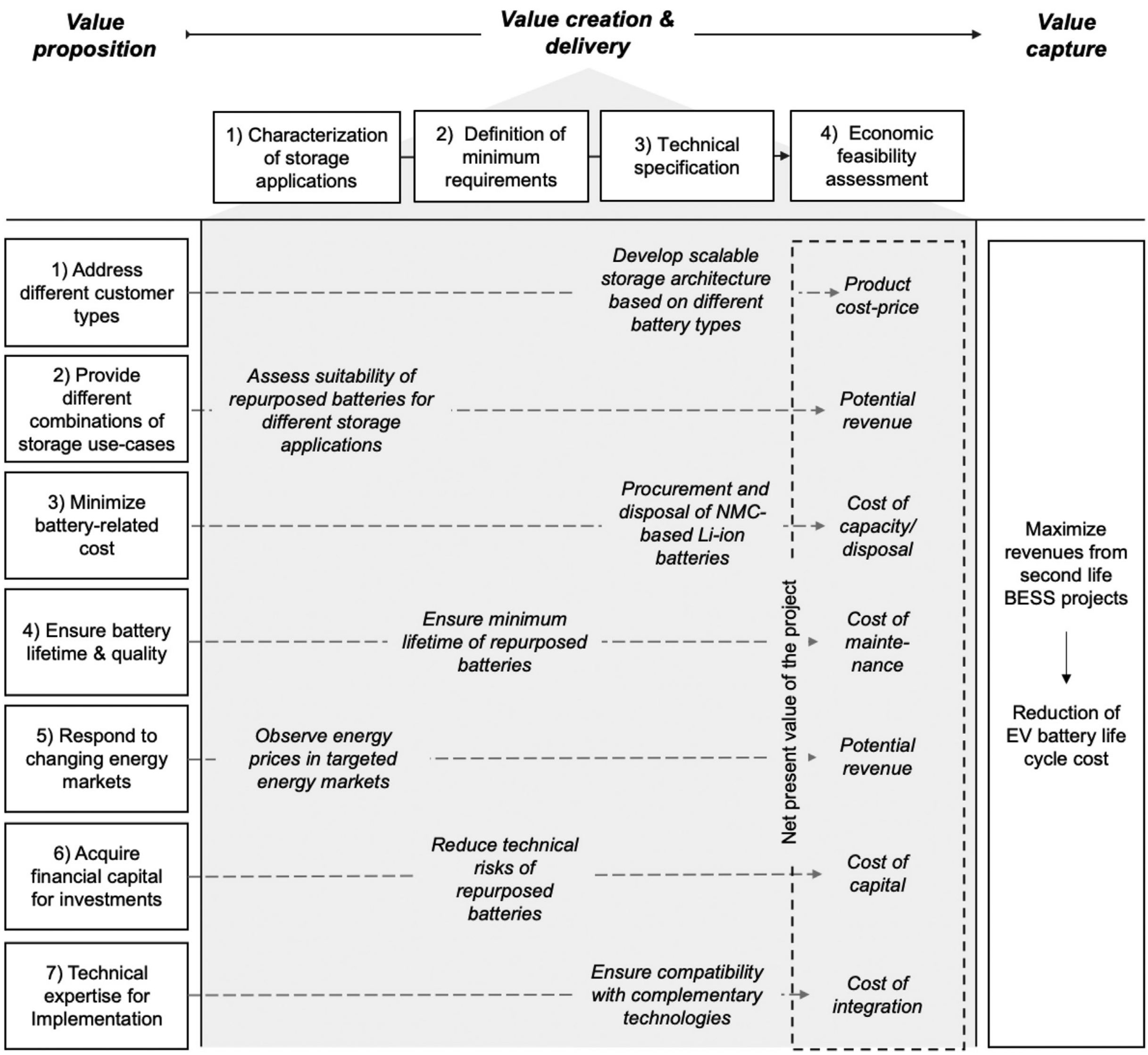

Fig. 3. Specific challenges for value creation and delivery for repurposed batteries based on the process of implementing battery storages as defined in EPRI (2017); Acronyms: NMC = nickel-manganese-cobalt.

the scenarios of economic boundary conditions in terms of energy prices, PCR revenues and interest rates, i.e. market scenario 1-3, and a combined best-case market scenario 4. All scenarios are calculated for two overall BESS configurations with either 1.4 MWh or 2.8 MWh capacity, which enables different types of use cases.

Based on the results, the operation of the BESS at 1.4 MWh in the scenario "base case" is only profitable in multi-use case 1, which combines RE integration, peak shaving and UPS provision and thereby achieves an NPV of 110 k€ after 10 years (or 90 k€/kWh). Meanwhile, the operation of the BESS at 2.8 MWh is only barely profitable in multi-use case 3, which combines RE integration, peak shaving, UPS and the provision of PCR. However, the absolute NPV is lower than in multi-use case 1. This means that increasing BESS size to capture additional revenues from PCR is not economically viable in the base case.

When taking into account market changes, increasing profitability can be observed especially for multi-use case 1, 2 and 3. Besides multi-use case 1, multi-use case 3 gains in relevance with the highest absolute NPV of 505 k€ (or 205 €/kWh) in the best case market scenario 4. In multi-use case 2, the negative NPV in the base case turns into a positive NPV when assuming favorable interest rates in scenario 3. This improves further to almost 200 k€ when assuming increasing PCR revenues in market scenario 2 and to around 400 k€ after 10 years when additionally taking into account increasing energy prices in market scenario 4.

Based on the analysis, it can be stated that BESS the system configuration, the combination of use-cases and the development of the targeted energy system affect the profitability of B2U as a business model. Hence, addressing these aspects in the development of B2U as a CBM through a suitable product architecture, customer engagement and operation concepts can be identified as drivers for ensuring economic viability.

4.3.2. Contribution to reduction of battery life cycle cost

Based on the economic value generated at the energy customer in different scenarios, we now calculate the possible contribution of B2U to the LCC of a battery. The results are presented in Fig. 5. In addition to the quantitative results, the protocols of several meetings held at the automotive manufacturer regarding the implementation of B2U were analyzed and included in the analysis to triangulate the findings.

Firstly, we assess the LCC in detail for the use stage in the BESS (see Fig. 5, top). For that, we assume a selling price of repurposed batteries of 100€/kWh. This assumption is in keeping with previous studies (Kamath et al., 2020b; Neubauer et al., 2015; Rallo et al., 2020) and is competitive with new batteries (for details see supplementary

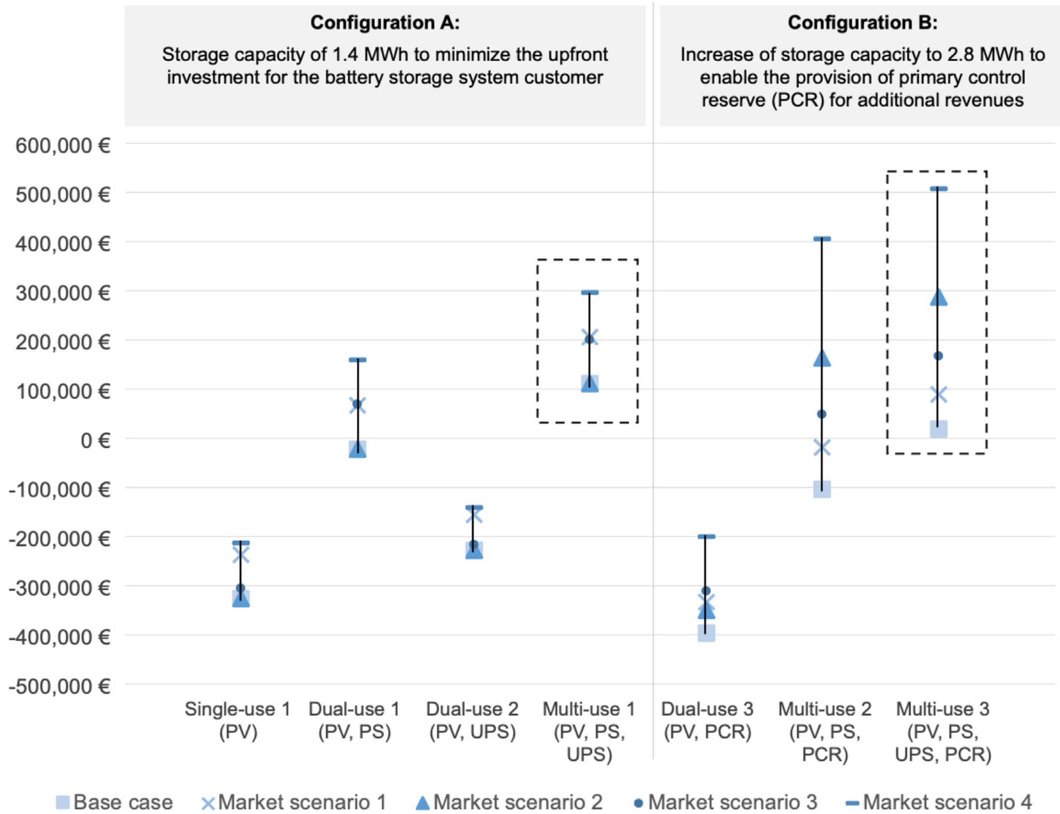

Fig. 4. Net present value of the second use storage project in the case study in different product configurations, use cases and market scenarios over a time frame of 10 years in Germany; Modelling based on parameters presented in (Schulz-Mönninghoff et al., 2021). Acronyms: PV = Photovoltaic; PS = Peak shaving; UPS = Uninterrupted power supply; PCR = Primary control reserve;

materials). In this regard, during one of the meetings at the automotive manufacturer held during the project implementation, it was mentioned that these cost need to cover the cost of implementation, i.e. testing, transport and installation of the repurposed batteries. Therefore, it was concluded that a validation of these cost in pilot projects is necessary (7).

Furthermore, the cost of power electronics for the BESS of 150€/kW and the balance of plant cost of 90€/kW are assumed to be fixed. The cost of operation & maintenance of 46€/kWh are linked to the quality and remaining lifetime of the batteries provided (4). By using (digital) tools for optimizing battery lifetime in BESS operation, the cost of maintenance can be reduced. Furthermore, IT systems and advanced BESS safety architecture can ensure a continuous operation of the BESS and reduce technical and financial risks. In this regard, the cost of capital at an interest rate of 8 % result in 170€/kWh, is related to the risk profile of the project and the corresponding source of financial capital (6). During a meeting at the automotive manufacturer, it was discussed which measures can be taken to reduce project risks and the cost of capital of B2U projects. On the one hand, it was seen as necessary to collaborate with suitable investors, who are specialized in long-term energy infrastructure projects and can adjust the cost of capital based on a technical risk valuation for circular projects. On the other hand, service-based offerings of BESS were suggested as a way to provide assurance of product quality of repurposed batteries to customers and investors. This was however not implemented within the case study, resulting in a lack of evidence regarding that strategy.

Furthermore, the cash flow benefits from using the BESS is calculated over 10 years is based on the base case of multi-use case 1. As described in Section 4.3.1, the BESS here provides the highest NPV, with cash flow benefits of 646€/kWh, which lead to an NPV of 90€/kWh for the energy customer. When considering the highest net profits in the best case scenario, multi-use case 3 can provide net benefits of 672€/kWh by offering PCR to energy grids, which results in an NPV of 205€/kWh. The results thereby suggest how the project can provide different value streams towards multiple benefiters in the energy system (2). This cost-benefit ratio can be optimized due to the scalable BESS architecture and the system configuration in the case study (1), as well as by monitoring future market conditions of the energy sector in Germany (5).

For the analysis of the impact of battery repurposing on the reduction of the LCC, we assume an estimated new battery price of appr. 150€ for an NMC battery at project start in 2020 based on (Neubauer et al., 2015). Even in the regular battery life cycle (see Fig. 5, center), EV batteries must be recovered from the markets after the use in the EV for disposal according to legal minimum requirements. The corresponding cost of transport are estimated to be 5€/kWh based on a cost of 0.71$/kg in Germany stated in (Slattery et al., 2021). The cost of disposal were assumed to be at around 10-15€/kWh, depending on the material composition (Lander et al., 2021). The resulting LCC in total amount to appr. 167€/kWh.

When repurposing batteries (see Fig. 5, bottom), the cost of repurposing are estimated at around 36€/kWh, which includes the transport cost as well as equipment and labor cost at the testing- and repurposing facility (Neubauer et al., 2015). At a selling price of repurposed batteries of 100€/kWh, repurposing provides a sales profit of 64€/kWh for the manufacturer (see Fig. 5). Additionally, the cost of of disposal are avoided in 2020, which is linked to finding (3) on the cost of disposal and the resource value.

Lastly, the recycling of NMC batteries is expected to yield additional profits at the end of the BESS lifetime in 2030, i.e. after B2U, resulting in another 25€/kWh revenue (Lander et al., 2021). Together with the saved cost of disposal of 12€/kWh and the revenues of 64€/kWh, the total LCC contribution of B2U amounts to 109€/kWh of repurposed battery capacity. The additional recycling profits were addressed in a

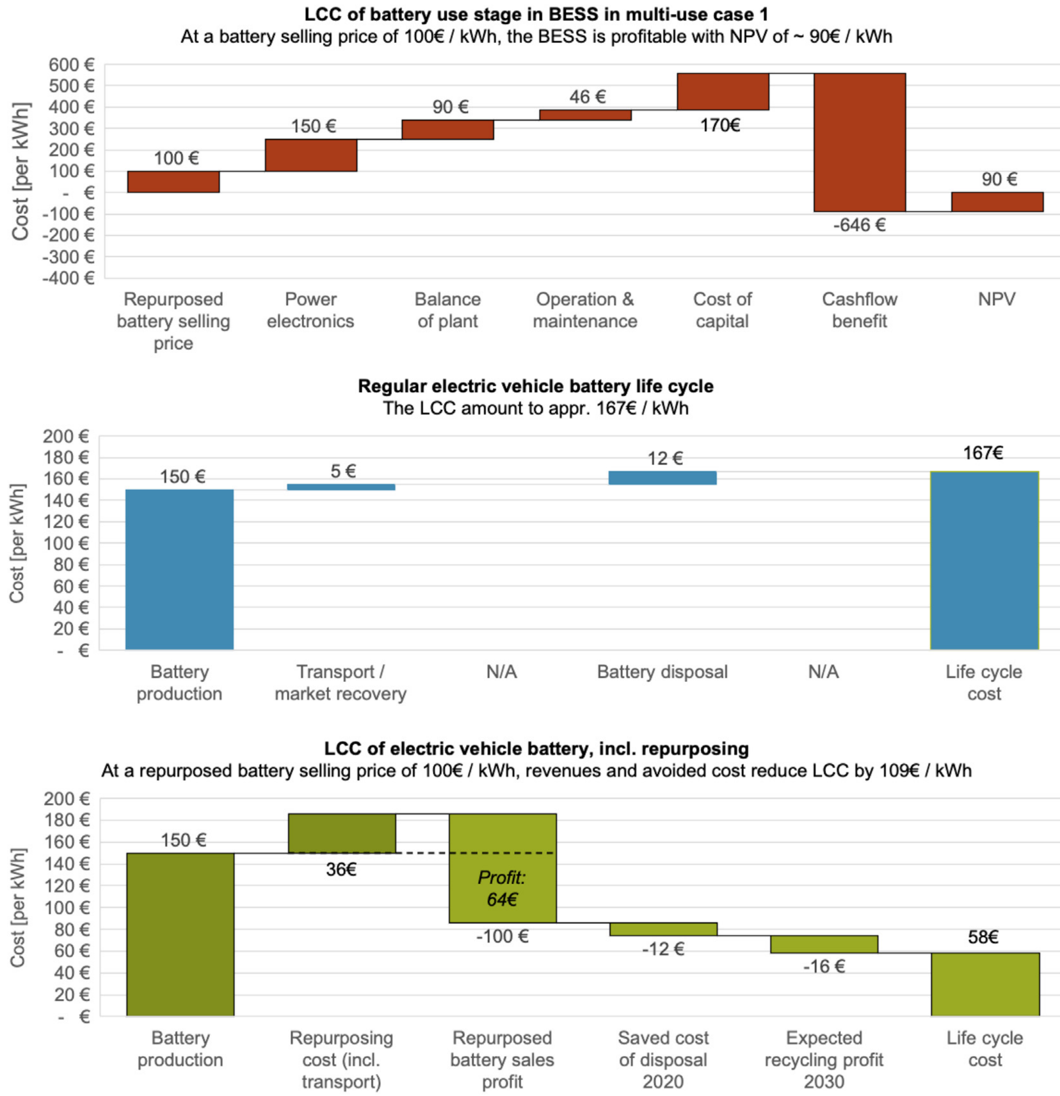

Fig. 5. Life Cycle Cost (LCC) analysis of electric vehicle repurposing. Top: Analysis of use stage in battery energy storage system (BESS); Center: Regular electric vehicle battery life cycle; Bottom: Analysis of impacts of battery repurposing on the reduction of LCC.

meeting held at the manufacturer, stating that in order to capture the material value of repurposed batteries, an agreement with BESS customers is necessary to allow access to EoL batteries at the end of B2U. Besides contracting, another strategy was seen in providing storage capacity as a service-based offering and maintain ownership of the batteries during B2U. In this way, an obligation of disposal remains with the manufacturer, which enables value capture from battery material recovery. However, this strategy was not implemented within the case study.

4.4. Synthesis: key tasks for implementing the circular project

Based on the findings presented in the previous sections, Table 3 presents the synthesis in the form of seven key tasks, which were addressed for implementing the circular project in the case study and to ensure economic viability.

In the case study, the assessment of the BESS planning process and the economic study together reveal how the scalability of the BESS based on repurposed batteries allows the variation in system configurations in order to address different customer types and optimize revenues at the lowest system cost (cf. Fig. 4). In the case study, this required the development of a flexible BESS product architecture, which can accommodate different battery types at different sizes which can be repurposed from the EV market. Hence, we refer to this key task as "*develop the product platform*".

Furthermore, the case study reveals how offering of multi-use cases determines the profitability of the BESS. For that, an assessment of the suitability of using repurposed batteries was varied out via simulation of different scenarios, taking into account the characteristics of the batteries and the corresponding use cases. The analysis revealed that the repurposed batteries can indeed address and capture multiple value streams, including revenues from offering grid services as well as cost reductions in energy use and infrastructure upgrades. Hence, we refer to this key task as "*assess multiple value streams*".

Thirdly, and as presented in Fig. 4, the contribution of B2U to the reduction of LCC is twofold: on the one hand, it generates revenues through the sale of repurposed batteries. On the other hand, we show how B2U postpones battery recycling while at the same time allows generating additional revenues from improvements in future recycling. This shows how automotive manufacturers can leverage on the material value of EoL batteries to support the competitiveness of repurposed batteries compared to new ones. We thus refer to this key task as "*leverage on battery resource value*". In relation to this task, the findings also indicate that capturing this full value requires access to batteries after B2U,

Table 3
Identified key tasks for ensuring economic viability when implementing battery second use as a circular business model.

Key task	Value proposition	Value creation & delivery	Value capture
1. Develop the product platform	Address different customer types	Develop scalable battery storage architecture based on different (repurposed) battery types	Maximize storage revenues at lowest system cost
2. Assess different value streams	Provide different storage use-cases	Assess suitability of repurposed batteries for different storage applications (e.g. via simulation)	Maximize economic benefits (energy cost savings, energy infrastructure cost savings, revenues)
3. Leverage on resource value	Minimize battery-related cost	Minimize cost of procurement and disposal of NMC-based Li-Ion batteries; *(Optional: Maintain ownership of batteries)*	Assure market access; Capture avoided cost today and future revenues of battery recycling
4. Provide risk assurances on product quality	Ensure battery lifetime & quality	Ensure minimum lifetime of repurposed batteries in operation *(Optional: Introduce battery-as-a-service)*	Reduce cost of maintenance/battery replacement; *(Optional: Capture revenues from service-based offerings)*
5. Observe trends in targeted downstream markets	Respond to changing energy markets	Observe energy prices and grid service revenues in targeted energy markets; Allocate sufficient batteries to repurposing;	Unlock additional revenues from profitable battery storage applications
6. Acquire suitable financial capital	Acquire financial capital for storage investments	Reduce technical risks profile of the project when using repurposed batteries (in collaboration with suitable investors)	Reduce cost of capital to optimize net-present value for customers
7. Carry out pilot projects under market conditions	Technical expertise for implementation	Ensure compatibility with complementary technologies in pilot projects	Minimize cost of integration (power electronics, equipment, software etc.)

i.e. through contracting or by maintaining ownership of the BESS in service-based business models, which was however not further investigated.

For key task number four, the risk perception of customers regarding the lifetime of repurposed batteries represents a barrier for adoption. We find that this can be addressed through specialized actors and software tools, which ensure the minimum lifetime of repurposed batteries. This affects the cost of maintenance and operation for the customer and hence ensures the economic viability of the project. We hence refer to this key task as "*provide risk assurances on product quality*". As an addition, the interview results suggest that service-based offerings might support this aspect towards customers while at the same time providing additional revenues for BESS suppliers. This effectiveness of this aspect has however not been verified in the case study and requires further investigation.

Another key task can be derived from the sensitivity of the model to the changes in energy prices in energy markets. Here, the ability of BESS suppliers to respond to changing market conditions is found as a key aspect of the value proposition. As a consequence, the monitoring of market trends in the case study has stirred discussions on the amounts of EoL batteries allocated to B2U. This implies an increased focus on downstream activities for manufacturers in addition to upstream management of battery supply chains. Hence, we refer to this key task as "*observe market trends in targeted downstream markets*".

Key task number six refers to the financing of BESS and the corresponding cost of capital, which drive the economic viability of the project in the case study. As illustrated in Fig. 3, the risk profile of the project affects the profitability of the BESS. Hence, the collaboration with suitable investment partners and the reduction of technical risks can be seen as a key task for optimizing the NPV in the case study. Therefore, we refer to this key task as "*acquire suitable financial capital*".

Lastly, the study shows how the pilot project in the case study is used to acquire the technical expertise for the technical integration of the BESS and thereby ensure customer value in the project. Relevant aspecst include e.g. testing, logistics and installation and the required software integration. As shown in the LCC analysis, this affects the cost of integration via the cost of repurposing, as well as the cost of the power electronics and balance of plant. The pilot project here serves to identify unforeseen cost. Thus, we refer to this key task as "*carry out pilot projects under market conditions*".

5. Discussion

In this section, we discuss the findings in terms of theoretical contributions in relation to existing literature (Section 5.1), as well as the resulting managerial contributions for EV batteries and for CBM implementation in general (Section 5.2). An overview of the they arguments is provided in Table 4. Finally, we discuss implications of the results for CE policy-making (Section 5.3).

5.1. Theoretical contributions

In terms of the theoretical contributions, the framework applied in this study takes a multi-stakeholder approach to economic viability of circular projects, focusing on the value proposition of repurposed batteries towards the targeted BESS customers. The assumption is that circulated products, components and materials need to satisfy the same requirements as their linear counterparts in order to achieve sustainable production and consumption patterns at scale. For that, the framework in the study provides a structured process for ensuring economic viability of circular projects by investigating value proposition, value creation & delivery and value capture based on dedicated methods (see Fig. 6).

Meanwhile, this process has case-specific implications. The investigation of the value proposition was based on individual interviews with potential BESS customers. Here, other data collection methods such as customer workshops might be required for less established products. Moreover, in terms of the analysis of characteristic challenges for ensuring value creation & delivery, the analysis in the case study was based on the battery storage implementation process defined in (EPRI, 2017). In this regard, it must be noted that for other products, services or circular strategies, such processes might not exist. In such cases, a similar customer-oriented process would need to be developed in order to apply the framework presented in this study. This should take into account the considerations when describing and analyzing processes in organizations in terms of the series of events, the unit of analysis and other trends and underlying changes taking place in the background of the process investigated (Langley, 1999). Additionally, the analysis of economic feasibility at the customer in the case study was carried out via the NPV, which is one of the relevant metrics for assessing BESS projects. For other products, different economic evaluation methods might be applicable. While the present study argues for applying the same standards as for assessing economic implications of CBM as for existing, linear products, more work is needed to integrate such assessments with the CBM implementation process, e.g. as described in (British Standard Institution, 2017). Despite the fact that LCC is an established method in scientific literature (Sonnemann and Manuele, 2015), only few methods exist in scientific literature which establish a link between material circularity and economic results at product level (Corona et al., 2019). Future studies should thus further develop such approaches and e.g. integrate LCC considerations with material circularity indicator methods. By drawing from accounting methods such as NPV or return-on-invest calculations, the mostly

Table 4
Implications of case-specific findings for circular business model literature and management of circular projects in general and for the case of electric vehicle batteries.

Key task	References in existing literature	Managerial implications
1. Develop the product platform	Circular economy maturity level (British Standard Institution, 2017) Design for product integrity (den Hollander et al., 2017)	- Allocation of resources for implementing circular business models (time, budget, competences)
2. Assess different value streams	Downstream value logic (M. de P. Pieroni et al., 2019; Urbinati et al., 2017); Network value (Antikainen et al., 2016; Nußholz et al., 2019); Organizational capabilities (Lewandowski, 2016)	- Stakeholder/customer engagement for unlocking different value streams - Co-designing CBM for customer value
3. Leverage on resource value	Maintain product ownership (Sigüenza et al., 2021); Cascading across multiple circular strategies (Richa et al., 2017).	- Integrate cascading across CBM options in a battery eco-system; - Combine considerations on material circularity (SDG 12) with other sustainable development goals
4. Provide risk assurances on product quality	Service-based business models (Kjaer et al., 2019; Simone and Remmen, 2019; Tukker, 2015; Urbinati et al., 2017) Implement a pay-per-use principle (Sigüenza et al., 2021)	- Collect statistical evidence on product lifetime - Explore customer risk perception in circular projects - Test mitigation potential of service-based business models
5. Observe trends in targeted downstream markets	Organizational capabilities (Lewandowski, 2016); Internal and external barriers for circular adoption (Hina et al., 2022; Vermunt et al., 2019)	- Ensure competitiveness of products - Engage with technology partners - Monitor market trends
6. Acquire suitable financial capital	CBM innovation approach (Geissdoerfer et al., 2020) Investments in eco-innovation (Rizos et al., 2016; Schultz and Reinhardt, 2022)	- Organizational setup for the CBM implementation - Align financing strategy with risk profile of the circular project
7. Carry out pilot projects under market conditions	Circular economy maturity level (British Standard Institution, 2017)	- Include considerations for scalability of the CBM - Validate the cost-price offered to customers

project-based character of CE implementation efforts today can be addressed to support decision-makers in gaining a full picture of benefits of investments in circular solutions.

Regarding the theoretical implications of the identified key tasks, different links to existing studies can be found in scientific literature. The development of the product platform (task 1) in the context of a CE can be linked to the maturity level of CE adoption in an organization, in which the alignment of the value proposition with CE principles at process- and product level is a pre-requisite for business model innovation for CE (British Standard Institution, 2017). Furthermore, the design of products for upgradability, i.e. to be compatible with future versions of battery types is one example of "product integrity" (den Hollander et al., 2017). The results here show how such product design supports the optimization of the cost-benefit ratio of the circular project. Furthermore, the finding on assessing different value streams (task 2) on the one hand resonates with the focus on the downstream value logic of CBM as described in (M. P. P. Pieroni et al., 2019). The aspect of multi-use cases for BESS represents an example of addressing different benefiters in a network value (Antikainen et al., 2016; Nußholz et al., 2019a). Additionally, the need to build organizational capabilities to manage these value networks is mentioned in (Lewandowski, 2016).

Despite the lack of evidence provided in the case study, the findings for leveraging on resource value (task 3) and the provision of risk assurance on product quality (task 4) point towards the benefits of adopting of service-based business models in a CE. On the one hand, providing services and maintaining ownership of a product during the use stage enables sustainability benefits for manufacturers (Sigüenza et al., 2021) and cascading across multiple circular strategies (Richa et al., 2017). On the other hand, service-based business models enable revenues based on a pay-per-use principle while addressing the risk perception of the customers regarding reused products, as stated in (Tukker, 2015; Urbinati et al., 2017). This is in keeping with findings stated in previous studies, emphasizing the benefits of product-service systems for adopting the concept of a CE in general and dematerialize consumption (Kjaer et al., 2019; Simone and Remmen, 2019).

The observation of trends in targeted downstream markets (task 5) mostly requires companies to build organizational capabilities, e.g. expert knowledge on energy markets and regulation, to identify trends and opportunities for value capture (Lewandowski, 2016). At the same time, this focus on (external) market barriers for CBM implementation is mentioned in previous studies (Hina et al., 2022; Lieder and Rashid, 2016; Vermunt et al., 2019). In this regard, conducting pilot projects

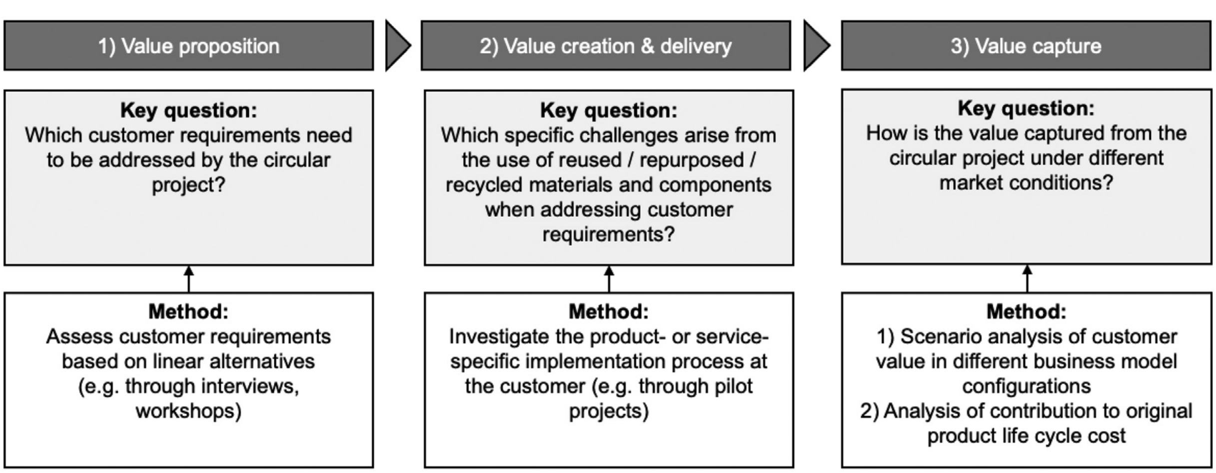

Fig. 6. Process for ensuring economic viability of circular projects derived from the conceptual framework applied in the case study.

under market conditions is identified as a way to validate performance and cost structures of implementing CBM (task 7). While there is little scientific literature on experimentation for CBM, this finding does relate to CBM innovation approaches and the level of maturity at which these are implemented (British Standard Institution, 2017).

Lastly, the acquisition of "circular" financial capital (task 6) refers to the alignment of the financing strategy for a CBM and the risk profile of the circular project. This task is both linked to the CBM innovation approach and the organizational entity which acts as an investor for a certain project (Geissdoerfer et al., 2020), as well as to the issue of access to capital for investing in CE-related eco-innovation in the first place (Rizos et al., 2016; Schultz and Reinhardt, 2022). Here, the findings show how the interest rate and the resulting cost of capital can affect the value captured from circular projects.

5.2. Managerial contributions

In terms of practical contributions to the management of product life cycles in a CE, the study provides several insights for the case of EV batteries. Here, the findings on the dependency of the profitability of B2U on the BESS size are confirmed by previous studies (Rallo et al., 2020). Moreover, the findings on the economic profitability suggest that the value captured from B2U depends on the market conditions and the respective BESS application (Kamath et al., 2020b). Especially the additional benefits from multi-use cases stated in other studies can thereby be confirmed (Lombardi and Schwabe, 2017; Tang et al., 2019; Tepe et al., 2021). The NPV values obtained are in keeping with the findings of previous studies (Balducci et al., 2018; Fitzgerald et al., 2015). While finding that the results correspond with previous studies for the case of B2U, a validation of the applicability to other cases is required. In this regard, especially the prediction of price developments in the energy sector are subject to some uncertainties. It can be expected that increases in energy cost and in the number of disruptions to energy supply as part of the ongoing transition towards RE are more likely than continuous and stable low-cost energy. Meanwhile, we address uncertainties by including a variety of potential future market scenarios in the study. The underlying assumptions are based on anticipated changes at the time of the study and should thus be carefully revised when interpreting the results.

From a managerial perspective, this suggests that B2U can indeed be a profitable CBM option for EV batteries today, but requires thorough development of the business model in the context of the energy system. This points to the need for closer collaborations between automotive manufacturers and stakeholders from electricity grids in order to develop integrated business models for the use of battery storages across sectors.

Moreover, and from the perspective of the manufacturer, some case-specific uncertainty is given by the cost of transportation, which can vary depending on the region and presumed transport modes- and distances (Slattery et al., 2021). Under the assumptions made in the present study, we show that the contribution of B2U to the LCC of the EV battery entails both additional revenues from EV battery sales and avoided cost of battery recycling. Practically, this implies that even when reducing the sales price of repurposed batteries from 100€/kWh to 36€/kWh, i.e. not capturing any profits from sales, manufacturers can still potentially gain benefits from B2U through savings and revenues from battery recycling. This shows how an integrated business case of a CBM for batteries based on the LCC contributions can reveal the margin for manufacturers to reduce product-related cost and ensure a positive value for customers. Hence, an eco-system view on CBM implementation for EV batteries could offer further insights into integrated business models between energy markets and recycling industry and provide economic leverage based cascading effects (Richa et al., 2017).

Towards more general implications for managing the economic viability of circular projects, the identified key tasks altogether show how the complexity of the CBM implementation process lies in coordinating numerous actors and competencies towards achieving competitiveness with linear alternatives. As such, especially key task 1 and 7 emphasize the need for companies to allocate sufficient resources, time and technical expertise to the development of CBM and the implementation of pilot projects. Both should entail considerations of scalability in order to achieve desired impacts for sustainable production and consumption at large. In this regard, the findings on task 3 and 5 together show the inter-connection between material circularity (SDG 12.3) and goals on clean energy systems (SDG 7) for the case of batteries (United Nations, 2015). In this sense, the present study thus shows how a CBM can serve as a conceptual basis for firms to combine considerations of sustainable management of resources across sectors and goals for sustainable development.

Furthermore, it follows from task 2 and 4 that customer value is perceived from the perspective of case-specific use cases and can entail aspects of minimizing risks. While the technical measures required to mitigate those risks, both aspects call for additional research on methods and format for co-designing CBM with the corresponding customers, focusing on value streams and de-risking circular projects. Here, the role of service-based offerings could not be finally clarified in this study and requires further investigation.

In summary, managerial tasks in relation to CBM need to gain in scale and relevance. For that, future studies should build on the results of the present study and analyze the characteristics of those business cases for CBM innovation, which sustain in comparison to the existing, linear models (Schultz and Reinhardt, 2022). In this regard, testing the approaches for CBM innovation mentioned in previous studies in the form of similar, long-term and in-depth case studies seems to be a promising avenue for determining the relationship between organizational setups for CE deployment, e.g. through circular startups, and the associated economic success (Geissdoerfer et al., 2020). Such studies could also reflect on the extent to which CBM for individual components such as EV batteries qualify the overall business model of vehicle-based personal mobility to become circular, e.g. by testing whether such approaches finally lead to a decoupling of resource consumption from economic growth in the mobility sector, which is stated as the overall objective in a CE (Geissdoerfer et al., 2017; Ghisellini et al., 2016).

5.3. Policy recommendations

In terms of implications of the results for policy-making, one aspect specific to the case of batteries is the availability of data in order to address several of the identified key tasks. As such, this affects the repurposing process, in which batteries are recovered from EV markets and qualified for further use (see Fig. 1). Here, knowledge of key battery data and the available number of charging cycles is a crucial aspect for integrating different battery types in the product platform (task 1), assessing their suitability for different combinations of BESS use cases (task 2) and for ensuring minimum lifetime requirements to reduce product risks (task 4). Hence, regulatory action is needed to ensure access to battery data, e.g. via product passports which enable third parties to request data access from original equipment manufacturers (Circular Economy Initiative Deutschland, 2020; Global Battery Alliance, 2021). Similar requests are identified in the revision of the EU battery directive and should be enforced in practice (European Commission, 2020c).

Moreover, the identified aspect of financing CBM points to the necessity of mobilizing suitable financial capital for implementing and scaling circular projects. Here, policy action should focus on creating favorable conditions for companies to gain access to investments, which are willing to support the displacement of linear alternatives in favor of CBM. One aspect here is the introduction of service-based offerings, which for companies is linked to major risks and financial efforts (Sigüenza et al., 2021; Tukker, 2015). While the role of service-based business models for reducing product risk perceptions of customers requires further investigation, policy support for companies to manage the shift from sales-based to subscription-based revenue models might enhance endeavors of manufacturers to increase their engagement in EoL management of products.

Lastly, several general issues exist for companies in relation to implementing a CE, e.g. the cannibalization of sales revenues when offering repurposed or remanufactured products compared to new ones and the corresponding lock-in effects with existing technologies (Korhonen et al., 2018; Okorie et al., 2021). While the results of the present study indicate positive shared value across different stakeholder groups for the case of B2U, policy-making for CE should focus on establishing mechanisms which prevent the discrimination of reused products but instead incentivize their use compared to virgin materials and components. In this sense, our findings suggest that a focus on customer value should also be adopted in CE policy-making, which today is found to be centered around obligations of manufacturers in terms of waste management and does not address the much needed customer benefits from a CE deployment at scale (Calisto Friant et al., 2021).

6. Conclusions

As the adoption of CE strategies at scale is still limited in industry today, the need to provide practical guidance on how to capture economic value from implementing CBM is needed. Based on the rational of an increasing need to focus on customers targeted by CBM, this study presents an in-depth case study on a real-world project of B2U in Germany with a particular focus on customer characteristics and value creation. For that we provide a framework for assessing customer-and market implications of CBM, which leads to the identification of seven key tasks for capturing economic value from circular projects.

In terms of the key contributions, this study provides a framework for exploring the value proposition, creation & delivery and value capture of circular projects and establishes a link to existing studies. From a managerial perspective, the findings reveal that the complexity of the CBM implementation lies in coordinating a number of tasks, actors and competencies towards competitiveness with linear alternatives, which calls for increasing collaboration across sectors in a CE. Moreover, we find that policy-action is required to support the battery repurposing process and enable a level playing field for actors in the battery ecosystem through access to full product functionality and the corresponding value streams.

In this sense, the present study approach aims at going beyond the identification of general drivers and barriers for CBM implementation. Rather than focusing on the original product life cycle and the responsibilities of manufacturers when recovering products from markets, we argue that an increasing focus on addressing customer requirements through in-depth studies is needed in order to move circular projects away from pilot-stage and towards a widespread adoption. Based on the economic assessments offered in this study, we aim to inspire the use of holistic assessments at manufacturers on the profitability of engaging in CBM, both for the case of EV batteries and for mobility in general. For future studies, we hence identify the need for further investigating methods for co-developing for CBM with targeted customers. Furthermore, we suggest to investigate the de-risking potential of CBM through service-based offerings in a CE, as well as organizational setups of CBM innovation and implications for access to downstream markets. These together should focus on assuring the validity of CBM from a customer perspective and hence drive sustainable production and consumption at scale.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

The authors would like to thank all the interviewees who have contributed to the results with their expert knowledge; Leonie Eigenbrodt and Lucas Nitsche for supporting this study as part of their thesis projects; Katrin Bauer for her support in validating the required data sources; A. Tukker, A. Remmen, as well as all anonymous reviewers for their fruitful comments to improve the manuscript. The authors acknowledge the general support of Mercedes-Benz for the data collection as part of this study.

Supplementary information

Supplementary information to this article can be found online at https://doi.org/10.1016/j.spc.2022.11.025.

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