38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

Blockchain Technology to Enable Battery Circularity: A Study on Supporting Battery Ecosystem Actors

Moshkan Ebrahimi, Koteshwar Chirumalla, Anas Fattouh
Digital and Circular Industrial Services (DigiCircle) research group, School of Innovation, Design and Engineering, Mälardalen University, Eskilstuna, Sweden, Email: moshkan.ebrahimi@mdu.se

Executive Summary

Achieving battery circularity requires a comprehensive evaluation of battery lifecycle encompassing design, manufacturing, first and second-life applications, and recycling, managed by various actors within the ecosystem. While engaging this diverse array of actors is essential for advancing circularity, progress is often hindered by challenges. Blockchain technology (BCT) offers promising solutions through secure, decentralized data management and enhanced traceability, fostering stronger collaboration across actors. However, there is currently a lack of consolidated insight into the specific needs of these actors and how BCT can address them. The purpose of this study is to map the existing literature on the needs of each actor and the potential gains they may realize from the adoption of BCT. Drawing on a systematic literature review, this paper proposes a conceptual framework that identifies four key BCT features and outlines how they can support ten distinct categories of actors across the battery ecosystem in achieving circularity.

Keywords: Batteries, Battery ecosystem, Blockchain, Traceability, Battery circularity.

1 Introduction

Growing concerns about environmental pollution, resource scarcity, and increasing waste are pushing many industries toward more sustainable and low-carbon practices. The automotive industry is particularly impacted, given its significant contribution to these challenges [1]. The transition from fuel-powered vehicles to electric vehicles (EVs) is widely regarded as a positive step toward cleaner and more environmental-friendly transportation. However, this shift also introduces new challenges. The growing number of EVs significantly increases the demand for batteries, placing additional pressure on limited natural resources and contributing to rising volumes of battery waste at end-of-life [2]. At the same time, the prices of key materials used in batteries such as lithium, cobalt, and nickel are going up due to growing increasing demand [3]. According to [4], global battery demand is expected projected to grow from 185 GWh in 2020 to over 2,000 GWh by 2030.

Effective battery management requires a shift from the traditional linear model to a circular economy (CE), which promotes both environmental and economic sustainability. A CE calls for a holistic rethinking of the battery lifecycle, encompassing design, manufacturing, and use, along with strategic approaches for transitioning batteries from their first life to second-life applications and end-of-life management. This approach aims to slow or close resource loops by extending product lifespans and preserving material value[5].

Adopting these strategies expands the battery value chain, by bringing together a diverse ecosystem of actors with varying interests. However, the successful implementation of circular strategy archetypes relies on proactive collaboration among all relevant actors. Close collaboration can foster trust and transparency across the battery ecosystem [5, 6]. According to da Silva et al [2], mutual trust is a crucial foundation for a successful sharing economy, as it directly impacts participants' willingness to share both information and resources. Cheng et al [7] emphasize that traceability is essential for the efficient management of batteries within the ecosystem. Transparency and traceability allow actors to transform raw data into actionable insights, enabling more accurate forecasting, classification, and quality assessments of batteries. Data is often considered a strategic asset, prompting actors to restrict its sharing due to concerns around security, confidentiality, and competitive advantage. As a result, relevant information is not always collected or shared, limiting transparency and impeding effective traceability across the ecosystem. [8].

Blockchain technology (BCT) has emerged as a pivotal solution for addressing key barriers to the implementation of CE strategies for batteries, particularly those related to traceability, transparency, and provenance across ecosystems [9, 10]. BCT is a distributed data storage system that integrates advanced features such as a decentralized environment, traceability, consensus mechanisms, and encryption algorithms [11]. It also supports the use of self-executing digital contracts, known as smart contracts, which automate processes and enhance efficiency across the network [10]. Additionally, BCT enables real-time monitoring and seamless sharing of accurate data on battery characteristics, performance, and condition [12]. Collectively, these features improve transparency while ensuring security, data immutability, and auditability, ultimately promoting trust and collaboration within various the business ecosystem [1]. Despite the potential of BCT to support battery circularity, its application in this domain has received limited attention in academic literature [2, 13]. Existing studies primarily focus on using BCT to enable traceability by identifying batteries across different various stages of their lifecycle, from manufacturing to end-of-life recycling [13]. However, future research should expand and move beyond traceability to investigate how other key features of BCT such as smart contracts can be leveraged within the battery ecosystem [10]. One of the main reasons for this research gap is the relatively nascent stage of BCT, with much of its potential yet to be fully explored or realized [7]. Experts, including [2], highlight that the battery aftermarket remains underdeveloped, characterized by a fragmented network of actors that hinders the adoption of CE practices. This sectoral immaturity underscores the need for substantial structural and systemic advancements. To address this gap, a deeper understanding is needed of how BCT can create value for diverse actors within the battery ecosystem beyond its commonly cited use for traceability. As the sector evolves, clarifying the specific needs of these actors and identifying the practical gains they may derive from BCT adoption is essential for guiding future development and implementation. By synthesizing existing knowledge, such insights can support more targeted research, inform technology design, and enable policy and business models aligned with circular economy goals.

The purpose of this study is to map the existing literature on the needs of battery ecosystem actors and the potential gains they may realize from the adoption of BCT. To achieve the research purpose, the following research questions are explored:
R1. What are the needs of actors in the battery ecosystem for achieving effective battery circularity?
R2. What are the potential gains of implementing BCT and its key features in enabling battery circularity?

The structure of this paper is as follows: Section 2 presents key concepts, and Section 3 outlines the research method. Section 4 presents empirical findings, while Section 5 discusses the theoretical implications, concluding with limitations and directions for future research.

2 Key Concepts

2.1 Battey Lifecycle

The battery utilized in EVs plays a pivotal role in converting chemical energy [10] into electrical energy and vice versa. Its performance is significantly influenced by the raw materials used in production. Recent studies highlight how the type, quality, and characteristics of these materials affect batterie’s key performance metrics, lifespan, and degradation [14]. Moreover, these raw materials hold substantial value due to their scarcity and the environmental impact of their extraction and mining processes. Therefore, the selection of sustainable raw materials, along with enhanced recovery and recycling initiatives, is essential to support CE strategies and promote environmentally responsible practices [3]. The battery production process can be segmented into three hierarchical levels: cell, module, and pack. A battery pack comprises modules, which consist of cells connected in series or parallel configurations to achieve higher voltages. Over time, electric vehicle batteries (EVBs) degrade due to factors such as cycle aging, calendar aging, and user driving behavior leads to a decline in battery performance and efficiency [14]. Typically, an EVB reaches the end of its first lifecycle when its capacity declines to 70–80% of its original maximum capacity [2]. At this stage, maintaining optimal performance, safety, and range of batteries for original application becomes increasingly challenging. Although EVBs reach the end of life in their primary use, they often retain substantial residual capacity, making them suitable for second-life applications such as energy storage systems or other less demanding applications [29]. CE strategies promote extending battery life that prioritize maintenance, restoration, and repurposing including repair, reuse, refurbishment, remanufacturing[5, 8]. The success of these approaches depends on the continuous monitoring of key parameters, including State of Health (SOH), State of Charge (SOC), and State of Aging (SOA) [8].

Assessing a battery's aging profile and SOH helps determine the most appropriate secondary use. When further use is no longer viable, recycling offers a pathway to reclaim valuable raw materials for next-generation battery production. Together, these integrated [5]. Adopting CE strategies necessitates the involvement of a diverse network of actors including raw material suppliers, EV battery manufacturers, and EV manufacturers/OEMs, whose conflicting interests can impede alignment and effective collaboration [9]. The lack of mutual trust and coordinated frameworks among actors often results in fragmented efforts, with each actor pursuing individual objectives based on limited or isolated information sources. Inadequate transparency and data sharing across the battery value chain further constrain the generation of actionable insights, impeding accurate forecasting, classification, and quality assessment of batteries. These limitations reduce the effectiveness of battery evaluation and hinder the optimization of CE strategies, ultimately affecting decision-making and ecosystem-wide collaboration [2, 7]. Additionally, challenges related to data traceability [7] and the reliability of battery information [6] further obstruct the successful implementation of CE initiatives. A platform integrating actors across the battery ecosystem could offer significant value by enabling seamless monitoring and traceability of batteries throughout their lifecycle by leveraging key indicators such as SOH [2].

2.2 Blockchain Technology and Features

Blockchain Technology (BCT) functions as a decentralized and distributed digital ledger that enables secure and transparent data sharing. It ensures traceability by recording real-time information in an immutable and tamper-resistant manner [11]. BCT is underpinned by four fundamental features, traceability, decentralization, automated execution through smart contracts, and consensus mechanisms, all of which enhance data integrity, foster collaboration, and build trust among actors [9, 10]. Through the integration of consensus algorithms and smart contract functionalities, BCT enables the reliable verification and validation of data from diverse and potentially untrusted sources [8]. Operating across a network of independent and potentially untrusted actors, BCT organizes data into a chain of cryptographically secured blocks. Each block is uniquely linked to its predecessor using hashing techniques, which maintain the continuity and integrity of the entire chain. This cryptographic linkage safeguards against data tampering, as any alteration would require recalculating and modifying all subsequent blocks, a computationally infeasible task [15]. The integration of real-time data recording with distributed storage infrastructure ensures seamless data sharing and accessibility, facilitates the continuous monitoring of products, enhancing traceability.

Smart contracts and governance mechanisms embedded in the BCT infrastructure support data evaluation and enforce rules to uphold data credibility, while cryptographic methods ensure protection against unauthorized modifications [8]. The capability of BCT to record and update data in real time, integrated within a distributed storage system enables seamless data sharing across networks and facilitates continuous product tracking traceability [15]. The quality of data contributed by each participant is assessed through governance protocols and cryptographic algorithms embedded within smart contracts and consensus mechanisms. These protocols ensure rigorous data verification and protect the integrity of information from unauthorized alterations or deletions. Consensus on data validity is collectively established by network participants through consensus algorithms, which support data immutability while enhancing overall system security and reliability [16]. As a result, decentralized BCT reduces dependency on intermediaries, promotes inclusivity among actors, and helps prevent the concentration of power among dominant entities [17]. Moreover, BCT enables a decentralized economic model for data sharing by combining traceability, consensus mechanisms, and smart contracts [15].

Actors are incentivized through utility tokens for contributing verifiable data, while staking mechanisms and consensus protocols ensure data integrity and trust without centralized oversight [16]. Reputation systems further align incentives by granting access to high-value services based on data quality and consistency. Smart contracts automate compensation and enforce usage conditions, creating a transparent and self-sustaining ecosystem for data monetization and governance [18].

3 Research Methods

This study adopted a Systematic Literature Review (SLR) approach to synthesize existing knowledge, identify research gaps, and evaluate collective evidence relevant to the study objectives [19]. It follows a structured methodology that includes research question formulation, study identification and retrieval, selection and critical appraisal, data analysis, synthesis, and systematic reporting of findings. This process ensures methodological rigor, minimizes bias, and enhances the reliability of the results [20]. To further strengthen the reliability of the review, a comprehensive search strategy was designed with well-defined phrases that balanced specificity and breadth, capturing the interconnected aspects of the EVB circular economy, EVB ecosystem, and blockchain technology [21]. A preliminary search was conducted using Scopus and Web of Science, widely recognized as authoritative academic sources, to identify relevant literature. The search strings were based on three main themes: 1) blockchain; 2) EV batteries; 3) circular economy of EV batteries. Selected keywords were combined into two search strings using Boolean operators (AND and OR). The compiled list of search terms is presented in Table 1. These keywords were strategically selected to generate precise results aligned with the research questions. The search queries were executed across the Scopus and Web of Science databases, targeting the title, abstract, and keywords fields.

Table 1: Search strings theme and keywords

Search string theme	Search string keywords
Blockchain Technology	"blockchain*" OR" digital ledger" OR "traceability*" OR "decentralization"
Battery	"battery*" OR "EV* battery*" OR "Electric Vehicle* battery*"
Circular Economy	"second* life*" OR "circular* economy*" OR "value retention*" OR "repair*" OR "reuse*" OR "remanufacture*" OR "repurpose*" OR "refurbishment"

A rigorous quality assessment of the retrieved publications was conducted based on predetermined criteria to ensure relevance and reliability. Defining clear inclusion and exclusion criteria was pivotal in precisely define the scope of the review (table 2). These criteria refined the search results, focusing exclusively to retrieve only the most relevant publications. The review exclusively focused on peer-reviewed journal articles, which are widely recognized for their credibility and high-quality content, while excluding conference papers, books, book chapters, and reports. The review included English-language studies published up to 2024 and centred on research explicitly addressing the role of BCT to enable battery circularity. Studies that merely mentioned BC and/or CE without a focused exploration of their intersection, as well as research emphasizing chemical or technical aspects without broader relevance, were excluded.

The initial search retrieved 24 publications from Scopus and 27 from Web of Science. After eliminating duplicate studies, 34 unique publications remained. Titles and abstracts were initially screened against the selection criteria, and irrelevant entries were excluded. The content of the remaining publications was then thoroughly evaluated for alignment with the review objectives, resulting in 26 retained studies. To ensure comprehensive coverage, backward and forward citation searches were conducted, capturing all pertinent references. Following the final assessment, 30 publications were approved for inclusion in the review. Figure 1 displays the details of the article selection process. Then, the selected publications were evaluated based on various criteria. These included BC features such as decentralization, traceability, smart contracts, and consensus mechanisms; areas of application within the CE and battery ecosystem; actor requirements; barriers to implementing CE strategies; and blockchain-enabled solutions. Thematic analysis was conducted using the Gioia methodology to synthesize the findings and provide a nuanced understanding of the interplay between BCT and CE strategies and the battery ecosystem. This approach enabled the classification and contextualization of insights to address the research purpose effectively [22].

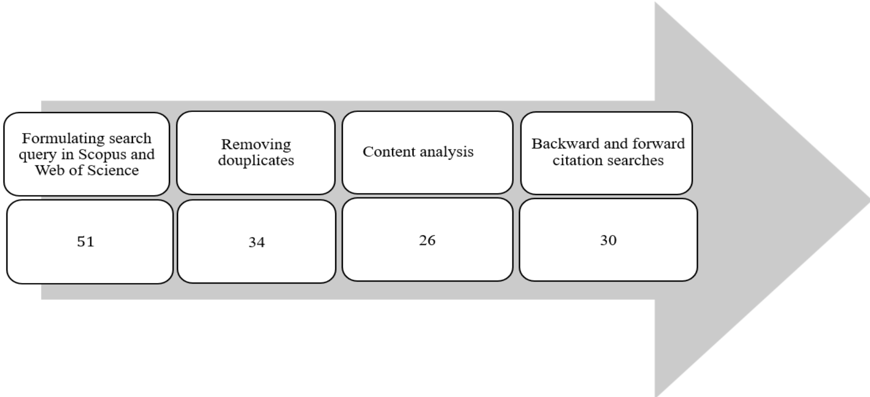

Figure 1: Article selection process

4 Findings

Based on the reviewed literature, we propose a framework (Figure 2) that illustrates the integration of BCT within the battery ecosystem and its potential to support circularity. The framework highlights the key challenges faced by various actors in achieving circularity, along with the potential gains derived from implementing BCT through its key features. From our analysis, we identified ten key actor groups within the battery ecosystem: raw material suppliers; electric vehicle battery (EVB) manufacturers; electric vehicle (EV) manufacturers and OEMs; EV owners/users; circular integrators (including remanufacturing and repurposing companies); energy and utility companies; recycling companies; IT and infrastructure companies; and other intermediary third parties (e.g., dealers, logistics providers, and insurance companies). These actors play essential roles in managing the battery lifecycle and advancing circularity. The central component of the framework focuses on key BCT features such as 1. traceability, 2. decentralization, 3. smart contracts, and 4. consensus mechanisms, numbered to provide clear insight into the specific gains associated with each. These features collectively enhance transparency, security, traceability, and operational efficiency across the ecosystem, thereby enabling more effective collaboration and informed decision-making to support CE goals. Below, descriptions of each battery ecosystem actor are provided, along with information on their needs and the potential gains from using blockchain technology (BCT).

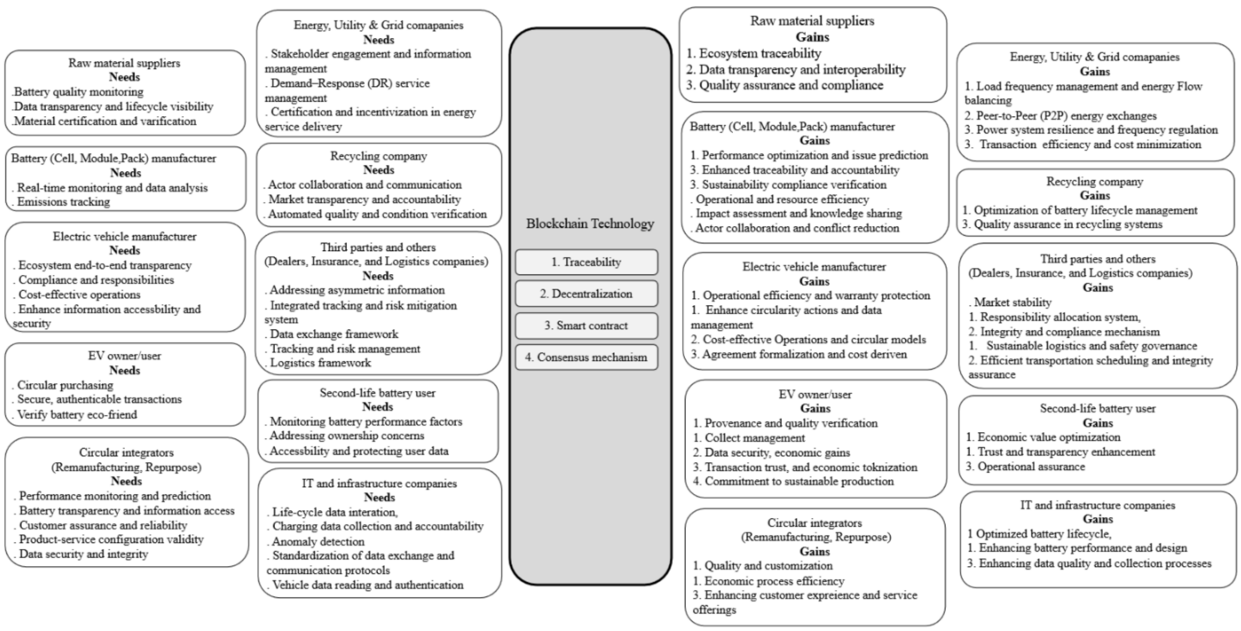

Figure 2: The conceptual framework of BC features to support battery ecosystem actors for battery circularity

4.1 Blockchain Technology for Battery Ecosystem Actors

4.1.1 Material Suppliers

Needs: Raw material suppliers require greater support in ensuring the quality and compliance of materials, as battery performance is significantly influenced by raw material quality [14]. They face major challenges in maintaining quality assurance and meeting regulatory standards [13]. A key need is improved transparency and lifecycle visibility, as the lack of these elements undermines efforts to certify materials for sustainable and ethical sourcing [2, 7].

Gains: Raw material suppliers stand to gain significantly from the adoption of BCT. BCT enhances traceability by enabling real-time tracking of material origins and improving visibility across supplier networks and operational facilities [13, 23]. It also supports data interoperability and integrity, helping to eliminate data silos that often hinder supply chain transparency [2, 24]. Additionally, smart contracts can be used to certify the origin of materials, thereby strengthening quality assurance and ensuring transparency and authenticity throughout the supply chain [9].

4.1.2 Battery Manufacturers

Needs: Battery manufacturers require real-time monitoring and data analysis capabilities to systematically track components, operational performance, and processes across the production, usage, and recycling stages [2]. They need tools that enable the evaluation of how variations in materials, design, and manufacturing processes affect battery quality and safety. Additionally, manufacturers must monitor emissions at each stage of production to ensure regulatory compliance and to address environmental and resource-related risks [8].

Gains: Battery manufacturers can derive multiple benefits from adopting BCT. A blockchain-based platform enables enhanced traceability and real-time analysis across the battery lifecycle, allowing manufacturers to optimize battery performance and proactively identify potential issues [2]. BCT also facilitates sustainability compliance by monitoring emissions and simulating eco-friendly production scenarios [9]. Through the use of smart contracts, manufacturers can automatically enforce standards, verify regulatory compliance, and enhance accountability thereby reducing human error, preventing data tampering, and enabling secure data sharing among actors [13, 25]. These features help ensure consensus on critical decisions, fostering trust and coordination across the battery ecosystem [3, 6]. Additionally, BCT supports robust impact assessments and enables manufacturers to make CE-aligned decisions [2], ultimately reinforcing CE initiatives and reducing reputational risks [6, 9].

4.1.3 EV Manufacturer and Original Equipment Manufacturers (OEMs)

Needs: To implement circularity, EV manufacturers/OEMs must comply with European legislation under Extended Producer Responsibility (EPR), which obliges them to recover used batteries and maintain oversight throughout the battery lifecycle. They need comprehensive traceability across the battery ecosystem, including the ability to share battery characteristics and operational data to enhance visibility and lifecycle transparency [2]. When delegating recovery tasks to third-party circular integrators, OEMs retain accountability for battery liability and regulatory compliance. Therefore, monitoring second-life battery data is essential to avoid moral hazards and protect brand reputation [6]. OEMs also require advanced traceability tools to track recycled content, calculate carbon footprints, and ensure compliance with environmental regulations [2]. Given the sensitivity of battery data, OEMs must implement robust decryption protocols to safeguard information and meet strict data-handling requirements [13].

Gains: EV manufacturers, particularly OEMs, can gain significantly from the adoption of BCT. Enhanced traceability through BCT enables more effective management of battery services, improving operational efficiency and extending battery lifecycles [6]. It also helps detect improper battery use or data tampering, thereby reducing disputes and lowering testing and remanufacturing costs [13]. BCT further strengthens warranty protection and supports rising consumer demand for authentic and reliable battery information [25]. Its decentralized architecture allows seamless integration and accelerates cost-effective operations across the ecosystem [6]. OEMs can formalize contracts and gain improved oversight of third-party battery recovery activities, ensuring better alignment and accountability [26]. Additionally, BCT ensures data security and integrity through immutable and verifiable storage, reducing risks associated with information asymmetry [6]. Techniques such as encryption, anonymization, and data aggregation also protect sensitive data while preserving system transparency [29].

4.1.4 EV Users

Needs: EV users occupy a critical position at both the end of the forward supply chain and the start of the reverse supply chain, making their involvement essential for effective battery management and collection [9]. With rising concerns about ethical and sustainable consumption, users increasingly need access to reliable battery history and lifecycle impact data to build trust and reduce uncertainty in purchasing decisions [25]. Verifying the eco-friendliness of batteries is a key priority, as users seek assurance that their choices align with environmental standards [3, 9]. Access to such information enables informed decision-making and supports the growing demand for high-quality batteries. Additionally, users require secure and authenticatable transactions to ensure battery quality, performance, and protection against fraud or tampering [9, 13].

Gains: EV users benefit from BCT through enhanced traceability, which supports provenance and quality verification, enabling them to assess battery sustainability, origin, and lifecycle thus fostering ethical and informed purchasing decisions [25, 27]. It also facilitates collection management by identifying battery ownership and usage history, streamlining reverse logistics [9]. ownership and usage history, streamlining reverse logistics [9]. Through decentralization, users gain improved data security and economic advantages, while transparent access to battery records helps mitigate opportunistic behavior [3, 28]. Smart contracts build transactional trust and promote fair collection and circular economy practices through economic tokenization, while the consensus mechanism ensures commitment to sustainable production via immutable and verifiable product data [9, 13].

4.1.5 Circular Integrators

Needs: Circular integrators require performance monitoring and prediction capabilities, including real-time tracking and model-based assessments to evaluate battery health and remaining useful life [8, 12]. Equally important is battery transparency and information access, as clear labeling and availability of technical and economic data are essential for making informed repurposing and recycling decisions [29]. To ensure customer assurance and reliability, integrators must perform extensive testing and maintain traceability to guarantee the safety and performance of second-life batteries [30]. Additionally, product-service configuration validity, along with data security and integrity, is necessary to verify correct configurations and ensure secure, confidential access to first-life battery data across the ecosystem [9].

Gains: Circular integrators benefit from enhanced quality and customization through blockchain-enabled traceability, which provides precise data on battery condition and history—enabling tailored configurations and reliable second-life performance [6, 13]. This traceability also enhances remanufacturing and second-life efficiency by providing verified first-life data for safer and more effective repurposThis traceability also improves remanufacturing and second-life efficiency by supplying verified first-life data for safer and more effective repurposing [25]. Economic process efficiency is enhanced by improving traceability and transparency in battery condition data, which reduces the need for manual testing and supports the extension of battery life [6]. Customer experience and service offerings are enhanced through smart contracts that automate validation and support personalized service bundles, fostering trust and satisfaction [3]. Finally, blockchain supports strategic business development and transaction optimization by enabling data-driven decisions and automating service agreements, thereby reducing transaction costs [2, 13].

4.1.6 Recyclers

Needs: Recyclers need stronger collaboration mechanisms due to challenges such as unstable cooperation among actors and ineffective information communication, compounded by competition from unregulated recycling channels and exploitable policy loopholes [9]. Improved data sharing is essential for accurately assessing battery recyclability, ensuring effective quality control, and establishing clear liability management mechanisms [3, 27]. To enhance market transparency and accountability, recyclers also require clearly defined responsibilities for battery recycling and greater visibility in the power battery recycling market [8].

Gains: Recyclers gain from optimized battery lifecycle management through digital tracking of battery health, usage history, and degradation rates, enabling informed recycling decisions [2, 31]. Quality assurance in recycling processes is enhanced by decentralized and tamper-proof data, which helps prevent the circulation of substandard batteries and mitigates fraudulent practices [9].

4.1.7 Energy, Utility & Grid Companies

Needs: Energy, utility, and grid companies need effective stakeholder engagement and information management to address conflicting interests, enhance data coordination, and reduce information asymmetry. They also require robust demand–response (DR) service management to balance grid loads efficiently [26]. Certification and incentivization mechanisms in energy service delivery are essential for building trust and encouraging participation in Vehicle-to-Grid (V2G) networks, especially when integrating second-life EV batteries for grid support [32].

Gains: Energy, utility, and grid companies benefit from improved Load Frequency Control (LFC) performance and more balanced energy flow through traceability features in digital energy platforms [25]. Decentralization facilitates peer-to-peer (P2P) energy exchanges, enabling direct interaction among actors and reducing reliance on central authorities [33]. Smart contracts enhance participation, strengthen system resilience, and support the maintenance of frequency and tie-line power within acceptable ranges [36]. They also lower transaction costs, reduce reliance on intermediaries, and enable efficient decision-making and contract formation, streamlining operations and reducing overall costs [26].

4.1.8 Second-Life Battery Users

Needs: Second-life battery users need reliable tools to monitor battery performance, as they often face information asymmetry regarding the extent of battery stress during its first life [6]. They also require clarity around ownership and strong contract compliance mechanisms to ensure reliable and transparent battery operations [33, 34].

Gains: Second-life battery users benefit from economic value optimization through BCT, which enhances purchasing confidence by providing transparent and immutable records of battery provenance and performance applications [6]. Smart contracts further support the monetization of battery services, ensuring proper usage and securing transactions through warranties or service agreements [13, 34].

4.1.9 Dealers

Needs: Dealers face significant challenges due to information asymmetry in the second-life battery market [6]. As highlighted uncertainty about the quality of used products, such as second-life batteries, can lead to mistrust between dealers and customers. This lack of transparency can push high-quality batteries out of the market, discouraging fair transactions and risking overall market collapse [26].

Gains: BCT fosters trust between actors by ensuring data integrity and accuracy, thereby protecting both dealers and customers from opportunistic behavior [3, 26]. As a result, BCT enhances market stability, supports fair trade, and improves the overall credibility of the second-life battery market [42].

4.1.10 Insurance Companies

Needs: Insurance companies require an integrated tracking and risk mitigation system to address challenges such as falsified charge/discharge data and to monitor battery degradation influenced by user behavior, extreme temperatures, and V2G program participation [35]. A secure data exchange framework with mutual authentication and accountability mechanisms is crucial to prevent data manipulation, especially in light of persistent concerns around data falsification [9, 10].

Gains: For insurance companies, traceability through BCT enables a responsibility allocation system, ensuring clear attribution of battery misuse or degradation to specific users or events [9]. With decentralization, insurers gain access to tamper-proof historical data from multiple actors, enhancing transparency and reducing fraudulent claims. Smart contracts enforce a data integrity and compliance mechanism, automatically detecting manipulated data, such as falsified charge/discharge records, and issuing risk alerts [10]. Finally, consensus mechanisms guarantee that all battery data is validated collectively, preventing unqualified actors from exploiting regulatory gaps for subsidies [35].

4.1.11 Logistics companies

Needs: Logistics companies play a critical role in the battery ecosystem, working with various actors including OEMs for battery collection, integrators for second-life storage systems, and EV charging stations [35]. They need streamlined logistics processes through standardized procedures, enhanced traceability, and coordinated real-time information exchange among actors. Once batteries are returned, clearly assigned responsibilities are essential for efficient handling, whether batteries are sent back to manufacturers for repair or forwarded to integrators for disassembly [36]. Given the hazardous nature and encrypted components of EVBs, logistics providers also require specialized and secure handling procedures to meet safety and data protection standards [6].

Gains: Logistics companies benefit from blockchain-enabled information traceability, which enables real-time supervision and establishes clear accountability across all actors in the battery ecosystem. By leveraging BCT, they can access battery-related data and manage hazardous materials in compliance with safety standards [6, 9]. The decentralized structure of BCT also supports efficient transportation scheduling and ensures the integrity of battery shipments. During delivery, critical information such as transactions and logistics operations is automatically recorded, providing verifiable and tamper-proof documentation [9].

4.1.12 IT and Infrastructure Companies

Needs: IT and infrastructure companies, particularly those operating charging stations, need integrated life-cycle data to effectively monitor battery aging and state of health (SOH) [8]. Improving charging data collection and accountability requires enhanced data transparency, stakeholder participation, and anomaly detection to support second-life battery use [37]. Seamless collaboration among actors depends on standardized data exchange, secure communication protocols, and mutual authentication schemes between EVs and charging systems [38]. Accurate vehicle data reading and authentication are also essential for reliably tracking battery degradation and supporting informed decisions on repair, reuse, or recycling [36].

Gains: IT and infrastructure companies, particularly those managing charging stations, gain from blockchain-enabled traceability that supports an optimized battery lifecycle. Battery usage data such as SOH, charging cycles, and temperature can be aggregated to facilitate second-life applications [2]. Smart contracts further ensure that only validated data is exchanged, improving the accuracy of vehicle-specific power data and supporting ongoing battery performance monitoring [38].

5 Discussion

5.1 Theoretical Implications

This study contributes to the CE literature in general and the battery circularity literature in particular by linking the needs of EVB ecosystem actors to the potential benefits of BCT. Specifically, it highlights how BCT's four key features, traceability, decentralization, smart contracts, and consensus mechanisms, can address critical barriers to circularity. The study advances theoretical discourse in CE by examining how BCT can mitigate persistent system-level challenges across the EVB lifecycle, from production to end-of-life. Previous research has noted a lack of focus on foundational enablers such as standardized data protocols, sufficient data granularity, and battery design characteristics, elements essential for facilitating effective allocation, reuse, and recycling strategies [2]. Although BCT has been proposed as a promising solution for enhancing traceability and coordination within EVB aftermarkets and recycling networks [3, 7], its application remains limited in addressing the broader principles of circularity in a comprehensive manner [13]. Significant theoretical gaps persist in achieving full-process supervision, lifecycle data integration, and system-wide transparency [9]. Additionally, existing literature offers limited guidance on how BCT can be operationalized in ways that align with the practical requirements and business models of the diverse actors within the EVB ecosystem [2]. By addressing these gaps, this study provides a theoretical foundation for future research on the role of BCT in enabling circularity across complex industrial systems.

5.2 **Managerial Implications**

This study offers valuable insights for a range of battery ecosystem stakeholders including sustainability managers, supply chain coordinators, compliance officers, and policymakers by underscoring the importance of coordinated efforts to achieve battery circularity. Given the complexity of the ecosystem, collaborative approaches such as industry consortia, public-private partnerships, pilot projects, and joint partnerships, or risk-sharing partnerships are essential for aligning goals, minimizing implementation barriers, and building consensus around the adoption of BCT. A clear understanding of BCT and its core features can help organizations assess its strategic relevance within their operations. Integrating BCT with complementary technologies such as IoT devices (e.g., RFID, sensors) and Digital Product Passports can enhance data reliability and foster trust among actors. To fully leverage BCT's potential, firms should prioritize investment in digital infrastructure, data governance, and cross-functional collaboration. Finally, enabling regulatory frameworks that promote interoperability, provide legal clarity, and support the standardization of smart contracts and cross-border data sharing are critical for scaling BCT-enabled circular solutions across the battery ecosystem.

5.3 **Conclusions, Limitations, and Future Work**

This study explores the role of BCT and its four core features, traceability, smart contracts, consensus mechanisms, and decentralization, in advancing circularity within the EVB ecosystem, based on a systematic literature review. BCT emerges as a promising enabler, offering secure and immutable traceability, decentralized data sharing, and transparent decision-making. These features collectively enhance battery performance, lifecycle visibility, and resource recovery efficiency. The study identifies the specific needs of each actor group involved in the battery ecosystem and links them to the potential benefits of BCT, reinforcing its practical relevance for circular battery management. By integrating BCT into battery lifecycle processes and broader ecosystem operations, actors can improve transparency, trust, decision-making, and operational efficiency thereby contributing to a more resilient and circular battery economy. In addition to advancing academic discourse on circular economy and ecosystem innovation, this study provides actionable insights for industry practitioners and policymakers seeking to scale CE initiatives using digital technologies such as BCT. However, the research is not without limitations. This study is based on a systematic literature review, and future research should validate the findings through empirical investigations involving actors across the battery ecosystem. Additionally, while the paper emphasizes the potential benefits of BCT, it gives limited attention to implementation challenges. Future studies should explore the practical barriers to BCT adoption in battery circularity and assess its broader applicability and long-term impact across diverse sectors and regulatory contexts.

Acknowledgments

This work was supported by the Circul8 (Smart Battery Circularity) funded by the Knowledge Foundation in Sweden (1602, 2019), and SmartCharg (Smart and Circular Battery Charging Solutions) funded by Vinnova FFI Circularity program in Sweden (00814, 2023). We gratefully acknowledge the academic and industry collaborators involved in the Circul8 and Smart Charge projects. Their combined expertise and commitment to advancing battery circularity have significantly enriched this research. We appreciate the opportunity to contribute to these impactful, cross-sector initiatives.

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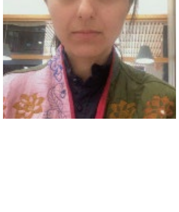
Presenter Biography



Moshkan Ebrahimi is a PhD student in Digital and Circular Industrial Services (DigiCircle) research group at the School of Innovation, Design, and Engineering at Mälardalen University, Eskilstuna. Her academic background includes expertise in supply chain management, sustainability, circular economy, blockchain technology, and statistics. She holds a master's degree in Logistics Supply Chain Management, specializing in industrial systems, from Molde University, Norway. Additionally, she earned a master's in mathematical Statistics. She has conducted research on the role of blockchain technology in enhancing circular economy practices. Her PhD focuses on Blockchain technology, Circular Economy, and Battery value chain.