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Smart Circular Business Model for Electric Vehicle Batteries: A Proposal of a Conceptual Framework

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Executive Summary

Transitioning to a circular economy for electric vehicle (EV) batteries requires both systemic circular business models (CBMs) innovation and practical implementation, where the 10R strategies (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, reuse, recycle, and recover) provide more operational approaches within the battery lifecycle. Smart CBMs integrate digital technologies into CBMs to enable real-time data use, automation, and optimization across the battery lifecycle. However, the understanding of how these technologies support CBMs, particularly regarding the 10R, lacks conceptual integration at strategic and operational levels. Hence, the study contributes to map the literature on smart circular business strategies for EV batteries and identifies five key dimensions for smart CBMs: digital technologies, battery ecosystem actors, service types and KPIs, policies, barriers and enablers, and 10R strategies. A conceptual framework is then proposed to illustrate how their interconnections support smart CBM development in the EV battery ecosystem.

Keywords: Batteries, Life Cycle Analysis, Recycle & Re-use, Design for second life, Energy storage system

1 Introduction

The rapid growth of EV adoption raises concerns, as degrading batteries can release toxic metals like cobalt, nickel, and manganese and risk environmental contamination if improperly managed [1]. This makes effective life cycle management of EV batteries crucial. Circular economy (CE) extends battery lifecycles by maximizing resource efficiency and reducing waste [2]. CBMs are key enablers that integrate CE principles into business value creation, delivery, and capture [3]. Its implementation often relies on operational approaches such as the 10R circular strategies, including Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8), and Recover (R9) to provide a closed business loop [4]. They align with CE and battery circularity by minimizing material waste and promoting sustainability throughout the life cycle of materials [4]. A high degree of synergy between CBM and 10R needs to be further exploited [5].

Advanced digital technologies enable companies to apply CE principles through innovative business models and redesigned value chains. In this context, digital technologies act as key enablers of the 10R strategies by supporting data-driven decision-making, automation, and real-time monitoring across product life cycles [6-7]. The term “Smart and digital technologies” is often discussed in conjunction with industry 4.0 (I4.0), since only with the help of technologies, the digital transformation of all processes within the organization is possible [8]. Zheng et al., identified core technology areas for I4.0, including cyber-physical systems (CPS), the Internet of Things (IoT), big data and analytics (BDA), cloud technologies, artificial intelligence (AI), blockchain, simulation and modelling, visualization technologies, industrial robotic automation, and additive manufacturing (AM) [9]. Integrating advanced digital technologies can promote sustainable development [7], by enhancing value chain efficiency, recycling, and battery business strategies. For example, Kumar et al., [10] mentioned that using digital technologies can reduce transport costs for end-of-life batteries by 11%~44% and increase value recovery by 52%~60%.

Current research has widely explored CBMs and circular strategies for batteries [11], with digital technologies applied across various fields [12]. However, the systematic application of these technologies to a CBM or circular strategy for EV batteries is still in its infancy. Existing literature focuses on drivers, barriers and policy support, digital product passport (DPPs) and battery ecosystems [13-15]. There is still a lack of a unified conceptual framework to advance smart CBM for EV batteries. Thus, the primary objective of this study is to sort out and summarize the existing literature on smart CBM for EV batteries and to propose a conceptual framework. During the literature review, it is found that the vast majority of CBMs are highly associated with 10R strategies at the operational level [3]. Thus, this study organizes and summarizes existing literature on the application of 10R strategies for EV batteries as the principal realization of smart CBM, and investigates the use of digital technologies as a driver for CBM implementation. Finally, a conceptual framework is proposed to outline future research targets through answering the following research questions:

RQ1: What are the key dimensions that define smart CBMs for EV batteries?
RQ2: How do these dimensions interact to influence the implementation of such CBMs?

2 Methodology

This study follows the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) framework to conduct a systematic literature review [16-17]. Keywords are *digital technologies*, *circular business models*, and *batteries*. “Truncation” was used to create a search string in the data base of Scopus and Web of Science (WoS). The search string is Digital technologies ("digitali*" OR "digital*" OR "Industry 4.0" OR "smart*" OR "digital capabilit*" OR "IOT" OR "AI" OR "blockchain" OR "cloud computing" OR "big data" OR "Internet of things" OR "artificial intelligence" OR "machine learning" OR “cyber physical systems” OR “virtual reality” OR “cyber security” OR “5G” OR “automation*”) AND circular business models ("circular* business* model*" OR “CBM” OR “sustainable business* model*”) AND batteries ("batter*" OR "EV* batter*"). The search yielded 8 journal articles (n=8) in English. 5 relevant articles (n=5) were selected, and 2 additional articles (n=2) were added by recommendation. A snowballing method was then applied to identify additional literature from the 7 articles (n=7), resulting in 188 articles (n=188), of which 66 abstracts (n=66) were deemed relevant. After reviewing full-texts, excluding review articles, and including a recommended article, a total number of 33 (n=33; see Figure 1) articles were incorporated for analysis.

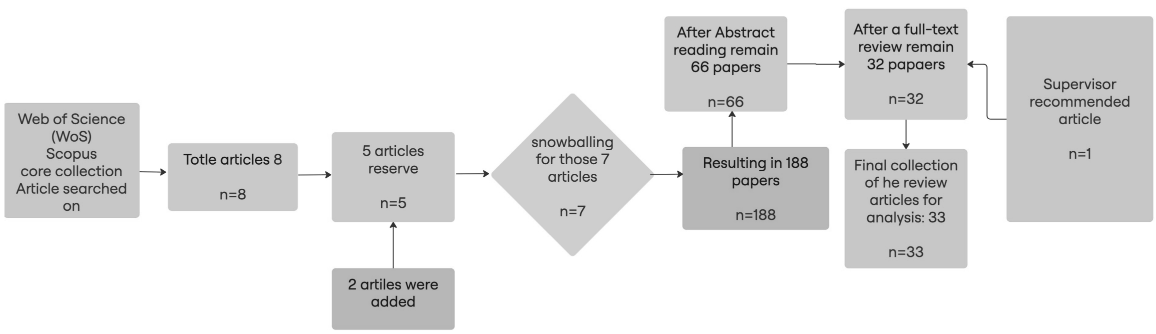

Figure 1: Literature review process according to PRISMA [16-17]

We extracted data from the selected literature using a pre-designed Excel template based on the research questions, covering items like research purpose, CBM type, limitations, and future directions [18]. Insights were developed through thematic analysis to cluster key dimensions and their relationships, following four steps: coding, categorizing, thematizing, and integrating, as outlined by Mayan and Spiggle [19]. Coding is based on content analysis, which summarizes and counts the frequency of themes in the literature according to autonomous understanding, thus ultimately creating common terms help the categorization and merging of thematic content [18]. The method thus builds a foundation to gain descriptive results as a way to develop a conceptual framework for subsequent analysis [20].

3 Results

The thematic analysis identifies five key dimensions for enabling smart CBMs for EV batteries: 1) digital technologies, 2) circular strategies, 3) battery ecosystem actors, 4) policies and incentives, barriers, and enablers, and 5) battery service types and KPIs. Below, the results for each of the five dimensions are explained in detail.

3.1 CBM – from the lens of 10R

The 10R strategies can be grouped into three categories based on CE phases. First, the short loops, which include R0–R2 relate to design, smart production, and manufacturing, aiming to reduce raw material and energy use early in the value chain [21-22]. It is addressed in 18 times. Second, the medium loops, which include R3–R7 focus on extending product and component lifespan through second-life applications, maintenance, and repair [21-22], referenced 57 times. This phase allows smart CBMs to capture additional value and delay end-of-life costs. Finally, the long loops, where R8–R9 target on material recovery and energy generation at end-of-life to ensure that batteries still contribute to the CE by supplying secondary materials or residual energy[33]. It is important to note that not all articles precisely align with the 10R strategies. Some articles fail to match the appropriate 10R strategies due to their overly broad or narrow focus. Table 1 outlines the 10R strategies with description.

Table 1: The 10R strategies for EV batteries

CE Phase	Circular Strategies (Rs)	No. of times	Description	Loop Type
Design, smart produce use & Manu-facture	R0-Refuse	**2** [21-22]	Prevent the use of harmful or non-recyclable raw materials in batteries	Short Loops
	R1-Rethink	**5** [21], [24-26]	Redesign batteries with modular, replaceable components and adopt intensive-use strategies like leasing, sharing, or swapping to extend lifespans.	
	R2-Reduce	**11** [13], [15], [21-23], [26-31]	Minimize the use of rare or harmful materials or resources in battery production and optimize resource efficiency.	
Extend lifespan of product and its parts	R3-Reuse	**9** [10], [21-22], [24], [29], [32-35]	Allow secondary use of batteries in other devices or pass them on to new users for the same purpose.	Med. Loops
	R4-Repair	**7** [21-22], [24], [28-29], [36]	Provide repair services to fix or restore partially degraded batteries to extend their usability.	
	R5-Re-furbish	**9** [10], [14], [21-22], [24], [27-29], [30],	Refurbish old batteries by replacing worn components and improving performance to meet market demands.	
	R6-Re-manufacture	**13** [14], [15], [21-23], [26],[28-30] , [33], [35],[37], [38]	Use recovered battery components to manufacture new batteries, reducing dependency on raw materials.	
	R7-Repurpose	**19** [10], [21-24], [26],[28], [30], [32-36], [39], [40-44]	Adapt retired batteries for new purposes, such as energy storage systems or other industrial applications.	
Useful application of material-s	R8-Recycle	**9** [10], [21-22], [26], [29-30], [33-35]	Establish processes to extract valuable materials like lithium and cobalt from discarded batteries for reuse.	Long Loops
	R9-Recover	**4** [22], [28], [31], [33]	Recover energy or remaining materials from batteries that are no longer usable, reducing waste.	

3.2 Type of digital technologies

CPS, IoT, and industrial robotic automation provide real-time sensing for batteries. A battery management system (BMS) is a prime example of a CPS to embed sensors and controllers in the physical battery pack and link them to digital management algorithms [38]. Industrial robotics enhance the physical handling from automated battery pack assembly to end-of-life disassembly [45]. By linking intelligent monitoring with automated handling, CPS/IoT and robotics can establish a responsive loop between battery use and end-of-life processing to improve efficiency and safety in CBMs. BDA in the cloud coupled with AI drives predictive methods. Internet-connected batteries produce big data streams over their lifetime. By applying machine learning and AI techniques to historical and real-time data, stakeholders can identify degradation trends and predict battery SoH [32]. Simulation and modeling technologies are used by predicting and optimizing battery behavior across multiple life cycles. One example is that a battery analytics platform aggregates detailed in-vehicle BMS data in a cloud platform and then uses a digital twin to calculate how a used battery would perform in a stationary storage system [37]. Technologies like blockchain and transport layer security (TLS) ensure transparency and data security. While TLS and related cryptographic measures build stakeholder confidence in sharing data, blockchain provides a trustworthy platform for collaboration and exchange [44]. Blockchain ledgers can record each battery's material provenance, ownership, and usage history in a decentralized manner [49]. Table 2 outline types of digital technologies and their details mentioned in the reviewed articles.

Table 2: Type of digital technologies

Type of Digital Technologies	No. of times	Details of technologies and relevant references
Cyber-Physical Systems	14	Battery Management Systems (BMS) [13], [26], [38], [40], [42], [46], Thermal Management Systems [26], Specialized software tools/platform [37], International Material Data System (IMDS) [14], Real-Time Information Systems [14], ERP[21] , EIS [47], Digital twin [23] , Cyber-Physical Systems [22]
IoT	7	IoT [13], [44], [48], Enabler logistic (tracing) [13], Smart home [48], Smart sensor [44]
Big Data & Analytics	10	Data Analytics [13], [22-23], [26], [34], [42], [48]Trace and predict market trends [37], [49], ArcGIS integrates data management [41]
Cloud Technologies	8	Data sharing [21], [49], Cloud based service [22], [25], [26], [36], Homomorphic encryption [44], Cloud based platform [22]
AI	12	Reinforcement learning [10], AI-based Robotics Disassembly [31], Predictive Modelling for SOH [32], Trace and predict market trends [37], AI based robotic system [31], Algorithm [39], Machine learning [10], [21], [32], [47], Smart logistic [25], Battery performance [43]
Blockchain	13	Blockchain [14], [21], [26], [38], [50], (Real time) data secure and tracing [14], SoH tracing [10], Data transparency [14], Smart contract [10], [38], [44], Data protecting [49], MySQL/CouchDB [10]
Simulation & Modelling	13	Digital simulation [15], [22], [27] , [28], [33], [43], Simulation for Second life checking (Storage Applications) [31], [37], [39], BIM [14], KPI of battery circularity [10], KPI of battery performance test [15]
Visualization Technologies	1	Visual disassembly [26]
Industrial Robotic Automation	4	Robotic assistant disassembly [27], [31], [32], Human-Robot Collaboration [31], Automated Disassembly Systems [21]
Transport layer security	1	Communication encryption protocol [44]

3.3 Battery services and KPIs

Depending on the use stage, battery service can be categorized into its pre-use (mentioned by 5 times), 1st use (30 times), 2nd use (36 times), after use (10 times) and whole life cycle (4 times). Pre-use is the stage before a battery is actively deployed in the first intended application, where a battery's economic value can already be created at this stage. For example, material flow mapping tracks and visualizes materials, such as lithium and nickel. In its 1st use, the battery service can be linked with management and monitoring, and repairing, while in the secondary use, the battery's services are focused on complementing and extending grid services. This includes peak shaving, BESS, and new energy system integration. Systems such as home energy storage, community microgrids or renewable power plants can extend the value of batteries through digital management to track performance and enable dynamic participation in local energy markets. At the after-use stage, proper collection and sorting of batteries ensure that only end-of-life batteries are sent to recycling, and that hazardous waste and energy risks are minimized. While disassembling provides internal materials safely, recovery of valuable materials such as lithium and nickel reduces the dependency on mining. Table 3 summarizes the various service types across five phases.

Table 3: Type of battery services across five phases (X=number of times mentioned in articles)

Lifecycle Phase	Service Type	Service Description
Pre-use X7	Simulation models [49]	
	Pilot project [37]	
	Design	For repairability [28], Customize [29], 5/5/25 3:38:00 PM
	Monitor battery materials [25]	Map material flows [28]
First use X30	Management, Monitoring & Repairing X26	Assessment-Safety and screening [21], [39], SoH [10], [27], [50], Prediction [50], Software tools management (upgrade) [23], [37], [38], Liquid cooling [36], Diagnosis [13], [36], Installation [29], Reconditioning [22], Repair [14], [24], [27], [34], Upcycle [24], Warranties [23], Maintenance [29],[37], Refurbishment [10], [13], [34], 5/5/25 3:38:00 PM
	Logistics X4	X4 Reverse logistics[14], [23], [24], Repacking &Transportation [13]
Second use X36	Second life service solutions X27	Reuse [10], [14], [24], Repurposing [24], [36], Grid service (Include: Grid resilience, peak shaving [23], [29], [31-32], [37], [39], [40], Grid infrastructure support [40], [41], [43], BESS [23], [25], [27], [29], [31-32], [40], [46]. Maintaining ownership of BESS [37], Rental BESS [35], Home storage [47], EV charging [38]
	Management X9	Prediction of EoL [50], Contract preparation [44], SLBESS trading promotion [44], Experts share [42], Stakeholder engagement service [28], New energy system integration [15], [21], [43], [46],
After use X10	Recycling X8	Transportation [13], Remanufacturer [24], [27], Real time recycling [10], Cobalt assessment [24], Disassembling, reassembling and test [32], Deposit refund for recycling [24], Matric Tracking [48]
	Valuable materials recovery	Waste from battery manufacturing [25]
	Material recycling [29]	
Whole life cycle X4	Blockchain based platform [21]	
	DPPs [14]	
	Information tracing [10], [14]	

Battery KPI is categorized into performance and health (mentioned by times), lifetime and capacity (19 times), economic factors (9 times), and recycling (3 times). Battery performance and health reflect the immediate functional capabilities of batteries and the state of their internal conditions, where decline in health can lead to performance degradation. The mostly researched indicators like SoH and temperature behavior are closely tied to real-time performance metrics like battery's power output, internal resistance, and discharge efficiency [13], [23], [34], [37], [40], [47-52]. On the other hand, depth of discharge (DoD) helps understand how much usable energy a battery can safely deliver without reducing its lifespan too quickly [13], [34], [40], [47], [49], [51], As the secondarily important indicator, the charge/discharge rate (C-rate) describes the rate at which a battery is charged or discharged relative to its capacity [32], [34], [40], [49]. Higher C-rates may cause more heat generation, increasing the risk of accelerated degradation. The number of charging cycles indicates how many full or partial charge–discharge cycles a battery can perform before its performance drops below threshold that can be 70–80% of its original capacity [47], [49], [53]. Economic factors capture the cost-efficiency and value recovery potential of a battery over its life, which in turn reflects the investment and performance improvement of the battery. For example, if repurposing costs are too high, second-life applications become economically unattractive compared to producing new batteries, companies will abandon the research of previous batteries and turn to new batteries. In the end, as the primary recycling KPI, recycling rate is the percentage in weight or value of a battery's materials that are recovered and reused after it reaches end-of-life [13], [26], which is a direct indicator of how circular the value chain is in practice. Table 4 summarizes the various KPIs of battery across five phases.

Table 4: Battery KPIs (X=number of times mentioned in articles)

KPIs main theme	**KPIs sub-themes**	**KPI details**
Performance and health X33	Health X18	SoH [10], [22-23], [27], [32], [37], [43], [46], [51], [53] Uniform cell Health [53], Hours of use and mileage [53], Recovery/settling time [38] , Temperature [43], [13], [32], [27], [29]
	Performance X15	Maximum power [32], [31], Weight, volume, and energy parameters [32], Discharge efficiency [41], [33], DoD [37], [43], [51], [32], [53], [27], Charge/discharge rate [43], [32], [27], [31]
Lifetime and capacity X19	Lifetime X12	Number of charging cycles [22], [32], [33], Remaining useful life (RUL) [26], [53], [46], Cycle/calendar/cell aging [32], [32], Cyclic lifetimes [32], Energy storage life extension [28], SLB service time [27], First-life utilization [23]
	Capacity	Remaining battery capacity [40], [41], SoC [43], [32] , [53], [46], [10]
Economic factors X17	Cost X9	Life cycle cost [37], Cost of repurposing and recycling [51], [10], [42], Transportation cost [22], [55], [24], Labor costs [22], Cost of storage [54]
	Battery price [51], [40], [52], [34]	
	Value	The return of battery [23], Secondary utilization benefits [28], [39], Recycling profitability [26]
Recycling X3	X2 Recycling rate [13], [26], Average time from design to recycling [27]	

3.4 Ecosystem actors involved in SCBMs

The initial extraction of battery ecosystem actors identified 72 different actor types. These were then merged and reduced to 26 actor categories based on role overlap and relationship similarity. Each category was uniformly coded and their frequency of occurrence across 33 sources was recorded. As shown in Figure 2, larger circles indicate actors that appear more frequently in literature. Five groups were derived by classifying the entire life cycle of EV batteries and the cross-sectoral nature of the cycle: (1) business and market; (2) policy and society; (3) technology and research; (4) production and first life cycle; and (5) second life cycle. Figure 2 also follows the layered structure of the actor map from the center outwards. The inner layer consists of core partners, such as OEMs, manufacturers and recyclers. These participants appear most frequently in the literature and considered to be the core enablers of CBMs and technology implementation. The middle layer represents the primary actors, such as government, energy supplier, 2nd life consumer and universities, who can provide multi-dimensional interactions or use cases for battery circularity. For example, 2nd life consumers can repurpose used EV batteries for home energy storage system (ESS), especially with solar PV systems and grid-connected ESS, while governments can require battery traceability and encourage reuse before recycling through mandatory DPPs. The outer layer stands for the secondary actors, who engage in the ecosystem through indirect or supportive functions. For example, NGOs often act as neutral intermediaries to bring together actors in the first two layers and to co-develop circular solutions.

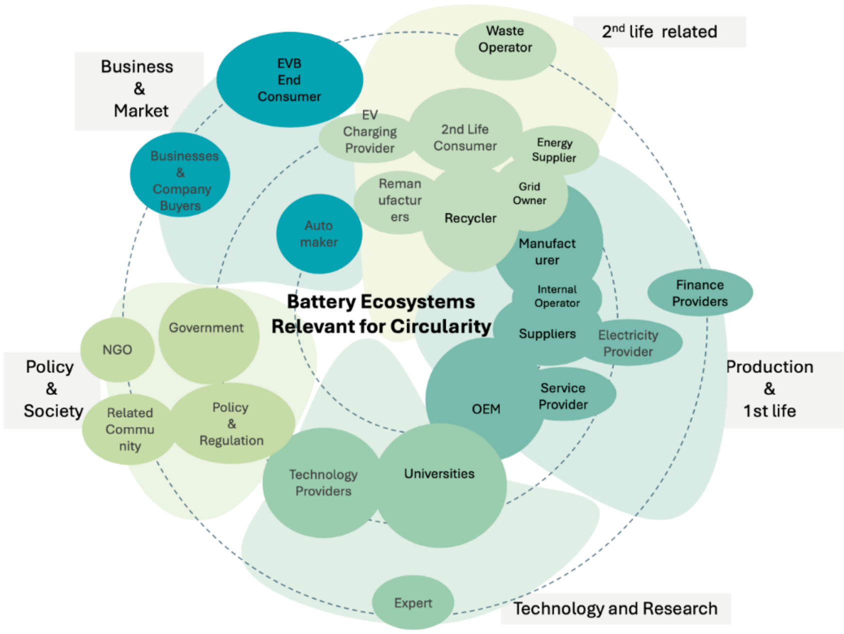

Figure 2: Self-mapped battery ecosystems actor relevant for circularity

3.5 Barries, enablers, and policies & incentives

The successful uptake of digital technologies requires transforming key barriers into enablers through targeted strategies. Cognitive & organizational barriers (mentioned by 17 times), such as decision makers' hesitation and organizational change, can be overcome (25 times) by intensive capacity-building initiatives to cultivate the necessary digital competencies and an innovation-friendly culture. Technical barriers (45 times), such as complex battery design and lack of standardization, can be addressed (12 times) by developing robust digital infrastructure and enforcing standardization of data formats to ensure compatibility and effective information management. Regulatory & legal barriers (12 times), such as unclear regulations and lack of policy support, can be converted into enablers (19 times) by establishing clear policy frameworks and standards, such as unified recycling and safety guidelines. Meanwhile, economic & market barriers (23 times) including high cost and market uncertainty require market alignment strategies to align incentives and business models with circular outcomes (18 times). It also needs to leverage economic instruments or policy incentives that improve the business innovation for circularity. Finally, industry & operational barriers (26 times), such as physical and logistical limitations and operational process issues, can be turned into drivers (27 times) of circularity through strengthened stakeholder coordination.

Policy incentives (6 times) make circular compliance mandatory, pushing firms to adopt reuse/recycling practices, which promote long-term business sustainability through clear legal frameworks. Current policy frameworks include EU battery directive, European CE action plan, and global battery alliance's DPPs, which have created legal foundations that CMBs are built on. While economic incentives (5 times) make CBMs more financially competitive through investing in advanced technologies, market-driven incentives (3 times) enable business model innovation by responding to market changes. One example is the OEM pricing. When OEMs strategically price their products and services with circularity in mind, they create economic signals that encourage circular practices across the battery value chain.

3.6 Framework for SCBMs for EV batteries

The five key dimensions are interconnected, forming a conceptual framework (Figure 3) to support smart CBM development for EV batteries, with each dimension closely interacting with the others. Digital technologies act as system enablers by promoting data flow and real-time monitoring, allowing organizations to design services and KPIs of EV batteries that drive efficient resource use and battery lifecycle management and facilitate the design and implementation of circularity strategies. The 10R strategies act as the operational methodology through which CBM value is created and realized in the context of battery circularity. It provides a structured approach for maximizing material utility and minimizing waste throughout the battery lifecycle. Policies, incentives, barriers, and enablers play a moderating role in the implementation of circular strategies. Externally, policies and incentives influence circular behavior through regulations, standards, and taxes. Internally, firms face barriers such as fragmented standards, limited technical capacity, and lack of expertise, which hinder battery recyclability. Cruicially, clear accountability systems, financial support, and stakeholder collaboration can enable circular practices. Overall, policy frameworks shape CBMs by guiding cycling strategies, digital technology adoption, and sustainability priorities. Battery ecosystem actors rely on digital technologies for data management, and the role of each participant influences the design and operation of CBM, while service types and KPIs of batteries become measurable outcomes that link policy and technology use.

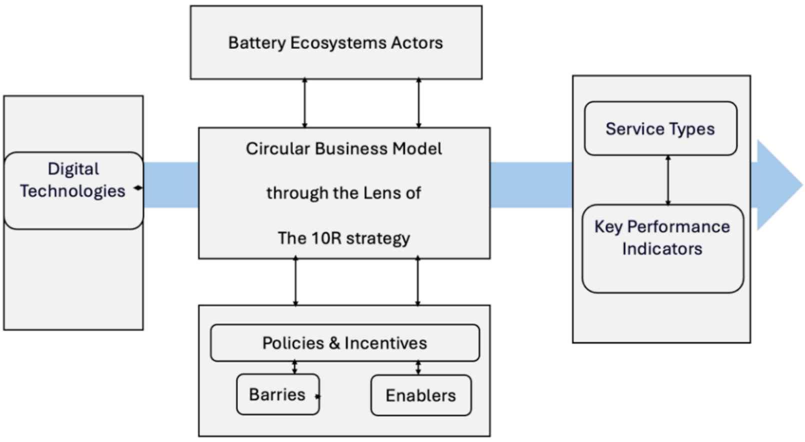

Figure 3: The conceptual framework of Smart CBM for EV batteries.

4 Discussions

While many studies explore EV battery circularity [11] and the role of digital technologies in CE [4], [11], [12], few systematically analyze smart CBMs, especially with integrated 10R strategies. This study, through a systematic review, addresses the gap by proposing a five-dimensional framework that conceptualizes and guides smart CBM implementation, moving beyond linear value models and offering a reference for future research in EV batteries and related sectors. In addition to its theoretical significance, the study also provides clear empirical value for researchers, industry practitioners, and policymakers. For researchers, it guides future studies on how digital technologies shape product circularity through CBMs. For practitioners, it introduces battery service types and KPIs to better assess circular interventions. Companies can use the five-dimensional framework as a practical reference to understand required data parameters and ecosystem interactions. For policymakers, it highlights where interventions are needed. For examples promoting reuse initiatives, regulating data-sharing agreements, and mitigating market inefficiencies in end-of-life treatment.

5 Conclusions, limitation, and future work

This study contributes a conceptual framework for smart CBMs specific to EV batteries theoretically and practically. The framework combines five key dimensions with eight interconnected building blocks. It outlines how digital technologies can be used to empower CBMs through formulating circular strategies such as 10Rs. It will provide guidelines for facilitating CBMs, 10R, and digital services, and developing circular activities in the battery ecosystem. It will also enable researchers and managers to capitalize on the potential of digital technologies to support battery circularity. The study clarifies pathways for implementing smart CBSs and serves as a basis for circular battery research. However, its validity requires empirical testing, given current research limitations. As this field of research is still in an exploratory stage, the available literature is limited by search constraints. In particular, references to the 10R strategies in the reviewed articles are largely based on the subjective interpretations of the original authors. Therefore, future research should aim to empirically validate this conceptual framework in real-world settings.

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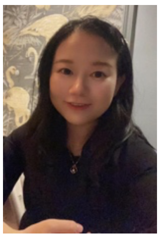
Presenter Biography



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