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Enabling battery circularity: Unlocking circular business model archetypes and collaboration forms in the electric vehicle battery ecosystem

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ABSTRACT

Achieving battery circularity is crucial for meeting the targets of net-zero emission vehicles by 2030 and enabling climate-neutral transportation by 2050. To facilitate this transition, firms operating in the electric vehicle (EV) battery ecosystem must reassess their value creation, capture, and delivery methods. Although EV battery second life presents a promising solution for circularity, many vehicle manufacturers and stakeholders in the battery ecosystem struggle to adapt their organizations internally and externally due to a lack of insights into suitable circular business models. The purpose of this study is to identify viable archetypes of circular business models for EV battery second life and examine their implications on company collaborations within the EV battery ecosystem. Three main archetypes of circular business models are identified (i.e., extending, sharing, and looping business models) and further divided into eight sub-archetypes. These models are elucidated in terms of key business model dimensions, including value proposition, value co-creation, value delivery, and value capture. The paper provides visual representations of the necessary interactions and collaborations among companies in the EV battery ecosystem to effectively implement the proposed business model archetypes. This research contributes to the theory of circular business models in general, with specific relevance to EV battery circularity.

1. Introduction

The transport sector plays a crucial role in achieving the European Union's commitment to climate neutrality by 2050, with climate-neutral electrification involving both the transition to electric vehicles (EVs) and the adoption of renewable power sources (Scarlat et al., 2022). As this transition aligns closely with circular economy principles, emphasizing waste minimization and resource optimization by closing loops (Aguilar Esteva et al., 2021), the adoption of EVs has been rapidly increasing in line with these climate-neutral objectives. Lithium-ion batteries serve as integral components in EVs, yet they degrade over time, typically losing 20 %–30 % of their capacity following the vehicle's expected service life (Barré et al., 2013; Sarasketa-Zabala et al., 2016; Marques et al., 2019). Although the battery retains 70 %–80 % of its power as it degrades, it can no longer be used in vehicle applications due to safety concerns (Foster et al., 2014; Groenewald et al., 2017).

Researchers have explored the potential for creating innovative circular business opportunities using EV batteries at the end of their expected 7 to 10-year service life (Shahjalal et al., 2022; Reinhardt et al., 2019). As millions of tons of EV lithium-ion batteries are currently approaching the end of their lifespan, it is imperative to preserve their value through a circular approach, which is crucial for achieving the objectives of climate-neutral electrification (Aguilar Esteva et al., 2021; Bonsu, 2020; Albertsen et al., 2021). The most significant environmental and economic benefits of battery circularity can be realized by initially repairing, refurbishing, remanufacturing, and reusing batteries, followed by recycling them after their initial use (e.g., Zhu et al., 2021; Iqbal et al., 2023; Chirumalla et al., 2023). Even after completing their first life, EV batteries can still find applications utilizing their remaining capacity in less demanding stationary systems, such as energy storage,

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charging stations (both on and off grid), and services like peak shaving, fast charging, energy arbitrage, and grid support (Martinez-Laserna et al., 2018; Vu et al., 2020; Hesse et al., 2017; Haram et al., 2021). Numerous vehicle manufacturers are actively exploring these emerging market opportunities through collaborations with energy utility companies and specialized third-party partners, such as second-life system integrators (Costa et al., 2022; Schulz-Mönninghoff and Evans, 2023; Reinhardt et al., 2020; Albertsen et al., 2021; Júnior et al., 2023). However, to achieve success, the implementation of battery second life and circularity must become more competitive than traditional linear "take–make–dispose" business alternatives (Reinhardt et al., 2019; Zhu et al., 2021; Júnior et al., 2023).

In this regard, identifying, designing, and implementing feasible and suitable circular business models (CBMs) for EV batteries is crucial (Martinez-Laserna et al., 2018; Reinhardt et al., 2019; Bonsu, 2020; Chirumalla et al., 2022). By drawing from the CBM literature as a starting point (e.g., Bocken and Ritala, 2022; Geissdoerfer et al., 2020; Lewandowski, 2016; Ludeke-Freund et al., 2019), several studies have explored potential suitable CBMs for EV batteries (Albertsen et al., 2021, Olsson et al., 2018; Wrålsen et al., 2021; Reinhardt et al., 2020; Jiao, 2019). For instance, Olsson et al. (2018) conceptualized four business model scenarios for second-life batteries, while Jiao (2019) categorized three types of second-life business models. In a similar vein, Wrålsen et al. (2021) proposed three CBMs with the highest potential, and Albertsen et al. (2021) examined CBM strategies such as repair, refurbishment, remanufacturing, repurposing, and recycling. Furthermore, Reinhardt et al. (2020) developed nine sustainable business model archetypes for EV battery second life, considering three dimensions of sustainability (i.e., environmental, social, and economic dimensions), and analysed their suitability in empirical cases.

Although the discussion surrounding CBMs for EV batteries has been expanding and several industrial actors have initiated second-life pilot or demonstration projects, many vehicle manufacturers and stakeholders in the battery ecosystem still encounter challenges in preparing their organizations both internally and externally for second-life operations, particularly in terms of selecting and implementing suitable CBMs for EV batteries (Wrålsen et al., 2021; Zhu et al., 2021; Chirumalla et al., 2022; Sopha et al., 2022; Olsson et al., 2018; Kifor and Grigore, 2023; Rönkkö et al., 2023). The increasing diversity of EVs used in cars, buses, trucks, and heavy-duty vehicles, along with the growing variations in battery types (e.g., chemistry, size, and configuration), adds complexity to the absorption of knowledge related to second-life business model strategies (Ahmad et al., 2021; Júnior et al., 2023; Chirumalla et al., 2022; Reinhardt et al., 2020).

Hence, many actors in the EV battery ecosystem face multiple layers of issues and numerous uncertainties related to the implementation of CBMs (Börner et al., 2022; Marcos et al., 2021; Júnior et al., 2023; Shahjalal et al., 2022). For example, some uncertainties are linked to challenges in achieving data transparency during the first life of the EV battery (Ducuing and Reich, 2023), which may, in turn, impact coordination and cooperation related to the battery's second life. Therefore, recent studies increasingly underscore the importance of collaboration in the context of CBMs (Trevisan et al., 2022; Gomes et al., 2023; Albertsen et al., 2021). More specifically, there is a lack of research demonstrating how multiple stakeholders need to collaborate when choosing the right CBM for their specific operations within the EV battery ecosystem (see, e.g., Schulz-Mönninghoff and Evans, 2023; Reinhardt et al., 2019; Chirumalla et al., 2022).

The implementation of CBMs is inherently context specific (Albertsen et al., 2021) due to significant variations in products and markets among different industrial actors (Reim et al., 2021). Furthermore, most studies delve into primarily conceptual or theoretical aspects, creating a void in terms of practical, industry-based examinations of these models in real-world settings. This gap is particularly crucial because gaining insights into the complexities of these models as they operate in practice can offer invaluable guidance for stakeholders along the entire value chain. In addition, many proposed CBM archetypes related to EV batteries remain conceptual and relatively broad, often combining several CBM strategies into a single category (for example, some CBM examples found in the literature include combinations like: remanufacture + reuse + recycle + waste management; battery production and use in a vehicle + repair and refurbishing for second use in the vehicle, whether in the same market or a new one, + state-of-the-art recycling). This approach is somewhat expected given that the CBM literature is still evolving, particularly in the context of EV batteries, which remains in its early stages of exploration. Even within these mentioned CBM types for EV batteries, limited information covers various elements of different business models, leading to uncertainties in comprehending the overall landscape. Moreover, there is a lack of clear descriptions regarding the interaction and collaboration among different actors concerning the various types of CBMs within the EV battery ecosystem. To establish a systematic understanding, it is necessary to propose CBM archetypes tailored to the specific context of EV batteries, which will enable the derivation of underlying forms of interaction and collaboration among actors within the EV battery ecosystem.

Therefore, the purpose of this study is to identify potential archetypes of circular business models for EV battery second life and examine their implications on company collaborations within the EV battery ecosystem. To achieve this goal, the following research questions are defined to guide the investigation:

> RQ1: What are viable archetypes of circular business models that can be employed to utilize electric vehicle batteries in their second life?
> RQ2: In order to implement these archetypes of circular business models in the electric vehicle battery ecosystem, what forms of collaboration among different companies could be suitable?

To address the research purpose and research questions, this study employed an exploratory research design involving 15 companies within the EV battery ecosystem. The study categorized three primary archetypes of CBMs for EV battery second life, further dividing them into eight sub-archetypes of CBMs. These sub-archetypes of CBMs are visually represented to illustrate suitable company collaborations within the EV battery ecosystem for their implementation.

This study contributes in two significant ways. First, it offers a comprehensive examination of viable CBM archetypes and sub-archetypes for EV battery second life, drawing on rich empirical data from actors in the EV battery ecosystem—an area that has received limited exploration in the existing battery-related CBM literature (Reinhardt et al., 2020; Albertsen et al., 2021; Júnior et al., 2023; Olsson et al., 2018; Wrålsen et al., 2021). Second, it enhances our understanding of how multi-stakeholder collaborations (e.g., Reinhardt et al., 2019; Chirumalla et al., 2022; Schulz-Mönninghoff and Evans, 2023) can be potentially suitable for successfully implementing the proposed CBM archetypes (e.g., Bocken and Ritala, 2022; Geissdoerfer et al., 2020; Lewandowski, 2016). These findings are valuable for both researchers and practitioners as they elucidate the CBM archetypes, their constituent business model elements, and the dynamics of interactions and collaborations among actors in the context of EV battery second life and battery circularity.

The structure of the paper is as follows: Section 2 presents the theoretical background of the study. Section 3 outlines the research approach and context, encompassing details of data collection and analysis. Section 4 provides a comprehensive description of the three primary archetypes and eight sub-archetypes of CBMs for battery second life. Finally, Section 5 offers a discussion and presents concluding remarks.

2. Theoretical background

This section delves into two essential theoretical foundations relevant to the investigation: CBMs and CBMs for the battery second life. The sub-sections explore various types/archetypes of CBMs as well as their implementation and collaboration aspects.

2.1. Circular business models

The circular economy, as defined by Geissdoerfer et al. (2017, p. 759), is a "regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". In this context, CBMs play a pivotal role in implementing the circular economy by fundamentally reshaping how goods and services are designed, produced, consumed, and disposed of (Geissdoerfer et al., 2020; Nußholz, 2017). CBMs are business models that create, deliver, and capture value based on the principles of the circular economy (Kirchherr et al., 2017).

Firms must implement CBMs by reformulating value propositions and developing value chains that prioritize "using as little resources for as long as possible while extracting as much value as possible in the process" (Geissdoerfer et al., 2020, p. 2). CBM innovation demands collaboration, communication, and coordination within complex systems (Antikainen and Valkokari, 2016) comprising interdependent yet independent stakeholders (Bocken et al., 2018; Schulz-Mönninghoff and Evans, 2023). Firms can adopt diverse approaches or strategies to develop their CBMs. Regardless of the approach taken, the concept of multi-stakeholder collaboration is an integral idea for achieving circularity (Chirumalla et al., 2022; Reim et al., 2021). In their study of five industry cases, Okorie et al. (2021) identified several factors affecting CBM adoption, including policies and legislation, customer acceptance, and the circular value network structure. These factors, from an organizational design perspective, pertain to barriers for CBM implementation at three organizational levels: the institutional, the strategic, and the operational level (Bocken and Geradts, 2020). These barriers can either hinder or enable dynamic capabilities within the organization (de Miguel et al., 2022; Ogunrinde, 2022). The business model innovation literature provides insights into factors that may help mitigate these barriers, such as strong organizational leadership and management support, the establishment of a clear organizational vision, the development of a proper organizational structure, the provision of relevant incentives, and access to necessary resources (e.g., Chesbrough, 2010; Foss and Saebi, 2017).

CBMs should harmonize two strategies: the resource strategy, linked to environmental goals and emphasizing the narrowing, closing, or slowing of resource loops, and the innovation strategy, related to the dynamics of opening and closing innovation processes (Bocken and Ritala, 2022). Narrowed loops relate to making production processes more efficient and using fewer resources; closed loops concern the reutilization of materials after initial use; and slowed loops refer to prolonging product life (Bocken and Ritala, 2022). These three types of loops, representing resource strategies for CBMs, may be further combined with closed or open innovation strategies (Bocken and Ritala, 2022). According to the authors, this combination provides six strategy archetypes for CBMs: open-narrowing, open-slowing, open-closing, closed-narrowing, closed-slowing, and closed-closing. Geissdoerfer et al. (2020) further expanded on this by proposing four generic resource loop strategies for CBMs: cycling, extending, intensifying, and dematerializing.

Researchers have made several attempts to classify CBM types. Nußholz (2017) presented a typology that maps CBMs against resource efficiency strategies. Many of these business models are related to the use phase, with examples of CBMs including product-life extension and sharing platforms (Moreno et al., 2016), extending product value (Bocken et al., 2016), and the gap-exploiter model that captures residual value through repair strategies (Bakker et al., 2014). De Angelis (2021) proposed slightly different typologies of CBMs, including resale, internalization, and performance-based CBMs. Lewandowski (2016) identified six classification criteria to map various CBMs: regenerate, share, optimize, loop, virtualize, and exchange. Ludeke-Freund et al. (2019) also identified six CBM patterns: repair and maintenance, reuse and redistribution, refurbishment and remanufacturing, recycling, cascading and repurposing, and organic feedstock business models. Meanwhile, Planing (2018) proposed a CBM typology with nine archetypes: access model/collaborative consumption, performance model/products as services/result-based models, reuse/refurbish/maintain/redistribute/next-life sales, hybrid model/gap-exploiter model, remanufacturing next-life sales, upgrading, product transformation, product recycling/recycling 2.0, and energy recovery. Finally, Pieroni et al. (2020) consolidated 20 archetypes of business models fit for the circular economy and organized them into eight categories, with access models and sharing or pooling systems/platforms being among the most recurring archetypes.

2.2. Circular business models for the battery second life

CBMs serve as the backbone of EV battery second life by narrowing, closing, and slowing the loops of EV batteries among different stakeholders. For instance, certain original equipment manufacturers (OEMs), such as Daimler and Renault, have already integrated CBMs by expanding into the energy sector and incorporating second-life applications (Albertsen et al., 2021). Closed-loop initiatives are also gaining popularity among vehicle OEMs, like Nissan, BMW, and Renault, which collaborate with energy companies on EV battery second-life projects (Bonsu, 2020). CBMs based on energy storage solutions can offer multiple services and create new value propositions, including grid stabilization services, backup power for private customers, peak shaving, and support for local solar power production (Albertsen et al., 2021).

Jiao (2019) identified three crucial factors essential for the functioning of second-life business models: battery ownership, inter-industry partnerships, and policy support. Naor et al. (2018) suggested that servitized business models would enhance affordability and control over batteries at the end of their lifecycles, promoting further reuse. Olsson et al. (2018) demonstrated that, although several stakeholders recognize the potential of second-life applications, they face various barriers, many of which pertain to organizational and cognitive aspects rather than technological dimensions. Cognitive barriers include a lack of interest in new business models or a perceived lack of value in second-life solutions, while organizational barriers involve investment risks and legal issues. Sopha et al. (2022) identified barriers to and enablers for incorporating EV batteries into the circular economy and proposed a framework of strategies for managing EV batteries. The identified barriers are associated with technology, infrastructure, supply chain operations, and management. Enablers encompass not only these aspects, but also economics, policy and regulations, and social factors.

In a comparison of circular economy approaches for EVs and conventional vehicles, Kifor and Grigore (2023) raised several issues concerning CBMs for second-life batteries. For instance, they highlighted the need to better understand the socio-economic-environmental impact of recycling retired EV batteries and the development of strategies for optimized recycling. Helander and Ljunggren (2023) investigated CBMs, including the multiple reuse and recycling of lithium-ion battery subpacks from trucks and loaders used in the mining industry. They found a conflict between maximizing the availability of secondary materials and extending product lifetimes, which policymakers must consider when setting targets for material recycling and reuse. Rönkkö et al. (2023) studied the current state of circularity options related to EV batteries in Finland and found that environmental legislation and regulations do not support circular economy options for such batteries. They also noted that unpredictable material flows and labour-intensive disassembly are factors affecting the EV battery ecosystem.

Research on CBMs for EV battery second life and circularity has seen significant growth, with researchers proposing various types of CBMs. For instance, Olsson et al. (2018) introduced four conceptual business model scenarios for second-life batteries: linear model, optimized recycling, the first circular model (i.e., battery production and use in vehicle + repair and refurbishing for second use in vehicle in the same or a new market + state-of-the-art recycling), and the second circular model (i.e., battery production and use in vehicle + repackaging and second life in a different application + state-of-the-art recycling). Although the last scenario is currently undergoing testing for household smart energy storage systems, it requires the highest degree of collaboration among various stakeholders in the value network, including OEMs, dismantlers, recycling, actors, and second-life actors (Marcos et al., 2021; Gebhardt et al., 2022; Liu et al., 2022). In this scenario, the most significant uncertainties revolve around defining the product, which may undergo changes during the transition from its first to second use.

Wrålsen et al. (2021) utilized the Delphi method to propose three circular business models that exhibit the highest potential for batteries: 1) remanufacture + reuse + recycle + waste management, 2) product life extension through durable design, update services, remanufacture, and 3) resource recovery of discarded materials. Schulz-Mönninghoff and Evans (2023) emphasized that, among the archetypes of CBM identified by Ludeke-Freund et al. (2019), three main options are applicable to batteries at their end-of-life stage: refurbishment and remanufacturing, cascading and repurposing, and recycling. Helander and Ljunggren (2023) analysed battery as a product-service system offer or as service, considering multiple reuse and recycling loops of lithium-ion battery subpacks for mining equipment. In their multi-case evaluation of automotive manufacturers, Schulz-Mönninghoff et al. (2021) found that repurposing is the most beneficial option among various CBMs for lithium-ion batteries, taking into account additional recycling benefits resulting from the delay of end-of-life.

Reinhardt et al. (2020) explored sustainable business model archetypes in five cases of the battery second-life market and identified the following archetypes: maximize materials and energy efficiency; close resource loops; substitute with renewables and natural processes; deliver functionality, not ownership; adopt a stewardship role; promote inclusive value creation; and develop sustainable scale-up solutions. Jiao (2019) explored the business models for EV battery second life through empirical cases and identified five typologies for battery second-life business models: a standard business model, three collaborative business models, and an integrative business model. The author also demonstrated how battery second-life stakeholders are interacting in different ways to create and capture value from battery second life. The study further suggested three critical business model design elements—namely, lifecycle thinking, system-level design, and the shift to services—as helpful aspects for battery second-life stakeholders to consider to better design their second-life batteries.

Furthermore, in the context of enabling battery circularity, Bonsu (2020) stressed the significance of closed-loop business models, Reinhardt et al. (2019) highlighted the importance of multi-stakeholder network-centric business models, and Chirumalla et al. (2022) focused on mapping win–win–win CBMs within the EV battery ecosystem, where the environment and society represent the third stakeholder benefiting from this circular approach.

Finally, Albertsen et al. (2021) examined CBM strategies like repair, refurbishment, remanufacturing, repurposing, and recycling for EV lithium-ion batteries within European vehicle manufacturers. Their findings highlight a predominant focus among many OEMs on repair, refurbishment, and repurposing. The strategies employed for lithium-ion batteries vary among OEMs and are significantly influenced by contextual factors. Notably, several OEMs are still in the experimental phase with CBMs for batteries. Importantly, all CBMs were observed to necessitate close collaboration among various stakeholders to foster trust and mitigate uncertainties. Table 1 summarizes extant literature on CBMs for the battery second life.

Table 1
Key messages in literature on circular business models for the battery second life.

Authors	Key messages
Olsson et al. (2018)	Four potential business models for second-life batteries are conceptualized.
Wrålsen et al. (2021)	Three business models are suggested for second-life batteries.
Bonsu (2020)	Closed-loop business models are critical for second-life batteries.
Reinhardt et al. (2019)	Business models for second-life batteries must consider multi-stakeholder networks.
Albertsen et al. (2021)	EU automotive OEMs mostly focused on repair, refurbishment, and repurposing CBMs. OEMs must design their CBMs based on their context and needs.
Chirumalla et al. (2022)	The EV battery ecosystem cannot only involve actors in the ecosystem, but must also consider the environment and society as stakeholders.
Sopha et al. (2022)	Barriers and enablers must be accounted for when devising EV circular business models that involve second-life batteries.
Kifor and Grigore (2023)	EV circular business models require better understanding of social-economic-environmental impacts of the recycling of retired EV batteries and strategies for optimized recycling.
Helander and Ljunggren (2023)	EV circular business models must consider the potential conflict between maximizing the availability of secondary materials and extending product lifetimes.
Rönkkö et al. (2023)	EV circular business models, including second-life batteries, rely on environmental legislation and regulations, but also need to consider unpredictable material flows and labour-intensive disassembly.

3. Methodology

3.1. Research approach

Considering that the two research questions aim to explore viable archetypes of CBMs (RQ1) and identify forms of collaboration to implement these archetypes (RQ2), an exploratory research design with a qualitative approach (Makri and Neely, 2021; Richard, 2018) is deemed appropriate. An exploratory research design is particularly suitable when the phenomenon under investigation is still emerging, lacks a clear definition, and has not been extensively studied (Stebbins, 2001; Saunders et al., 2009). This design approach proves valuable for understanding ongoing developments, uncovering new insights, and revealing underlying motivations and strategies (Saunders et al., 2009; Makri and Neely, 2021).

Mouton (1996) emphasized that the objectives of exploratory studies include the establishment of facts, the collection of new data, and the identification of meaningful patterns or themes within a relatively unknown research area, all with the aim of gaining fresh insights into the subject of research. Furthermore, employing an exploratory research design is beneficial for obtaining background information and serves to clarify research problems and hypotheses, thereby setting research priorities (Saunders et al., 2012). This approach is particularly relevant to the present research on EV battery second life and circularity. Prior studies have offered limited specificity regarding the CBM archetypes that could prove effective in this context. Furthermore, there is currently a lack of empirical evidence illustrating how collaboration and CBM archetypes can be synergistically combined, ensuring that collaboration challenges do not impede progress towards achieving circularity (Gebhardt et al., 2022; Trevisan et al., 2022).

An exploratory research design also aligns well with inductive research, where the researcher commences data collection and analysis to inform subsequent work (Saunders et al., 2009). This approach is particularly effective for theory-building endeavours, especially in situations where existing theories are limited or non-existent (Edmondson and McManus, 2007). In line with these considerations, a qualitative research methodology was selected for this study. Qualitative methods are well-suited for the identification and interpretation (Denzin and Lincoln, 2003) of CBMs as well as the implementation of CBM archetypes within real industrial settings. Notably, the qualitative approach is regarded as methodologically appropriate for exploratory research by multiple researchers, including Edmondson and McManus (2007), Saunders et al. (2009), and Easterby-Smith et al. (2002). Previous researchers have also employed a qualitative and exploratory research approach in their investigations of business model innovation, CBM implementation, business model archetypes, and capabilities development (e.g., Huang and Ichikohji, 2023; Reim et al., 2021; Reinhardt et al., 2020).

Table 2
Participants of EV battery ecosystem actors involved in the study and their corresponding information.

Actor	Ecosystem role	Current offerings	Research phase	Data collection	Participants	No. of. informants	No. of. instances	Duration (min)
A*	Original equipment manufacturers (OEMs)	Heavy-duty construction equipment and vehicles	I	Interviews	Senior global remanufacturing engineer; manager global parts and aftermarket options	2	2	110
			II	Interviews	Senior global remanufacturing engineer	1	2	90
			I	Workshops	Senior global remanufacturing engineer; manager global parts and aftermarket options	3	3	350
			II	Workshop	Senior global remanufacturing engineer; head of direct sales; circular business development; customer services; product manager	5	1	150
			II	Workshops	Senior global remanufacturing engineer	1	2	180
B		Mining and infrastructure equipment	I	Interview	Marketing manager	1	1	100
			I	Interview	Business developer	1	1	90
C*		Trains and mobility solutions	I	Interview	Head of innovation, strategy and portfolio; platform manager; strategic innovation on business models; technology manager	4	2	120
			II	Interview	Head of innovation, strategy and portfolio	1	1	90
			I	Workshops	Head of innovation, strategy and portfolio; director platform management; strategic innovation on business models	3	3	300
D	Battery manufacturer	Green batteries	I	Interview	Sales manager	1	1	100
E	Recycling companies	Recycling, battery parts	I	Interview	Business developer	1	1	90
F		Recycling	I	Interview	Marketing & sales director	1	1	90
G	Remanufacturer	Vehicle parts, remanufacturing	I	Interview	Business and technology developer	1	1	80
H	System integrator	Energy management, System integration, smart city applications	I	Interview	Head of digital delivery	1	1	110
I*	Energy utility companies	Energy and power sales, ESS	I	Interview	Strategy manager; business developer; specialist	3	2	120
			I	Interview	Strategy manager	1	1	90
			I	Workshops	Strategy manager; business developer	2	2	240
			II	Workshop	Strategy manager; business developer	1	1	120
J		Charging infrastructure, Power as a service (PaaS)	I	Interview	Head of R&D	1	1	100
K*		Energy and power sales, environmental services	I	Interview	Business developer; CEO	2	1	85
			I	Interview	Strategist	1	1	95
L*	Material supplier	Cables, harness, consultancy	I	Interview	CEO, managing director	1	1	125
			I	Workshops	CEO, managing director; sales & marketing manager; technical sales	3	2	250
M	Construction and housing company	Residential properties, R&D	I	Interview	Business developer	1	1	75
N	Public transportation company	City transportation	I	Interview	Head of sustainability and innovation	1	1	100
O	Refurbisher and circular integrator	Refurbishment and second life of the EV batteries	I	Interview	CEO and managing director	1	1	80
A*, C*, I*, K*, L*	OEMs, energy utility companies, material supplier	–	I	Joint companies' workshops	Senior global remanufacturing engineer; head of innovation, strategy and portfolio; strategy manager; strategist; CEO	5	5	900
A*, C*, I*, K*, L*	OEMs, energy utility companies, material supplier	–	II	Joint companies' workshops	Senior global remanufacturing engineer; head of innovation, strategy and portfolio; strategy manager; strategist; CEO	3	3	540

3.2. Research process, context, and selection of companies

The research was conducted in two phases. The first phase (Phase I) focused on exploring the overall implementation of CBMs for EV battery second life and circularity, involving numerous companies within the EV battery ecosystem. The second phase (Phase II) delved into detailed discussions regarding the design of CBM archetypes and validated these archetypes for EV battery circularity with the participation of five selected companies from the EV battery ecosystem. Table 2 provides details about the representative companies from the EV battery ecosystem that participated in this study; it also marks the research phases (i.e., I and II). The five companies that participated in Phase II are highlighted in bold and marked with an asterisk (*) for easy identification.

Purposeful sampling, as outlined by Patton (2002), was employed to select companies from the EV battery ecosystem. The objective was to encompass key actors within the ecosystem. During a comprehensive review of the literature, we identified the pivotal actors in the EV battery ecosystem, encompassing both first-life, second-life, and recycling companies. These actors include OEMs, battery manufacturers, remanufacturers, recycling companies, refurbishers and circular integrators, energy utility companies, engineering system integrators, material suppliers for battery components, construction and housing companies, and public transportation companies (Albertsen et al., 2021; Chirumalla et al., 2022; Jiao, 2019; Vu et al., 2020; Wrålsen et al., 2021).

This study is part of a four-year research project called RECREATE (Second-Life Management of Electric Vehicle Batteries). As a result, the process of selecting companies began by reaching out to partner organizations involved in the project. These partners include a heavy-duty equipment and vehicle manufacturer (Company A*), which also operates a remanufacturing unit (Company G); a train manufacturer (Company C*); two energy utility companies (Company I* and Company K*), with one of them also having a recycling unit (K*); and one material supplier specializing in battery components.

The selection of these companies was motivated by several factors. They not only possess essential expertise for enabling battery circularity, but they have also actively participated in the operationalization of second-life and circular solutions in this domain. They also exhibit varying levels of maturity in circularity efforts, reflecting diverse stages of their circular transition. In addition, they express clear ambitions to accelerate their circular initiatives. Furthermore, they have access to valuable empirical insights and are willing to share them. Finally, these actors have the potential to assume multiple roles in the EV battery ecosystem, ranging from OEM manufacturers and suppliers to users and system integrators. Collectively, these companies can offer detailed insights and experiences related to potential CBM archetypes (RQ1) and the necessary forms of collaboration to implement these archetypes (RQ2).

Moreover, to gain a comprehensive perspective from various ecosystem actors involved in the EV battery domain, this study extended its reach beyond the partner companies in the project. It identified and included an additional 10 companies in the empirical observation phase. As a result, the study encompasses a total of 15 companies. All of these selected companies are significant players with substantial knowledge and expertise that can contribute to this research. The selection process ensured that at least one company was chosen to represent each identified role within the ecosystem, as outlined in the literature. Table 2 presents an overview of the 15 selected companies, including details about informants, their roles, offerings, involved stages, and corresponding codes. These 15 companies encompass a diverse range, including three EV OEMs, three energy utility companies, two recycling firms, two remanufacturing and refurbishing entities, a battery manufacturer, an engineering system integrator, a material supplier, a construction and housing company, and a public transportation firm. Some categories such as OEMs, recyclers, and energy utility companies include more than one member, reflecting the significance of their roles and the need for a comprehensive data collection from their unique perspectives.

3.3. Data collection and analysis

To gather data, this study employed a qualitative inquiry approach (Yin, 2009), utilizing interviews and workshop methods. In total, the data collection involved 24 in-depth semi-structured interviews with 25 informants and 22 workshops with 26 informants, representing various stakeholders within the EV battery ecosystem. Specifically, 21 in-depth semi-structured interviews and 15 workshops took place during Phase I, while Phase II included 3 interviews and 7 workshops (further details are available in Table 2). The duration of the interviews ranged from 75 to 120 min, while workshops typically lasted between 90 and 180 min. All meeting sessions were recorded, and the audio or video files were subsequently transcribed.

Semi-structured interviews are a commonly employed and versatile method for gathering information in qualitative research (Hunt et al., 2011). Their flexibility and ability to yield insightful information make them particularly well-suited for comprehending complex issues (Fylan, 2005). At the research project level, we adopted an interactive research approach (Sandberg et al., 2022), which takes into account both industrial benefits and scientific needs. This approach is used to guide the design and execution of research studies and the co-production of relevant solutions and methods (Ellström et al., 2020).

In this context, workshops played a pivotal role in collecting and analysing data and ideas. They facilitated continuous dialogue and mutual learning between researchers and practitioners, allowing for the sharing of insights, knowledge, experiences, and lessons learned. Workshops proved especially valuable in endeavours requiring diverse perspectives, deeper insights from experts, and judgments (Sandberg et al., 2022). The workshops were particularly relevant for exploring topics such as the implementation of EV battery circularity, ongoing shifts, upcoming business model scenarios, and ecosystem partnerships, where verification is considered a crucial stage.

To address these needs, the workshops were conducted with cross-functional managers from different companies, taking the form of joint workshops (see Table 2). In addition, workshops were held with cross-functional managers within individual companies to gather insights and perspectives, disseminate information, facilitate discussions, and validate preliminary results and outcomes. Joint workshops were conducted throughout the project; each focused on specific themes and was guided by a series of questions (Sandberg et al., 2022). These workshops covered a range of important topics, including mapping barriers and opportunities within the second-life solutions in the value chain, developing business case scenarios for second-life applications, identifying suitable cases for second-life applications, exploring second-life battery business models and their ecosystem actors, analysing second-life project cases, and exploring potential circular business models and scenarios.

Similarly, individual company workshops were also guided by specific sets of questions on each occasion. Some examples of these questions include the following:

- What are the critical barriers and enablers for second-life batteries in both the short and long term?
- What potential business case scenarios exist for second-life applications?
- Which types of business models and products align with the identified business case scenarios?
- Who are the target customers for second-life applications, and can you categorize them?
- What steps must the company take to realize the identified business case scenarios?
- What internal and external capabilities need to be developed?

- What opportunities exist for second-life demonstrators, considering your ecosystem actors?

These workshops played an indispensable role in this research, providing valuable inputs, facilitating discussions, and validating results.

The number of participants in the interviews varied from 1 to 4, while in workshops, it ranged from 1 to 5 people. These informants held managerial positions across various functions, including R&D, technology, engineering, innovation, portfolio management, strategy, sales, marketing, business development, sustainability, remanufacturing, and digitalization. Participants were selected based on their in-depth expertise, knowledge, roles related to the research topic, and working contexts. We also employed the snowball sampling technique (Patton, 2002) to identify additional relevant participants until we reached data saturation, at which point no new insights could be gleaned from further interviews and workshops.

We conducted a thematic analysis of the data collected from both interviews and workshops, which involved reducing the data, displaying the data, and drawing conclusions (Miles and Huberman, 1994; Braun and Clarke, 2006). The triangulation of the data obtained from these two methods was performed based on specific thematic topics using thematic analysis. The thematic map of this coding is depicted in Fig. 1.

Data reduction and data display were achieved by reading transcriptions of the data from interviews, workshops, and field notes. Interesting phrases were transferred to a spreadsheet, and similar constructs and possible relationships were identified (Eisenhardt and Graebner, 2007). This process was carried out to explore potential opportunities and types of CBMs for EV batteries, coding the participants' views in their own words, phrases, or terms as first-order categories

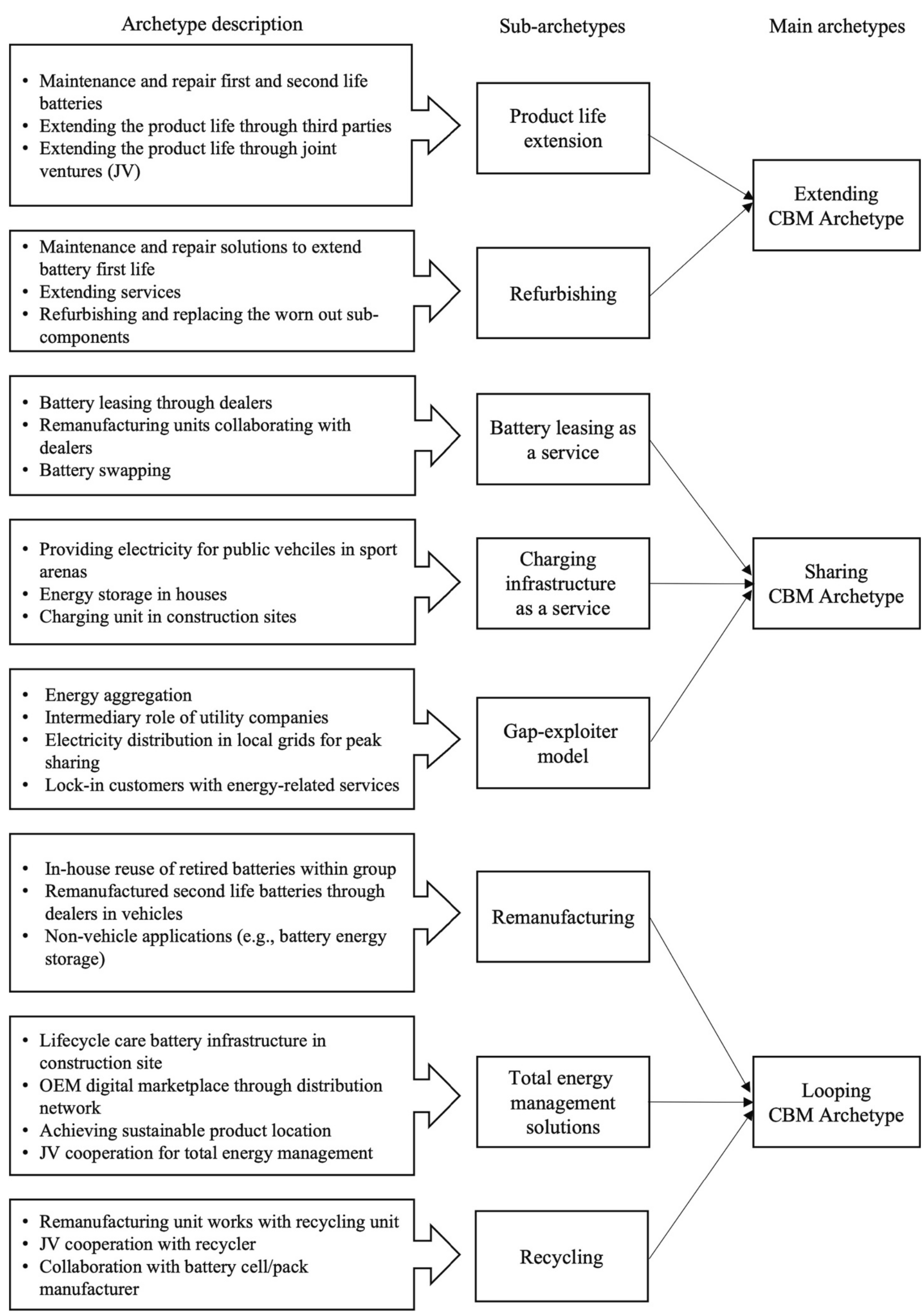

Fig. 1. Our analysis of archetype description, sub-archetypes, and main archetypes.

(Miles and Huberman, 1994). Meanwhile, key criteria considered important for categorizing various types of CBMs were listed in a separate Excel file. The analysis then built on identified patterns by comparing and combining first-order categories with their similarities to formulate second-order themes, representing sub-archetypes of CBMs. Theoretical concepts from general CBM innovation and CBMs for battery second life were analysed to improve construct validity (Yin, 2009), which either modified or validated the second-order themes.

Finally, another level of abstraction in coding was performed to identify overarching third-order aggregated dimensions. After compiling the second- and third-order categorizations, results and conclusions were drawn to address RQ1 (i.e., the main and sub-archetypes of CBMs for EV battery second life). The CBM archetype results were communicated to project partner companies to ensure precision and quality. Based on these archetypes and emerging concepts in first- and second-order categories, the research team began developing business model scenarios for each partner company (i.e., A*, C*, I*, K*, L*) using a mind-mapping technique. In total, 10 business scenarios were created. The initial business model scenarios were shared with partner companies and, after receiving feedback, the scenarios were updated. Following another iteration with partner companies and a detailed examination and analysis within the research team, the scenarios were finalized. These scenarios included details regarding value propositions, value co-creation, value delivery, and value capture, as shown in Table 2.

4. Results

The findings are structured into two parts, each corresponding to RQ1 and RQ2. In the first part, we describe three main archetypes of CBMs found for the EV battery second life (RQ1). In the second part, we provide detailed explanations of the eight identified sub-archetypes of CBMs within the framework of the main archetypes. This explanation is accompanied by visual representations that illustrate the appropriate forms of collaboration required to implement CBM archetypes in the EV battery ecosystem (RQ2).

4.1. Main archetypes of CBMs for enabling EV battery second life and circularity

The empirical results reveal a movement towards CBMs by companies in the EV battery ecosystem. The study found three criteria for identifying different CBMs, characterizing them, and categorizing them into archetypes:

- Resource flows: This criterion refers to the way or nature in which companies can manage the flow of resources within a closed-loop system, aiming to increase resource efficiency, minimize waste, and reduce environmental impact associated with both production and consumption.
- Collaborative ecosystem engagement: This criterion refers to the extent to which companies need to actively engage with external stakeholders, including dealers, suppliers, customers, third parties, and other organizations, to co-create value for battery circularity. It indicates the level of collaboration intensity (i.e., whether relationships are open, semi-open, or closed) and defines the depth and breadth of collaboration required to optimize resource flows, share knowledge, and collectively drive battery circular initiatives.
- Ownership dynamics: This criterion refers to the changing nature of ownership structures and their influence on the design, adaptation, and implementation of product-service combinations aimed at achieving circularity. It categorizes businesses based on their ownership structure and indicates the connection among ownership, governance, and product-service combinations.

Using these three criteria, the identified CBMs for enabling EV battery second life and circularity are categorized into three main archetypes and eight sub-archetypes. The three main CBM archetypes identified are extending, sharing, and looping. The analysis reveals that these CBM archetypes have significant implications for key business model elements, including value proposition, value co-creation, value delivery, and value capture, as well as for the way value is co-created, delivered, and captured in collaboration with partner companies and relevant stakeholders. Next, we provide a detailed description of three CBM archetypes. Table 3 summarizes the information on key business model elements for each archetype.

The first archetype is the extending CBM archetype. These business models aim to prolong the useful life of batteries (and their sub-components) while they are operating in their first life. The extension of battery life (and their sub-components) can also apply when the batteries are in their second life. This goal is typically achieved through practices such as maintenance, repair, upgrading, and refurbishing. As a result, these archetype business models minimize waste and reduce the demand for new resources. The study found that prolonging the first life of the battery, extending the second life of the battery, ensuring the availability of refurbished parts, and providing maintenance and repair services are potential value propositions within these archetype business models. In these archetype business models, value is co-created through collaboration with third-party system integrators and joint ventures with complementary asset providers as well as through companies' maintenance and repair units. The study further identified that value is delivered in these archetype business models through bundling or extending services for key customers via direct or indirect channels, such as dealers, service networks, or third-party integrators; maintenance and repair contracts; and refurbishment contracts. The companies deploying these archetype business models can capture revenue through the enhanced lifespan of batteries, the sale of refurbished parts, revenues from extended maintenance and repair services, and more. In these archetype business models, the major costs are usually related to maintenance costs, repair and refurbishing activities, and transportation.

The second archetype is the sharing CBM archetype. These archetype business models aim to maximize the underutilized batteries or battery-related systems by deploying different types of strategies such as shared access, shared ownership, shared responsibilities, and product-as-a-service. As a result, these archetype business models can reduce the demand for new products, thereby conserving resources. The study showed the following value propositions for these archetype business models: access to batteries through leasing, charging infrastructure or aggregation, swapping services, and a reduction in environmental impact. In these archetype business models, value is co-created through collaboration with dealers, energy utility companies, their local suppliers, battery cell or pack manufacturers, or companies that allow the shared use of EVs or batteries. In addition, the value co-creation process occurs through the network of battery-swapping stations, infrastructure, and trading platforms. Furthermore, the study identified that value is delivered in these archetype business models through subscription or leasing, infrastructure support, and direct and indirect distribution channels such as direct sales, dealers, digital or trading platforms, and customer segment extension. The companies deploying these archetype business models can capture revenues through subscription or leasing fees (monthly), battery-swapping fees, battery arbitrage, commission per sale or transaction, and the sale of energy or energy-related services. In these archetype business models, the major costs are usually related to refurbishing, infrastructure, inventory or integration, and transportation.

Finally, the third archetype is the looping CBM archetype. These archetype business models aim to keep batteries, their sub-components, and materials in closed and extended loops to the greatest extent possible to enable companies to retain as much value as possible from the original product, component, or material. The in-house reuse of retired batteries, total lifecycle battery or energy management in

Table 3
Detailed information on key business model elements for the three CBM archetypes (extending, sharing, and looping).

BM elements	Extending CBM archetype	Sharing CBM archetype	Looping CBM archetype
Value propositions	- Prolong 1st life of battery - Prolong 2nd life of battery - Refurbished parts - Maintenance and repair services	- Access to batteries through leasing (entry threshold reduction) - Charging infrastructure/energy aggregation - Swapping services - Reduction in the environmental impact	- In-house reuse of retired batteries - Total lifecycle battery/energy management in operations - Sustainable product location - Availability of virgin and recycled materials - Reduction of natural resource consumption
Value co-creation	- Value co-creation through collaboration: - with third party system integrators - joint venture(s) (with complementary asset provider(s)) - Value co-creation through companies' maintenance and repair units	- Value co-creation through collaboration: - with dealers - with energy utility companies and their local suppliers - with battery cell/pack manufacturers - with companies that allow shared use of EVs/ batteries - Value co-creation through network of: - battery swapping stations - infrastructure(s) - trading platform(s)	- Value co-creation through collaboration: - with energy utility companies and their local suppliers - with distribution networks - with digital marketplace - with battery cell/pack manufacturers - with recycling/remanufacturing units - with vehicle/construction/battery/other customers - joint venture(s) (e.g., with several OEMs, non-vehicle companies) - Value co-creation through transformation of waste materials back into the manufacturing process
Value delivery	- Value delivery through: - bundling/extending services for key customers via direct/indirect channels such as dealers or service networks or third-party integrators - maintenance and repair contracts - refurbishment contracts	- Value delivery through: - subscription/leasing - infrastructure support - direct and indirect distribution channels (direct sales, dealers, digital/trading platforms) - customer segment extension	- Value delivery through: - leasing - third-party recycling networks - direct and indirect distribution channels (digital market place, dealers, distribution networks, trading platforms, take-back incentive system(s), ecosystem) - customer segment extension
Value capture	- Revenues through: - enhanced lifespan of batteries - sale of refurbished parts - revenues from extended maintenance and repair services - Cost structure: - maintenance cost - repair and refurbishing activities' cost - transportation cost	- Revenues through: - subscription/leasing fees (monthly) - battery swapping fees - battery arbitrage - commission per sale or transaction - sale of energy/energy-related services - Cost structure: - refurbishment cost - infrastructure cost - inventory/integration cost - transportation cost	- Revenues through: - subscription/leasing fees (monthly) - sale/lease of remanufactured batteries or BESS - battery arbitrage - commission per sale or transaction - sale of energy/energy-related services - sale of virgin/recycled materials - cost savings from reduced raw material procurement - Cost structure: - remanufacturing and upcycling cost - infrastructure cost - recycling activities' cost - inventory/integration/operational cost - transportation cost

operations, sustainable product location, availability of virgin and recycled materials, and the reduction of natural resource consumption are some of the identified value propositions within these archetype business models. In the looping CBM archetype, value is co-created through collaborations with energy utility companies and their local suppliers; distribution networks; digital marketplaces; battery cell or pack manufacturers; recycling or remanufacturing units; vehicle, construction, or battery customers; and joint ventures (e.g., with several OEMs or non-vehicle companies). In addition, value co-creation can occur through the transformation of waste materials back into the manufacturing process. Furthermore, the study identified that value is delivered in these archetype business models through leasing, third-party recycling networks, direct and indirect distribution channels (e.g., digital marketplaces, dealers, distribution networks, and trading platforms), take-back incentive systems, ecosystems, and customer segment extensions. The companies deploying these archetype business models can capture revenues through subscription or leasing fees (monthly), the sale or lease of remanufactured batteries or a battery energy storage system (BESS), battery arbitrage, commissions per sale or transaction, the sale of energy or energy-related services, the sale of virgin or recycled materials, and cost savings from reduced raw material procurement. Finally, in these archetype business models, the major costs are usually related to remanufacturing and upcycling, infrastructure, recycling activities, inventory, integration, or operational costs as well as transportation.

In summary, this study has identified and categorized three distinct archetypes of CBMs for enabling EV battery second life and circularity: extending, sharing, and looping CBMs. Each archetype offers unique value propositions, co-creation strategies, and revenue-generation opportunities. These findings underscore the diverse approaches available for achieving battery circularity, contributing to resource conservation, environmental sustainability, and economic viability within the industry.

4.2. *Sub-archetypes of CBMs for the electric vehicle battery second life and circularity*

Gaining a comprehensive understanding of these main archetypes enhances the nuances in discussing and analysing the specific business models identified in our analysis, as presented in the following section. In total, our analysis found eight sub-archetypes of CBMs, as shown in Fig. 1. They include: (1) product life extension, (2) refurbishing, (3) battery leasing as a service, (4) charging infrastructure as a service, (5) gap-exploiter model, (6) remanufacturing, (7) total energy management solutions, and (8) recycling.

4.2.1. *Extending CBMs sub-archetypes*

Our analysis identified two sub-archetypes for extending CBMs for the EV battery second life:

(1) *Product life extension*. These business models focus on extending the life of a product or a component—in this case, batteries used in EVs.
(2) *Refurbishing*. These business models involve the refurbishment or rejuvenation of a product or component to extend their life and usability.

In the *Product Life Extension CBMs* sub-archetype, the study reveals two collaboration arrangements in how business models are implemented: one involves collaboration with a third-party system integrator, and the other entails the establishment of a joint venture with a complementary asset provider. Our analysis indicates that the train manufacturer (Company C in Table 2) primarily focuses on providing product-life extension CBMs to their customers within these two arrangements. Both of these collaboration forms are illustrated in Figs. 2 and 3,

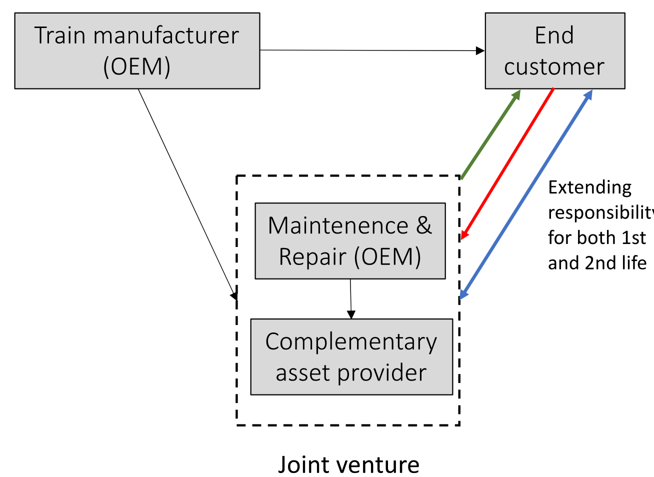

Fig. 3. Product-life extension CBM provided by the train manufacturer for EV batteries in the context of establishing a joint venture.

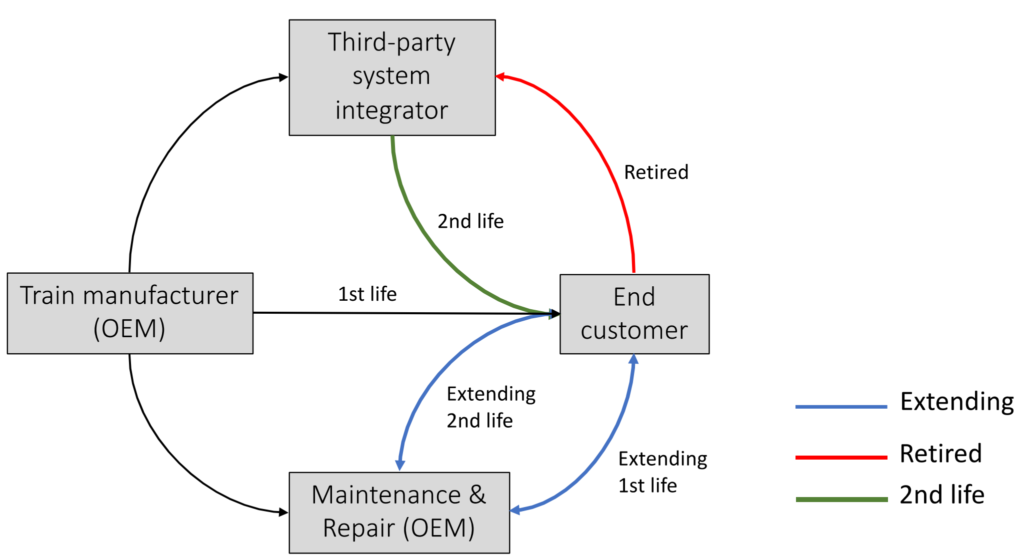

Fig. 2. Product-life extension CBM provided by the train manufacturer for EV batteries in collaboration with a third-party system integrator.

respectively. In these sub-archetype scenarios, blue lines represent the extension of batteries in their first life, red lines signify retired batteries from the first life, and green lines denote second-life batteries. The same colour scheme is used consistently throughout the paper to illustrate and explain collaborative forms in all identified business model scenarios. In the figures presented throughout the paper, these coloured lines (i.e., extending, retired, second life) indicate the business relationships to which the different business model archetypes are applied.

The train manufacturer, an OEM, has chosen not to own the batteries. Instead, they are considering three options to support train operators in the first arrangement (i.e., product life extension CBM in collaboration with a third-party system integrator):

- Extending the battery's lifespan while it operates in its first life through maintenance and repair solutions provided by their organization.
- Collaborating with third-party system integrators to collect retired batteries at the end of their first life and develop second-life batteries for reuse in the same application (i.e., trains) to support their customers.
- Extending the second-life battery while it is in operation through maintenance and repair solutions provided by their organization, as depicted in Fig. 2.

In the second arrangement, the train manufacturer is dedicated to providing product-life extension CBM to their customers through the establishment of a joint venture, as illustrated in Fig. 3. This joint venture is created between the OEM's maintenance and repair organization and a complementary asset provider. Once more, the manufacturer's preference is not to own the battery but to explore all possible options to support their train operators in extending the battery life, during both the first-life and second-life operations. The joint venture takes on the responsibility of extending the battery's lifespan during the first life, developing second-life batteries, and providing maintenance and repair solutions for second-life operations.

Our analysis revealed that a material SME supplier (Company L in Table 2) is involved in providing the *Refurbishing CBM* sub-archetype to the battery manufacturer (Company D in Table 2). This supplier is responsible for supplying and assembling cables and harnesses in batteries owned by the battery manufacturer. The material supplier offers maintenance and repair solutions to extend the first life of the batteries. They also provide an extension service to refurbish and replace worn-out cables and harnesses, both during the first-life operations and for retired batteries, as depicted in Fig. 4.

4.2.2. *Sharing CBMs sub-archetypes*

Our analysis identified three sub-archetypes for sharing CBMs for the EV battery second life and circularity:

(3) *Battery leasing as a service*. This business model involves offering batteries to customers on a lease or rental basis rather than selling them outright. Customers pay a fee to use the batteries for a specified period or until a certain level of usage is reached.

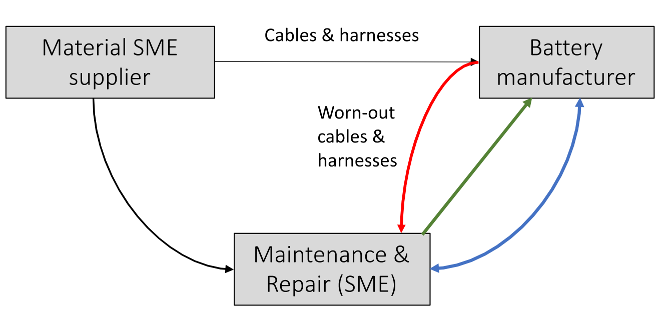

Fig. 4. The refurbishing CBM provided by a material SME supplier for EV batteries.

(4) *Charging infrastructure as a service*. In this business model, companies provide charging infrastructure for EVs as a service. This includes setting up and maintaining charging stations at various locations, such as public areas, sport arenas, construction sites, and residential complexes. Users of EVs can access these charging services, often through subscription or pay-per-use arrangements, making it convenient to charge their vehicles.

(5) *Gap-exploiter model*. This business model involves identifying and capitalizing on gaps or inefficiencies in existing markets or business processes. Companies following this model seek opportunities where they can provide a solution or service to fill these gaps or address inefficiencies.

Our analysis revealed that the heavy-duty vehicle manufacturer (Company A in Table 2) is engaged in providing battery-swapping solutions through the *Battery Leasing as a Service CBM* in collaboration with their dealers (as illustrated in Fig. 5). This vehicle manufacturer owns the batteries; in fact, they customize their batteries for their vehicles by purchasing battery cells from an external company. They lease their vehicles, along with the batteries, to local dealers, who subsequently lease both the vehicles and batteries to construction site/vehicle customers. When the batteries reach the end of their first life, retired batteries are collected by the dealers from the swapping stations, as depicted in Fig. 5. The heavy-duty vehicle manufacturer is part of a larger group that includes a remanufacturing organization as a business unit. Retired batteries are then processed to create second-life batteries at the remanufacturing unit. These second-life batteries are subsequently distributed to vehicle customers through the OEM dealers. The swapping stations are provided and owned by the OEM in partnership with their local dealers. To ensure continuous service for their customers, the OEM establishes two new partnerships in this business model: one with an energy utility company, enabling their battery-swapping stations to provide uninterrupted electricity based on emerging demand, and the second partnership is formed between the battery pack manufacturer and their remanufacturing unit to ensure a continuous supply of battery packs to the swapping stations.

Our analysis reveals that one of the energy utilities companies (Company I) is providing *Charging Infrastructure as a Service CBM* to a sports and event arena customer, offering electricity for charging public vehicles. Company I, the energy utility company, comprises two distinct business entities: one responsible for owning the electric grid and providing related services, and the other focused on power generation. Collaborating with the infrastructure provider (Company H) and the battery manufacturer, the power generation unit has taken on the role of a BESS system integrator and provider. This unit also utilizes second-life batteries from OEMs and trading platforms, adding them to their pool of battery resources. The company offers a BESS for lease to a sports and event arena customer, supplying electricity for charging public vehicles in the form of charging stations, as illustrated in Fig. 6. When batteries reach the end of their first life, the retired batteries are collected by the power generation unit and sent to the battery manufacturer for creating second-life batteries. These second-life batteries are then reused in the BESS charging stations. One of the company's entities, the electric grid unit, collaborates with the infrastructure provider to provide the necessary maintenance and repair support to the BESS customers.

Our analysis also revealed that two energy utility companies, Company I and Company J, had transitioned into energy aggregators by embracing the *Gap-Exploiter CBM* to address value gaps in both the frequency market and the energy sector (as depicted in Fig. 7). In this role, they utilize their extensive customer base to act as intermediaries, thereby pioneering a new business model concept. These companies have adopted the *Gap-Exploiter CBM* to bridge value gaps in the frequency market and the energy sector, as illustrated in Fig. 7. Gap-exploiter business models are built upon seizing opportunities arising

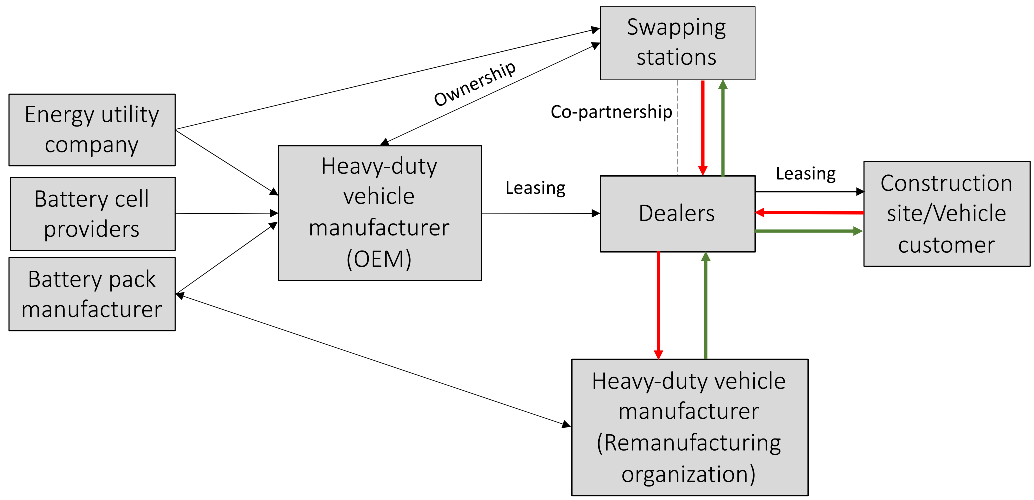

Fig. 5. Battery leasing as a service CBM provided by the heavy-duty vehicle manufacturer in collaboration with dealers.

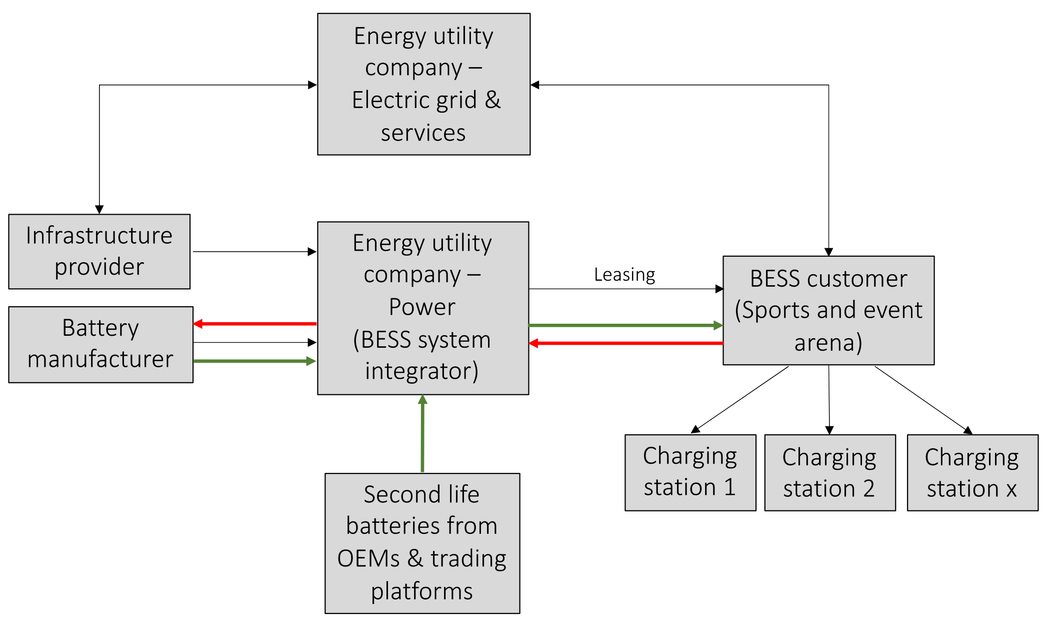

Fig. 6. Charging infrastructure as a service CBM provided by the energy utility company, consisting of both the power company and the electric grid company, for the sports and event arena.

from the activities and business models of other actors, akin to third parties and facilitators within an ecosystem. In the context of the EV battery ecosystem, third-party business model concepts encompass middleman and battery-sorting and analysis business models.

The electric grid units of these energy utility companies source electricity from various providers, including battery suppliers, external power suppliers, second-life batteries from OEMs and trading platforms, PV cell systems from both energy utility companies, and a cloud-based wind power system company. In their role as aggregators, the companies supply this electricity to the national power board, which in turn distributes it to regional grids and markets to alleviate peak loads on local grids. Upon reaching the end of their first life, retired batteries undergo processing by the battery manufacturer to create second-life batteries. These second-life batteries are subsequently reused in the BESS by the electric grid unit.

4.2.3. *Looping CBMs sub-archetypes*

The empirical analysis identified three sub-archetypes of looping CBMs in the EV battery ecosystem:

(6) *Remanufacturing.* This business model involves taking used or worn-out products or components and restoring them to a like-new condition. This process often includes disassembling the product, inspecting and repairing or replacing worn parts, and then reassembling it to meet original specifications.
(7) *Total energy management solutions.* This business model involves comprehensive strategies and systems for optimizing energy use within an organization or across multiple entities such as construction sites. These solutions encompass a range of practices, technologies, and policies aimed at maximizing energy efficiency, reducing energy consumption, and minimizing environmental impact in operations. They often include the monitoring, control, and optimization of energy usage across various operations and processes.
(8) *Recycling.* This business model includes the process of collecting, sorting, processing, and reusing materials from discarded products or waste materials.

Our analysis revealed that the heavy-duty vehicle manufacturer

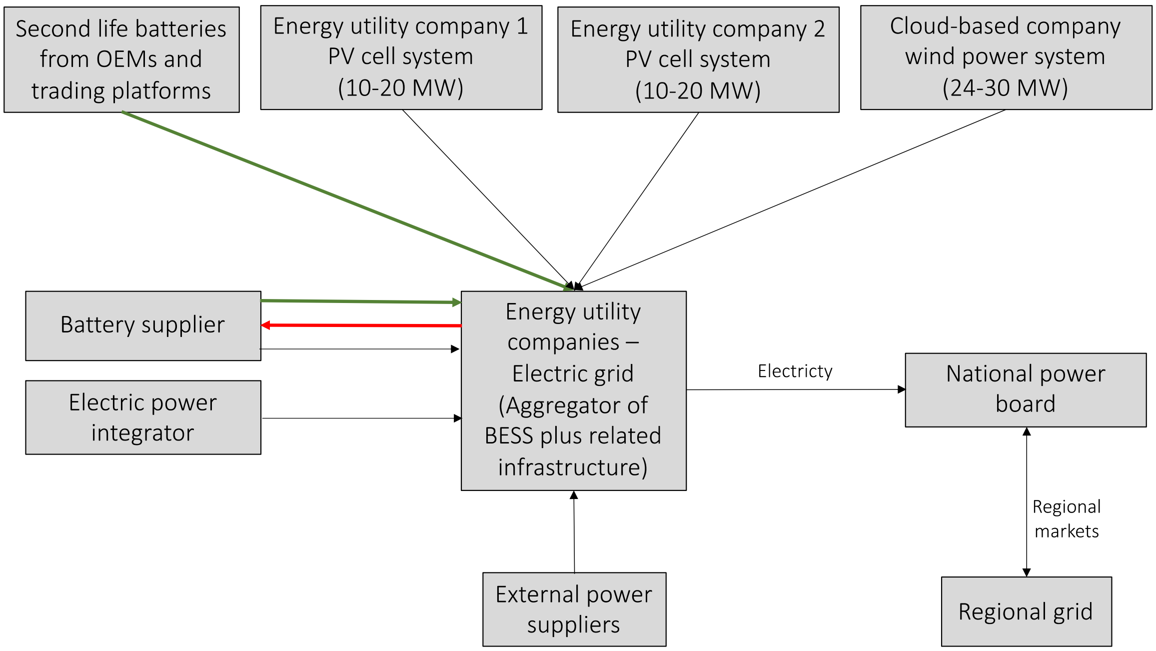

Fig. 7. Gap-exploiter CBM provided by two energy utility companies in their role as aggregators to supply electricity to the national power board.

(Company A) collaborates with their dealers to provide a *Remanufacturing CBM*, as depicted in Fig. 8. Similar to the previously mentioned business models, the heavy-duty vehicle manufacturer offers battery leasing services to their customers through their dealer network. When batteries reach the end of their first life, the retired batteries are sent to the vehicle manufacturer's remanufacturing unit through the dealers. The remanufacturing unit processes these batteries and provides remanufactured second-life batteries to the vehicle customers through the dealers. These remanufactured second-life batteries can also find applications beyond the OEM's vehicles, such as in BESS in other non-vehicle applications.

In this business model, we observed a need for partial collaboration between the battery cell and battery pack manufacturer and the remanufacturing unit to share knowledge and resources on an as-needed basis (see Fig. 8). The remanufacturing unit can also participate in the *Recycling CBM* when they identify retired batteries that are unsuitable for creating second-life batteries. In such scenarios, the remanufacturing unit can consider two options: either sending the batteries to a recycling unit or returning them to the battery cell/pack manufacturer, as indicated by the red lines in Fig. 8.

Finally, the last identified sub-archetype is the *Total Energy Management Solutions CBM* provided by the heavy-duty vehicle manufacturer. The vehicle manufacturer had recently developed a new product known as the battery-based power unit for charging, aimed at offering total energy management solutions to their construction site and vehicle customers. As a result, total energy management solutions are extended to key customers in the form of lifecycle care for battery infrastructure, encompassing both vehicle batteries and power unit batteries, as well as network development. The provision of such offerings is further facilitated by advancements in digital technologies, which enable the capture, storage, and management of data for remote monitoring services. The vehicle OEM recognizes the potential to develop total energy management solutions to meet their customers' demands and productivity expectations. These solutions can be strategically established near

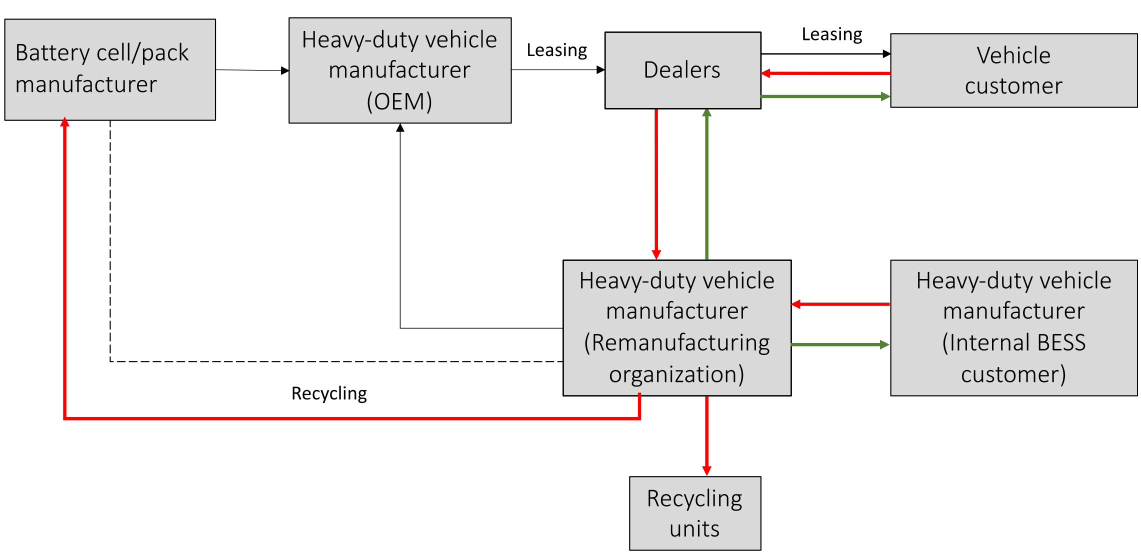

Fig. 8. Remanufacturing and recycling CBM provided by the heavy-duty vehicle manufacturer in collaboration with their dealers.

customer premises or in different parts of the city in a sustainable manner, ultimately enhancing productivity and performance. This type of CBM is also referred to as a sustainable product location.

Both the battery-based power unit (i.e., BESS) and vehicle batteries are offered as leases by the vehicle OEMs to their construction site and vehicle customers through the distribution network (see Fig. 9). When batteries reach the end of their first life, retired batteries are sent to the vehicle manufacturer's remanufacturing unit via the distribution network. In this business model, the remanufacturing unit establishes a joint venture with a complementary asset provider. This joint venture expands the scope of their activities, including the consideration of retired and second-life batteries from external OEMs, non-vehicles, and other sources of energy generation, such as photovoltaic (PVC), wind, and hydro plants (see Fig. 9). With a substantial pool of batteries available through the joint venture and external collaborations, the vehicle OEM operates a digital marketplace in this business model. This digital marketplace is owned by OEM in co-partnership with the distribution network. It offers comprehensive information on retired batteries, second-life batteries, and available power units/BESS at regional and local levels. This information is accessible to both OEM internal and external customers. The joint venture also engages in *Recycling CBM* when identifying retired batteries unsuitable for second-life purposes (see Fig. 9). In such scenarios, the joint venture can sell the retired batteries for recycling to extract core raw materials.

5. Discussion

Recognizing the critical importance of selecting the right CBMs for a specific context, this study addresses various archetypes of CBMs feasible for EV battery second life (answering RQ1) and illustrates how companies can collaborate to successfully implement these CBMs (answering RQ2). These results provide significant implications for both theory and practice in the following areas: (1) CBM archetypes for EV batteries; (2) ecosystem management in CBMs, particularly in the context of EV battery 'circularity' and (3) CBM archetypes for enabling the circular economy.

5.1. Theoretical implications

The study offers three significant theoretical contributions. First, it provides a detailed understanding of viable CBM archetypes and sub-archetypes for the utilization of EV batteries in their second life. This knowledge offers new insights into the development and implementation of CBMs for EV battery second life by proposing three main CBM archetypes and eight sub-archetypes and describing their key business model elements to enable battery circularity. The proposed archetypes are presented in a simple and easy-to-understand manner at both the main archetypes and sub-levels. Most of the research related to battery second life is predominantly focused on challenges, enablers (Börner et al., 2022; Zhu et al., 2021; Sopha et al., 2022; Shahjalal et al., 2022), technological aspects, or techno-economic analyses (e.g., Helander and Ljunggren, 2023; Schulz-Mönninghoff and Evans, 2023; Chirumalla et al., 2023). Only a handful of previous papers have concentrated on CBMs (e.g., Costa et al., 2022; Júnior et al., 2023; Wrålsen et al., 2021; Schulz-Mönninghoff and Evans, 2023; Reinhardt et al., 2020; Bonsu, 2020). Furthermore, even within these papers, only a few research works have examined different types of CBMs for EV battery second life (e.g., Albertsen et al., 2021, Olsson et al., 2018; Wrålsen et al., 2021; Reinhardt et al., 2020; Jiao, 2019). These works often depict CBM archetypes conceptually (e.g., Reinhardt et al., 2019), take a broader perspective (e.g., Olsson et al., 2018), combine several combinations of business model types (e.g., Wrålsen et al., 2021), or discuss business model elements from a general standpoint (e.g., Reinhardt et al., 2020).

Our study contributes by presenting an overarching CBM archetype structure comprising three main archetypes (extending, sharing, and looping). These archetypes are established based on three criteria: resource flows, collaborative ecosystem engagement, and ownership dynamics. Furthermore, we provide a more detailed perspective by suggesting eight sub-archetypes for battery circularity. These sub-archetypes are derived from empirical data gathered not from a single or a few companies, but from a comprehensive sample of 15 companies, representing a majority of EV battery ecosystem actors. This diverse group includes EV OEMs, energy utility companies, recycling firms, remanufacturing and refurbishing companies, a battery manufacturer, a

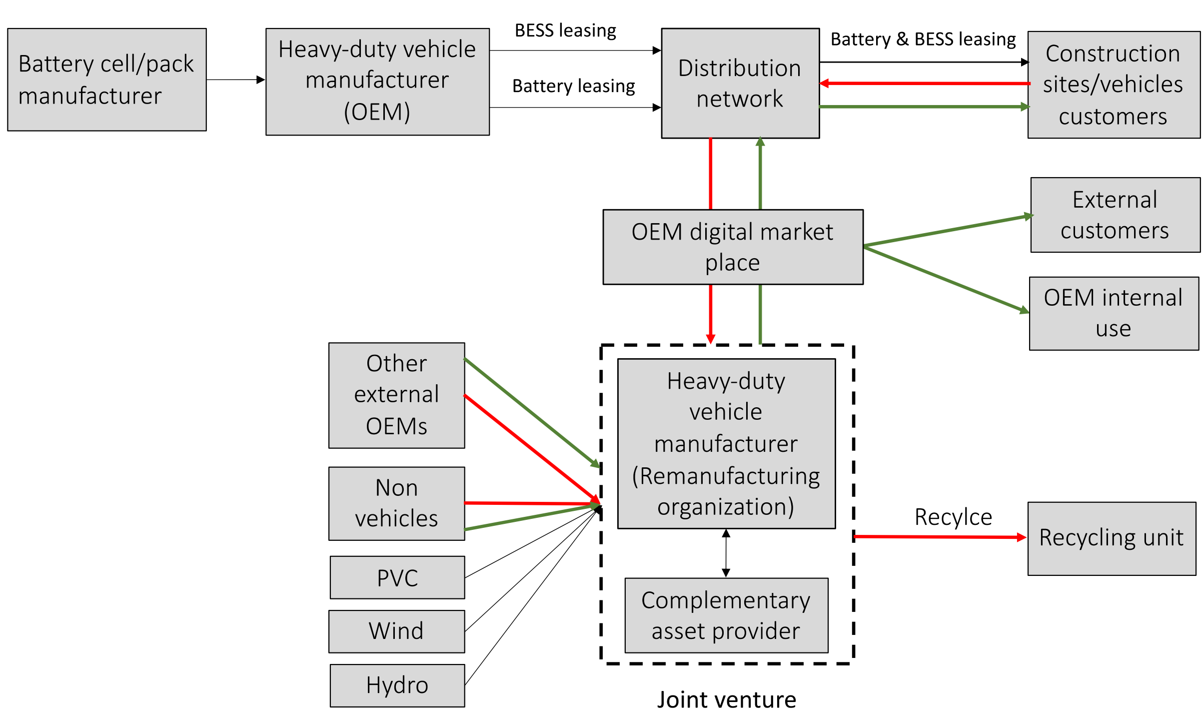

Fig. 9. Total energy management solutions and recycling CBM provided by the heavy-duty vehicle manufacturer in collaboration with distribution networks and a digital marketplace.

material supplier, a transportation firm, and a housing company. Together, they encompass various aspects of the battery ecosystem, covering battery manufacturing, first-life users, second-life users, system integrators, and recycling. Earlier research has emphasized the context-specific nature of CBM implementation; in this context, our study contributes to the development of a contextual understanding of CBM archetypes for battery circularity.

Second, this study offers an in-depth understanding of the necessary forms of collaboration among actors in the EV battery ecosystem to implement each CBM archetype. It provides eight illustrative collaboration forms involving EV battery ecosystem actors for the eight sub-archetypes of CBMs. The mapping of actors and their interdependencies related to each CBM sub-archetype offers practical insights for exploring and optimizing the dynamics of interactions and collaborations within the EV battery ecosystem. In this way, this study contributes to the field of ecosystem management in CBMs and the circular ecosystem literature (Trevisan et al., 2022; Gomes et al., 2023; Schulz-Mönninghoff and Evans, 2023), particularly in the context of EV battery circularity, aligning with the strategic resource and innovation strategies inherent in CBMs (Bocken and Ritala, 2022). The ecosystem management and circular ecosystem literature has seen recent development in the realm of CBMs (e.g., Kanda et al., 2021; Gomes et al., 2023). However, this study provides an empirical, data-rich description from the EV battery context, encompassing a broad range of EV battery ecosystem actors. There is a notable scarcity of research available on CBMs for EV battery second life from an ecosystem perspective. Although prior research has acknowledged the importance of multi-stakeholder collaboration (Reinhardt et al., 2019; Chirumalla et al., 2022; Chirumalla et al., 2023), through which value can be co-created, delivered, and captured, this paper makes a significant contribution in this regard by identifying eight viable sub-archetypes of CBMs and elucidating various forms of interaction and collaboration among actors to implement such business models, representing a crucial advancement in this emerging field.

Third, this study significantly contributes to advancing knowledge on CBMs, their archetypes, and their implementation (e.g., Bocken and Ritala, 2022; Geissdoerfer et al., 2020; Lewandowski, 2016; Ludeke-Freund et al., 2019; Reim et al., 2021). Although a substantial body of literature exists on CBMs, their types, and archetypes (Nußholz, 2017; De Angelis, 2021; Ludeke-Freund et al., 2019; Planing, 2018; Pieroni et al., 2020), significant overlaps and variations in interpretation persist among researchers when it comes to different types of CBMs and strategies (see, for instance, Lewandowski, 2016; Geissdoerfer et al., 2020; Planing, 2018; Ludeke-Freund et al., 2019). Researchers often highlight multiple categories of a few CBMs as one category or emphasize one category of CBM type as two or more categories. In this context, this study proposes a user-friendly CBM archetype structure consisting of three main archetypes (i.e., extending, sharing, and looping), aligning with the principles of reduce, reuse, and recycling in the context of circular economy. Furthermore, it divides these archetypes into eight sub-archetypes, all informed by rich empirical insights gathered from 15 companies within the EV battery ecosystem. The study also presents comprehensive information on the three archetypes of CBMs, including their respective value propositions, mechanisms for value co-creation, strategies for value delivery, and methods of value capture. The results of this study, encompassing archetypes, sub-archetypes, business model elements, and the dynamics of collaboration among actors, provide a novel contribution and valuable insights to the broader literature on CBM archetypes and their implementation.

5.2. Managerial implications

The findings from this study are valuable for practitioners in the EV battery ecosystem, including those in managerial, engineering, and developer roles across various functions such as technology and supply chain management, strategic business development, future ecosystem development, innovation and portfolio management, sales and marketing, sustainability development, and digitalization. Given that the topic addresses battery circularity and lifecycle management, spanning design, manufacturing, use in various operational contexts, second life, and recycling, these results can benefit a wide range of functional organizations within a company and among ecosystem participants.

More specifically, these results have significant implications for various stakeholders, including project partner companies (A*, C*, I*, K*, L*) and actors within the EV battery ecosystem. First, the proposed CBM archetypes can be used by these practitioners as overarching categories to reflect on and assess their current and ongoing business models related to EVs and batteries. They can then use these archetypes to plan, define, and formulate new business models, taking into account the aspects of second life and circularity. The market landscape in EVs and batteries will change significantly in the coming years, with various possible combinations of offerings. For example, EVs may be sold traditionally while batteries are available for lease, or vice versa. Both EVs and batteries may be sold traditionally or offered on a lease basis. By considering other business models such as availability and performance-based contracts, pay-per-use models, and different operational entities like energy storage systems, multiple business model scenarios become possible. The proposed CBM archetypes facilitate the exploration and identification of suitable trade-off solutions aligned with customer expectations.

Second, practitioners and companies within the EV battery ecosystem can employ the proposed primary archetypes as a boundary object when constructing appropriate CBMs. This can serve to initiate a dialogue both within and outside the organization, with the aim of achieving full circularity in their operational contexts. This study also offers a detailed description of key business model elements (as outlined in Table 1), including value propositions, value co-creation, value delivery, and value capture for the three primary CBM archetypes. Practitioners, particularly managers across various relevant functions, can leverage this information to contemplate its implications on their daily responsibilities, both within and outside the organization, as well as their role and contributions towards the realization of battery circularity.

Third, the main CBM archetypes provide valuable guidance to managers in several ways. For companies looking to extend CBMs, their managers should concentrate on prolonging product lifecycles, reducing waste, and improving efficiency by offering services such as battery repair and refurbishing. Collaborating with third-party system integrators and complementary asset providers can prove advantageous. For companies contemplating the adoption of shared CBMs, their managers can investigate resource-sharing possibilities, including battery leasing or providing a charging infrastructure as a service. This necessitates a re-evaluation of not only their operational strategies, but also their customer relationships, shifting towards a more service-oriented approach. For companies exploring looping CBMs, their managers should devise strategies for repurposing or recycling retired batteries. Collaboration with distribution networks, energy utility companies, and remanufacturing and recycling units is essential. The implementation of digital marketplace platforms serves as an informational hub and provides transparency regarding the availability and condition of batteries.

Fourth, our project partner companies and other actors within the EV battery ecosystem can leverage the eight proposed sub-archetypes of CBMs to assess and validate their readiness, both internally and externally, while developing new capabilities. They can also expand upon these eight sub-archetypes by continuously introducing and suggesting new sub-archetypes within the extending, sharing, and looping categories. Furthermore, they can conduct a more comprehensive evaluation of the information in Table 1, delving into a deeper analysis to derive key business model elements specific to each sub-archetype of CBMs.

Fifth, the study places strong emphasis on various collaboration forms necessary to implement sub-archetypes of CBMs for project partner companies. These collaboration structures, which encompass third-party collaborations, joint ventures, digital marketplaces, and open, semi-open, and closed networks, are instrumental in helping companies identify the specific value required for different stakeholders within the network through co-creation. Furthermore, company managers can visualize the entire co-creation network during the development and implementation phases of CBM archetypes. They can assess and enhance the dynamics of these interactions to align with the intended value they aim to create. Considering that the EV battery second-life industry is still in its infancy and faces a lengthy and challenging path towards widespread commercial adoption, this study, with its visualization of collaboration forms, provides a solid foundational step for companies. These companies can subsequently leverage this information to prioritize their current and future relationships, strategic partnerships within the EV battery ecosystem, and strategic investments, all of which are vital in expediting their transition from traditional linear models to new CBMs. Furthermore, managers can use this information to comprehend and navigate the intricacies of these collaboration forms and adapt their strategies as necessary to maximize the benefits of their CBM initiatives.

6. Conclusions

Enabling battery second life and circularity requires the identification of the right CBMs to ensure that the solutions are competitive enough for commercialization. In this regard, this study describes three main CBM archetypes (extending, sharing, and looping) and eight sub-archetypes: product life extension, refurbishing, battery leasing as a service, charging infrastructure as a service, gap-exploiter model, remanufacturing, total energy management solutions, and recycling. A detailed explanation of the appropriate collaboration forms needed to implement CBM sub-archetypes for involved companies is also provided. The study provides a systematic structure with proposing CBM archetypes and sub-archetypes for EV battery second life and required collaboration forms in the EV battery ecosystem to implement them. This comprehensive understanding of CBMs provides a foundation for both academic and industry practitioners to navigate the nascent and complex landscape of EV battery second life and circularity.

Managers and top management within the EV battery ecosystem should strategically consider CBMs as an innovative way to extend product lifecycles and unlock new value propositions, supporting the industry in establishing cross-company or sectorial boundary collaborations. Furthermore, our analysis of collaboration patterns to implement eight archetypes of CBMs sheds light on the critical role of strategic partnerships in the EV battery ecosystem. Implementing CBMs is not a solitary endeavour, but rather involves intricate interplays among various stakeholders within the ecosystem. From the OEMs to third-party service providers, each stakeholder brings unique competencies to the table, underscoring the need for robust collaborative mechanisms. The patterns of collaboration observed in our study highlight the value of cooperative relationships in realizing CBMs. For example, some companies leveraged their strategic alliances to access the crucial resources, expertise, and markets necessary for CBMs. Others formed partnerships to co-create value and innovate through different means, such as digital platforms, demonstrating the essence of synergy in the successful deployment of CBMs.

As the demand for EVs and the subsequent surge in used batteries continue to rise, these insights have significant implications for shaping and implementing sustainable and circular strategies in the EV industry, thereby paving the way for systematic transformation towards climate-neutral electrification.

A shift to CBMs reduces dependency on raw materials, minimizes waste, and contributes to the circular economy's goals. This has far-reaching implications, not only for individual firms, but also for the entire electric and battery value chain, enhancing the industry's sustainability and resilience. Our work emphasizes the importance of multi-actor collaboration and network-centric circular business model innovation within the EV battery ecosystem, highlighting the need for an ecosystem-level perspective in circular economy research. As the demand for EVs and the subsequent increase in used batteries continue to rise, these insights hold significant implications for shaping and implementing sustainable and circular strategies in the EV industry, paving the way for systematic transformation towards climate-neutral electrification.

6.1. Limitations and future research

The study has encompassed an extensive set of key actors—specifically, 15 companies representing various roles within the EV battery value chain. Although we have addressed pivotal roles in the EV battery ecosystem with 10 different sets of companies, it is possible that some actors, such as insurance companies, logistics companies, and government bodies, may have been overlooked. Future research could expand the number of actors within the EV battery ecosystem by incorporating these additional stakeholders into their investigation. This expansion would enable an analysis of how the inclusion of these associated actors could influence the CBM archetypes and the necessary collaboration forms required for their implementation.

Furthermore, the study employed an exploratory research design with a qualitative approach. Given the nature of the study, this approach was appropriate, but it may have imposed certain limitations. In future research, more detailed case studies could be considered to obtain in-depth information on archetypes and collaboration forms, enabling the validation of archetypes and the identification of the necessary adjustments or required capabilities for commercial implementation. In addition, longitudinal studies covering the battery lifecycle from manufacturing to use, second life, and recycling could provide valuable insights. In the study, semi-structured interviews and workshops served as the primary data collection methods. In future work, an exploration of a mixed-method approach, combining qualitative and quantitative methods, could be beneficial as it would allow for the quantification of benefits associated with each archetype, providing a more comprehensive understanding.

Furthermore, the study identified three criteria for categorizing various CBM archetypes. In future research, these criteria can be applied and extended across different research contexts and ecosystem setups, enabling a more comprehensive analysis. Similarly, the proposed CBM archetypes and sub-archetypes can be empirically tested and validated, taking into account diverse research contexts and ecosystem setups. The study did not incorporate room for conducting a techno-economic analysis of the proposed CBM archetypes and sub-archetypes. In future research, this aspect can be expanded to encompass a comparative analysis of business scenarios, focusing on techno-economic considerations. Currently, actors in the EV battery second-life ecosystem approach partnerships and cooperation in a scattered and unstructured manner. This study has made a substantial contribution in this regard, laying a strong foundation for further exploration. Future research could concentrate on building, organizing, managing, and orchestrating a circular ecosystem for EV batteries through joint ventures, alliances, and strategic partnerships. Of particular interest is the development of capabilities, at both the firm and ecosystem levels, and the interplay between these levels to implement the proposed CBM archetypes for battery circularity. The development and implementation of new CBMs within the EV battery ecosystem are closely tied to policies and regulations. This aspect was not the primary focus of this research, particularly in terms of how various policies and regulations could impact the implementation of CBM archetypes and the necessary collaboration forms. Future studies could encompass an examination of regulatory and policy factors and their influence on CBM archetypes for EV batteries.

This study offered information on key business model elements, such as value proposition, value co-creation, value capture, and delivery, with a primary focus on the three main CBM archetypes related to battery second life (including repair, remanufacturing, reuse, and repurposing). In future research, the focus could be extended to include battery recycling and a more in-depth analysis of key business model elements for the eight sub-archetypes. We also encourage researchers to conduct separate detailed analysis studies on each specific key business model element to gain an in-depth perspective on each of these elements.

Finally, the study acknowledges the significance of advanced digital and Industry 4.0 technologies, including the Internet of Things (IoT), artificial intelligence, blockchain, cloud computing, and digital platforms, in the implementation of CBM archetypes and the necessary collaboration forms. However, this research has not primarily focused on analysing business model scenarios from a digitalization perspective. For example, IoT can enable real-time tracking and monitoring of battery health and usage, facilitating efficient battery lifecycle management. Artificial intelligence and machine learning algorithms can assist in predicting battery degradation and determining optimal repurposing strategies. Blockchain technology can promote transparency and traceability in the battery supply chain, ensuring responsible and efficient circular processes. Future research that explores the interaction between Industry 4.0 technologies and CBMs for EV battery second life can offer a deeper understanding of the opportunities and challenges involved, which can, in turn, inform practical strategies and policy directions to promote battery circularity. An emerging body of literature links advanced digital technologies to CBMs in general. Future research should utilize the proposed CBM archetypes and collaboration forms to analyse business scenarios from a digital technologies perspective, examining which technologies are best suited and how they can enhance the processes of value proposition, value co-creation, value delivery, and value capture. Our research serves as a starting point for future scholarly endeavours aimed at developing circular solutions for EV batteries to achieve climate-neutral electrification and sustainability goals.

Submission declaration and verification

The work described has not been published previously.

CRediT authorship contribution statement

Koteshwar Chirumalla: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ignat Kulkov:** Formal analysis, Investigation, Project administration, Writing – review & editing, Conceptualization. **Vinit Parida:** Conceptualization, Project administration, Supervision, Writing – review & editing. **Erik Dahlquist:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing, Funding acquisition, Data curation. **Glenn Johansson:** Funding acquisition, Investigation, Methodology, Writing – review & editing, Data curation. **Ioana Stefan:** Conceptualization, Investigation, Project administration, Visualization, Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT 3.5 in order to enhance the English language proficiency and fluency of the manuscript. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

None.

Data availability

The authors do not have permission to share data.

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