

Information Strategies in the Electric Vehicles Battery Reverse Supply Chain with Blockchain Technology

Tianqin Shi, PhD Yanting Huang, PhD



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16. Abstract The surge in demand for electric vehicles (EV) and EV batteries, coupled with supply chain vulnerabilities and price instability, has driven the need for efficient and sustainable EV battery recycling processes. This report investigates the potential of blockchain technology to address the challenges in the EV battery reverse supply chain (moving goods from the end customer back towards the manufacturer), focusing on enhancing transparency and coordination, as well as mitigating the impact of unregulated recycling. Key stakeholders in this analysis include manufacturers, recyclers, and regulatory bodies. To achieve these objectives, the study employs a mixed-methods approach. It includes semi-structured interviews with industry experts from EV and battery manufacturing companies to gather qualitative insights into the current challenges and the potential of blockchain technology. Furthermore, the study used a model based on the Stackelberg game theory to analyze the impact of blockchain adoption on the behavior and profitability of supply chain members, specifically focusing on the interaction between regulated and unregulated recyclers. The findings show that blockchain technology can offer significant benefits to the EV battery reverse supply chain. Specifically, blockchain adoption can increase the total recycling quantity, provided that the implementation costs are relatively low. Additionally, blockchain can help empower regulated recyclers to achieve higher buyback prices and recycling quantities compared to unregulated recyclers, enhancing the competitiveness of responsible recycling practices. However, the adoption of blockchain technology depends on its cost-effectiveness and the intensity of competition within the recycling sector. These results highlight the importance of strategic blockchain implementation and regulatory support to foster a sustainable and efficient EV battery recycling ecosystem, which supports a sustainable transportation industry.			
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Executive Summary

The rapid expansion of the electric vehicle (EV) market has led to a significant increase in the demand for the critical metals used in EV batteries. This surge in demand has created challenges in the supply chain, including potential shortages and price volatility. To address these issues and promote sustainability, efficient recycling of EV batteries is crucial. However, the EV battery recycling process faces several obstacles, such as difficulties in tracing battery origins, the complexity of coordinating the reverse supply chain, and the presence of unregulated recyclers. This research explores the potential of blockchain technology to overcome these challenges and enhance the efficiency and transparency of the EV battery reverse supply chain. The primary research goal is to analyze the impact of blockchain technology on the recycling of EV batteries, with a particular focus on the role of unregulated recyclers in this process.

This study used a mixed-methods approach, combining qualitative and quantitative research techniques. First, semi-structured interviews were conducted with six experts from EV and EV battery manufacturing companies in the United States and China. These interviews gather in-depth insights into the challenges faced in the current EV battery recycling processes, the impact of unregulated recyclers, and the potential benefits and barriers to implementing blockchain technology. Second, a Stackelberg game theory model was developed to analyze the strategic interactions among different stakeholders in the EV battery supply chain. The model includes a manufacturer, a retailer, a regulated recycler, and an unregulated recycler. It compares scenarios with and without blockchain adoption to assess its impact on recycling quantities, prices, and profits. The model uses mathematical equations to represent the decision-making processes of each stakeholder and to derive equilibrium outcomes.

The interviews revealed challenges in the current EV battery recycling process, including difficulties in tracing the source of waste batteries and the negative impacts of unregulated recyclers. Unregulated recyclers lead to market disorder and price competition and often use environmentally harmful recycling methods. Blockchain technology was identified as a potential solution to enhance supply chain transparency and enable better tracking of batteries throughout their lifecycle. The game theory model provided further insights into the economic implications of blockchain adoption. The model demonstrated that blockchain adoption could increase the total recycling quantity if the blockchain implementation costs are sufficiently low. Blockchain technology can also enable regulated recyclers to achieve higher buyback prices, recycling quantities, and profits compared to unregulated recyclers given lower per-unit operational costs. The model also showed that the regulated recycler's decision to adopt blockchain is influenced by the cost of blockchain implementation and the level of competition in the recycling market.

The findings of this research suggest several policy and practice recommendations. Regulators should actively explore and promote the application of blockchain technology in EV battery supply chains to enhance transparency and combat unregulated recycling. Given the challenges posed by

unregulated recyclers, policies should be developed to incentivize the adoption of blockchain among supply chain participants. To compete effectively with unregulated recyclers, regulated recyclers should focus on improving their recycling technologies to reduce costs. Blockchain platforms should strive to reduce implementation costs to encourage wider adoption and maximize the technology's benefits in addressing the environmental challenges associated with EV battery recycling.

1. Introduction

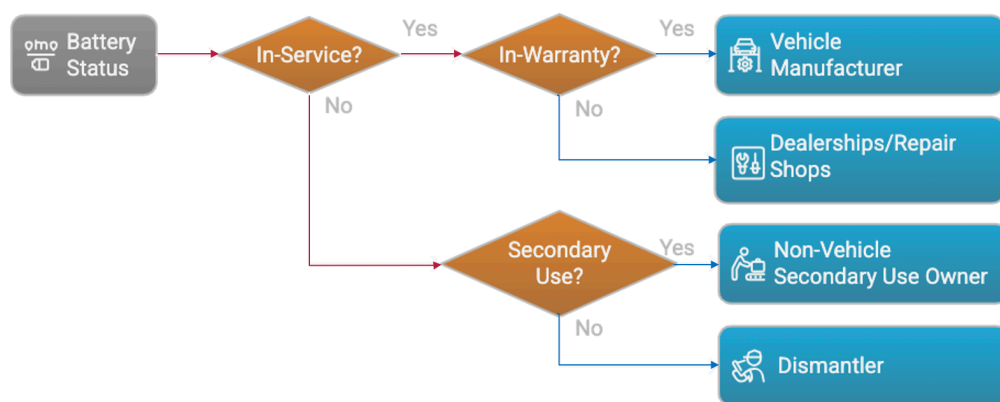
Amidst escalating environmental concerns and a heightened need for energy, the global production and market share of electric vehicles (EVs) and EV batteries has expanded rapidly. According to the International Energy Agency (IEA), the need for electric vehicle batteries surged in 2023, exceeding 750 GWh, marking a 40% increase from the previous year (IEA, 2024b). The surge in EV lithium-ion battery demand has significantly driven up the need for critical metals such as lithium, cobalt, and nickel. In 2023, batteries consumed approximately 140 kt of lithium (85% of total demand, a 30% increase from 2022), 150 kt of cobalt (70% of total, a 15% rise), and 370 kt of nickel (10% of total, a 30% increase) (IEA, 2024b). Despite this growth, short-term supply constraints for these critical metals pose a challenge. Battery manufacturers might face difficulties in obtaining crucial raw materials such as lithium, Class 1 nickel, and high-purity manganese; by 2030, only 20–30% of the high-purity manganese sulfate monohydrate supply will be suitable for battery applications, which will make up just 5% of the total manganese demand (Fleischmann et al., 2024). To mitigate a mismatch between supply and demand, along with supply chain volatility and price instability, EV and battery companies are seeking reliable, local sources of raw materials, including remanufacturing, repurposing, and recycling used batteries (Wei et al., 2021; Rufino Júnior et al., 2022; Zhou et al., 2023). In fact, a report by McKinsey & Company (Breiter et al., 2023) forecasted that the next decade will see over 100 million electric vehicle batteries reach their end of life, providing a consistent supply for recycling operations.

To foster EV battery recycling, pertinent regulations and initiatives have been enacted globally (Cheng et al., 2021; Neumann et al., 2022; Popova, 2022). For example, the Council of the European Union (EU, 2023) adopted a regulation to address the environmental and social impacts of batteries across all stages, including end-of-life management (collection, recycling, and recovery). In particular, the regulation sets ambitious targets for the collection and recycling of waste batteries, including specific targets for materials recovery (e.g., lithium, cobalt, nickel). The minimum levels for the recovery of cobalt, copper, lead, and nickel are 90% by 2027 and 95% by 2031. For lithium, the regulation sets a target of 50% by 2027 and 80% by 2031 (EU, 2023). While there is no federal law mandating EV battery recycling in the U.S. as of 2024, the U.S. EPA (2023) is working on best practices and guidelines. Twenty states have battery recycling requirements in effect, while 10 states and the District of Columbia require battery producers to offer or fund battery recycling (Wilkins & Kuna, 2023; Call2Recycle, n.d.). In 2024, the U.S. Department of Energy announced the funding of over \$880 million on seven projects that involved the recycling of battery materials (Voloschuk, 2024). In China, a 2023 regulation requires EV and battery manufacturers to manage the traceability and recycling of EV batteries, aiming to connect suppliers and consumers of end-of-life batteries more closely (IEA, 2024a).

Despite the benefits of EV battery recycling that allow manufacturers to address the supply chain challenges and achieve regulatory and environmental, social, and governance (ESG) goals, EV and EV battery companies are facing various challenges in the recycling of used batteries. First of all,

the market price for lithium and the low residual value of lithium iron phosphate currently make recycling economically unfeasible in Europe and the United States (IEA, 2024a). Second, it is crucial to determine the state of health and remaining value of used batteries for deciding whether to recycle, reuse, or repurpose them; however, such assessment can be difficult and costly (Fallah & Fitzpatrick, 2024). Third, it is challenging to coordinate the reverse supply chain for EV batteries that involves multiple stakeholders such as manufacturers, dealers, battery collectors, recyclers, third-party logistics operators, regulatory bodies, and customers (Toorajipour et al., 2024). Figure 1 depicts various EV battery end-of-life responsible parties based on a report by the Alliance for Automotive Innovation (2022). Fourth, the rapid growth in supply for recyclers and the increase in small, unofficial, and unregulated recycling companies deviates the supply for recovery operations (Liu et al., 2016; van Wyk, 2023; Esenduran et al., 2024). This situation has sparked concerns about these companies lacking sufficient battery technology expertise, environmental and safety standards, and reliable traceability systems (IEA, 2024a), preventing licensed or regulated recyclers from achieving economies of scale and blocking manufacturers from payment for licensing (Huang & Wang, 2019). Other challenges include, but are not limited to, organizational immaturity, commercial infeasibility and business uncertainty, complexity in partnerships and responsibilities, as well as variations in battery types and technology (Rajaeifar et al., 2022; Toorajipour et al., 2024).

Figure 1. EV Battery End-of-Life Responsibility



Given the main challenges (high costs, assessment inaccuracy, reverse supply chain coordination issues, and unregulated recycling), industry practitioners are exploring technological solutions such as blockchain (CTECHi, 2021; Everledger, 2022; Choi et al., 2023). Blockchain is a distributed and decentralized digital ledger that records transactions in blocks, linked chronologically, and secured through cryptography and consensus mechanisms; once validated, records become immutable, preventing tampering and ensuring data integrity. This design enables secure, transparent, and verifiable transactions across a network without the need for a central authority (Treiblmaier, 2018). Different from public, permissionless blockchain systems such as Bitcoin, where no central authority exists, blockchain applications in supply chains are typically developed

as permissioned or consortium blockchains, without the risk of losing passwords (Francisco & Swanson, 2018).

In supply chain contexts, blockchain enhances traceability, transparency, and trust by enabling provenance tracking, automated enforcement of agreements through smart contracts, and greater visibility into material flows. These capabilities help address persistent challenges such as counterfeiting, information asymmetry, and sustainability verification (Saber et al., 2019; Cole et al., 2019). Specifically, in battery management, blockchain supports health assessment by aggregating charging data from multiple stakeholders, applying anomaly detection and scoring data sources to filter out unreliable inputs. This mechanism improves data quality and reduces estimation errors, achieving up to 25% greater accuracy in state-of-health evaluations (Jin et al., 2021). The improved assessment accuracy helps recyclers determine the best recovery strategies among reusing, remanufacturing, repurposing, and recycling, thus achieving minimum environmental impacts and maximum economic benefits.

Moreover, blockchain-powered reverse supply chains ensure supply chain transparency, control, and collaboration among forward or reverse supply chain participants (Moors, 2023; Feng et al., 2024; Chen et al., 2025). Blockchain can enhance accountability throughout the recycling lifecycle by tracking products at every stage, ensuring responsibility is shared among all participants, not just the producer (IBM, 2019; Li et al., 2022; Meier et al., 2023; Wang et al., 2024). Additionally, blockchain prevents unregulated recycling by providing a tamper-proof ledger that tracks waste throughout its lifecycle, ensuring transparency and making unregulated activities difficult to conceal (Shen et al., 2022).

One prominent effort is the BATRAW project funded by the European Union's Horizon 2020 program (<https://batraw.eu/>). The BATRAW project, involving 17 partners from 7 different countries and running from 2022 to 2026, aims to develop innovative processes for the recovery of critical raw materials (CRMs) from EV batteries. A key aspect of BATRAW is its use of blockchain technology to enhance transparency and traceability in the supply chain. The project develops a blockchain platform that tracks raw materials, products, and supply chain activities. This platform includes a digital Battery Passport, which stores key information about batteries and their lifecycle on the blockchain. The Battery Passport aims to meet regulatory requirements and support sustainable practices in battery recycling and management (BATRAW, 2023).

This report examines the use of blockchain in the EV battery supply chain by answering the following questions: (1) What is the status quo of blockchain implementation in EV battery recycling? (2) What are the impacts of blockchain technology on closed-loop supply chains (CLSC), including unregulated recycling?

The remainder of this report is organized as follows: Section 2 provides the interview results with automobile industry practitioners to understand the status quo of blockchain implementation in EV and EV battery recycling, the impacts of unregulated recycling on battery recovery supply

chain, and the motivation of supply chain participants to adopt blockchain technology to facilitate battery recycling. In Section 3, we develop a Stackelberg game theory model by considering a supply chain with a manufacturer, a retailer, a regulated recycler, and an unregulated recycler. We will derive a closed-form equilibrium and conditions and obtain numerical results. Section 4 summarizes this report and provides managerial implications. All proofs are presented in Appendix A.

2. Interviews

We conducted six semi-structured interviews with experts from four EV manufacturers (two of which are pure-play EV firms) and one EV battery manufacturer located in the United States and China. The interview questions can be found in Appendix B. The main results are summarized below.

Challenges in the current EV battery recycling process. Interviewees highlighted challenges in tracing the source of waste batteries within the current EV battery recycling process. The diverse battery models and lack of unified coding standards result in poor traceability, making it difficult to accurately assess the usage history and performance status of used batteries.

Unregulated recycling. The presence of unregulated recyclers creates several problems in the process of recycling EV power batteries. These unregulated entities contribute to market disorder, engage in price competition, and often employ recycling methods that lead to environmental pollution. Additionally, they can cause a waste of resources, pose safety hazards, damage the reputation of legitimate companies, and complicate regulatory efforts.

Application of Blockchain to EV batteries. The primary purposes for using blockchain technology include enhancing supply chain transparency, enabling source and identity verification, and facilitating battery life cycle tracking. While some of the companies we interviewed have implemented global traceability of certain raw materials used in its batteries by applying blockchain technology, none of them integrate blockchain in the finished goods.

Benefits of blockchain implementation in EV battery industry. Experts suggested that implementing blockchain technology could bring various benefits. Blockchain's features, including decentralization, immutability, and traceability, can improve supply chain transparency, allowing consumers to trace a product's journey from raw materials to the final sale. This detailed tracking can increase consumer confidence. Furthermore, blockchain's immutability helps prevent counterfeiting and tampering, while its transparency and accountability features can assist companies in addressing issues promptly, maintaining product quality, and fostering a positive brand image. Finally, by enabling better tracking and management of a product's lifecycle, blockchain can support green and sustainable development, which can attract environmentally conscious consumers and expand market potential.

Economic Feasibility of Blockchain Integration in EV batteries. The economic feasibility of implementing blockchain technology in EV battery manufacturing is considered viable to some extent. The main costs associated with implementing blockchain technology involve investments in technology research and development, equipment procurement, system deployment, and costs related to network maintenance, data storage, and energy consumption. While introducing blockchain technology does involve costs, it also presents potential long-term economic and

environmental benefits (Dou et al., 2024). These benefits may include improved efficiency in supply chain management and battery recycling, reduced risks through enhanced transparency and traceability, and increased competitiveness by establishing a green and sustainable brand image.

Blockchain in EV battery recycling. The main drivers of employing blockchain technology are improving the efficiency and accuracy of the recycling process, ensuring compliance with relevant laws and standards, reducing management and operating costs, and enhancing the environmentally friendly disposal of used batteries. Starting in 2027, battery passports will be required in the EU, which may promote the adoption of blockchain. However, experts also point out that blockchain technology is still in the early stages of development, with technological stability and scalability needing further improvement, which may explain why it is not widely adopted by EV and EV battery manufacturers.

Barriers to blockchain implementation in EV battery recycling. Barriers to blockchain implementation include privacy concerns, as publicly sharing battery usage data could reveal private information such as vacation times or daily travel distances. One expert believed that the Manufacturing Execution System (MES) of their company and their suppliers are sufficient to achieve traceability. Additionally, blockchain technology is energy-intensive and inefficient, which negatively impacts battery life and environmental sustainability. While immutability is beneficial, one expert mentioned that it can be achieved more cost efficiently with certificate (hash) chains. Different from a blockchain that establishes decentralized trust in data and transactions without a central authority, certificate hash chains establish hierarchical trust in identities and rely on trusted Certificate Authorities. They can be faster and less energy-intensive. Trust issues also arise, as blockchain does not guarantee data accuracy, suppliers or batteries could provide false or inaccurate information, and immutable bad data remains untrustworthy. Accuracy must be enforced by data validation at the entry point through IoT, independent audits, smart contracts, and governance mechanisms.

In addition, we notice different reverse supply chain models in different countries based on our interviews. The interviewees acknowledged the crucial role of third-party recyclers in the recycling process in the U.S. Very few EV companies have developed their own battery recycling processes to recover valuable materials from used batteries. Most rely on third-party recyclers such as Li-Cycle, Redwood Materials, Ascend Elements, Cirba Solutions, Umicore, and American Battery Technology Company (International Council on Clean Transportation, 2023) to handle the bulk of recycling due to the complexity and cost involved. However, EV makers in China often procure batteries along with recycling services from their battery suppliers such as CATL, BYD, and Ganfeng Lithium. Thus, in China, battery manufacturers act as key catalysts in recycling.

Another finding is that some manufacturers approach battery recovery reactively, aiming only to meet the minimum regional regulatory requirements despite having the global capacity to achieve higher recovery performance. These manufacturers conduct careful cost-benefit analyses when engaging in EV battery recovery.

3. Models and Analysis

3.1 Model Assumptions

We consider a CLSC as consisting of a manufacturer, a retailer, a regulated recycler, and an unregulated recycler. The manufacturer produces both EVs and EV batteries. In this report, a regulated recycler is defined as either an approved business partner of a manufacturer or a licensed recycler.

In the forward supply chain, the manufacturer makes production using raw materials and/or recycled materials. The manufacturer sets the wholesale price ω , and the retailer then sets the retail price p . The demand function for the market without blockchain adoption is $q^N = \alpha - \beta p$, where α represents the market size without blockchain. The manufacturer's unit production cost using new materials is c_M , and the unit production cost savings using recycled materials is Δ .

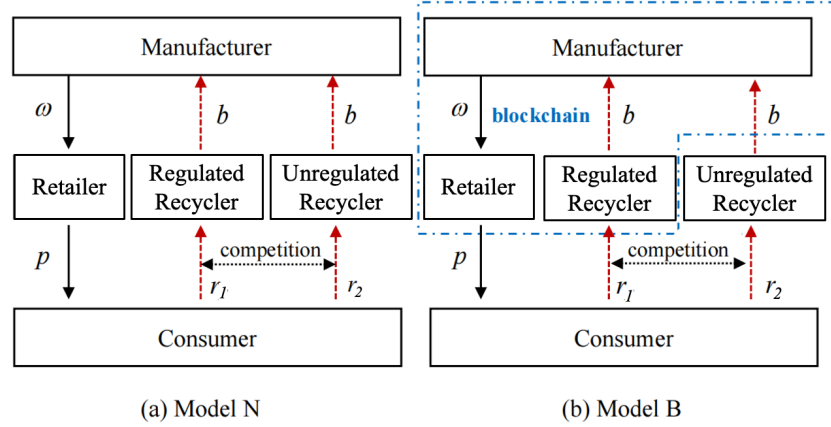
In the reverse supply chain, the manufacturer determines the transfer price b paid to the recycler for collecting and recycling used batteries. The regulated (unregulated) recycler sets the unit buyback price r_1 (r_2) paid to consumers to collect used EV batteries. Due to the lack of emphasis on environmental and safety aspects, the unregulated recycler incurs a lower per-unit recycling cost compared to the regulated recycler (i.e., $c_2 < c_1$). The recycling quantity is affected by the buy-back prices and the competition between recycling channels. Consequently, in Model N (without blockchain adoption), we assume that the regulated recycler's recycling quantity is $Q_1 = a + fr_1 - hr_2$ and the unregulated recycler's recycling quantity is $Q_2 = a + fr_2 - hr_1$, respectively, where a is the initial recycling quantity, f is the own-price coefficient, and h is the cross-price coefficient. We restrict our attention to the practical case that the total recycling quantity is less than the total battery demand (i.e., $Q_1^N + Q_2^N < q^N$ and $Q_1^B + Q_2^B < q^B$, where superscript B represents the model blockchain adoption) and that the own-price coefficient is greater than the cross-price coefficient (i.e., $f > h$), which allows us to derive closed-form results. We assume all recycled materials can be used in production with no waste.

With blockchain adoption (Model B), the manufacturer, the retailer, and the regulated recycler use a third-party blockchain platform. The blockchain platform charges each business user a fee based on the volume of transaction data on the blockchain. That is, each blockchain implementer incurs a per-unit cost of A . The regulated recycler can access more reliable battery information, which helps reduce the per-unit recycling cost of the regulated recycler to be $c_1(1 - \eta)$, where η denotes the relative recycling cost reduction due to blockchain adoption. The regulated recycler's net saving of blockchain adoption is $c_1\eta - A$ per unit. We assume $A < c_1\eta$ to focus on the non-trivial case. Note that the per-unit recycling cost of the unregulated recycler remains the same as the unregulated recycler is not permitted to join the blockchain platform. For retailers, adopting blockchain can increase brand impact, consumer surplus, and market potential (Li et al., 2024).

The demand with blockchain adoption is assumed to be $q^B = (1 + \lambda)\alpha - \beta p$, where $\lambda > 0$ represents the relative increase in market size due to blockchain implementation.

In Model N, none of the supply chain members do not use blockchain technology. In Model B, all supply chain members except the unregulated recycler adopt blockchain technology. The supply chain structures of the two models are depicted in Figure 2.

Figure 2. Supply Chain Structure of Models N and B



We assume that the manufacturer is the market leader while the retailer and recycler are the followers in a Stackelberg game. The sequence of the game is as follows. First, the manufacturer determines the wholesale price of the product (ω) and the transfer payment price (b). Second, the retailer determines the retail price of the product (p). Lastly, the regulated recycler and the unregulated recycler decide their respective buyback prices (r_1) and (r_2) paid to consumers. All supply chain members are profit maximizers. The profits of i under Model j , where the subscript $i \in \{M, R, 1, 2\}$ represents the manufacturer, retailer, regulated recycler, and unregulated recycler, respectively. The superscript $j \in \{N, B\}$ represents the model without blockchain adoption (Model N) and with blockchain adoption (Model B), respectively.

The decision sequence of supply chain members in both Model N and Model B is as follows: Firstly, the manufacturer determines the wholesale price and the transfer price. Secondly, the regulated recycler and the unregulated recycler separately determine their respective buyback prices. Subsequently, the retailer decides on the retail price of the product, ultimately leading to the generation of profits.

3.2 Models

In Model N, supply chain members do not use blockchain technology. The manufacturer's profit function is $\Pi_M^N = \max_{\omega, b} (\omega - c_M)(\alpha - \beta p) + (\Delta - b)(a + fr_1 - hr_2 + a + fr_2 - hr_1)$, the

retailer's is $\Pi_R^N = \max_p(p - \omega)(\alpha - \beta p)$, the regulated recycler's is $\Pi_1^N = \max_{r_1}(b - r_1 - c_1)(a + fr_1 - hr_2)$, and the unregulated recycler's is $\Pi_2^N = \max_{r_2}(b - r_2 - c_2)(a + fr_2 - hr_1)$.

In Model B, the manufacturer, the retailer, and the regulated recycler adopt blockchain technology. The profits of the manufacturer, the retailer, and the regulated recycler under Model B are $\Pi_M^B = \max_{\omega, b}(\omega - c_M - A)((1 + \lambda)\alpha - \beta p) + (\Delta - b)(a + fr_1 - hr_2 + a + fr_2 - hr_1) - A(a + fr_1 - hr_2)$, $\Pi_R^B = \max_p(p - \omega - A)((1 + \lambda)\alpha - \beta p)$, and $\Pi_1^B = \max_{r_1}(b - r_1 - c_1(1 - \eta) - A)(a + fr_1 - hr_2)$. The profit function of the unregulated recycler Π_2^B remains unchanged as in Model N.

3.3 The Impact of Blockchain Technology on Supply Chains

By comparing Model N with Model B, we obtain the following propositions on the impacts of blockchain technology on recycling quantities, buyback prices, profits, and the willingness to adopt blockchain.

Proposition 1. Blockchain adoption increases the total recycling quantity if and only if $A < \frac{c_1\eta}{2}$.

Proposition 1 concludes that, regardless of competition intensity, blockchain adoption will result in higher total recycling quantity ($Q_1^B + Q_2^B < Q_1^N + Q_2^N$) only when the blockchain unit cost is relatively low. The change of total recycling quantity due to blockchain adoption is largely determined by the change of the regulated recycler's recycling quantity.

Proposition 2. With blockchain adoption, the buyback prices, recycling quantities, and profits of the regulated recycler are higher than those of the unregulated recycler, respectively, if and only if $A < c_2 - (1 - \eta)c_1$.

Intuitively, without blockchain adoption, the buyback prices, recycling quantities, and profits of the unregulated recycler are higher than those of the regulated recycler due to the fact that the per-unit recycling cost of the unregulated recycler is lower than that of the regulated counterpart ($k_2 < k_1$). With blockchain adoption, however, the regulated recycler can achieve higher buyback prices, recycling quantities, and profits compared to its opponent, provided its per-unit operational cost is lower.

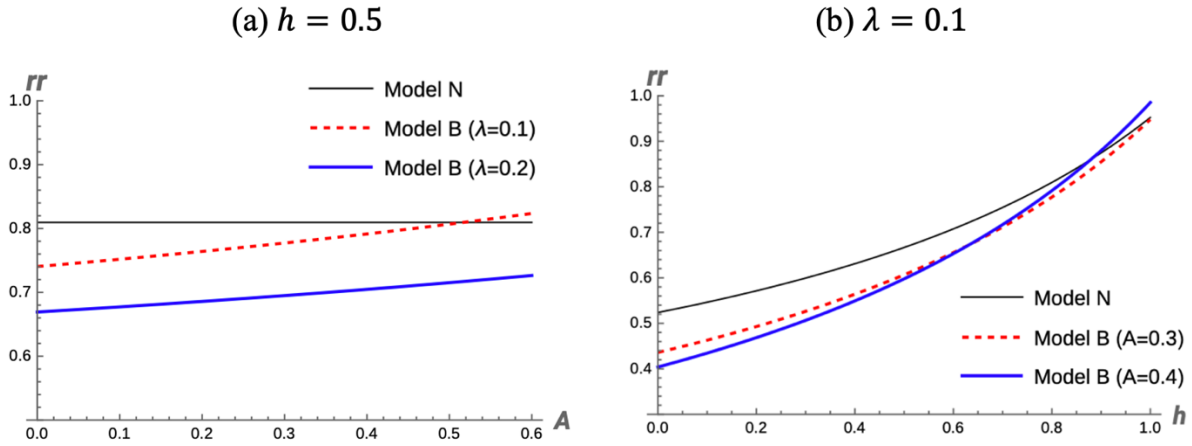
Proposition 3. The regulated recycler will adopt blockchain only if $A < \frac{(6f^2 + fh - 3h^2)c_1\eta}{4(2f^2 - h^2)}$.

Proposition 3 points out that blockchain will increase the regulated recycler's profit only if blockchain cost is sufficiently low, which explains why many multinational companies are hesitant to participate in blockchain due to concerns about the costs associated with participation.

3.4 A Numerical Study on the Recycling Rate

To evaluate the impacts of blockchain on the actual recycling rate, we conduct a numerical study with $\alpha = 5$, $a = f = 1$, $\beta = 0.8$, $c_M = 1$, $\eta = 0.6$, $\Delta = c_1 = 0.4$, and $c_2 = 0.2$. Figure 3(a) illustrates that the recycling rate with blockchain technology ($rr^B = \frac{Q_1^B + Q_2^B}{q^B}$) generally remains below the recycling rate without blockchain ($rr^N = \frac{Q_1^N + Q_2^N}{q^N}$) as the blockchain cost (A) changes. However, when the relative increase in market size due to blockchain (λ) is sufficiently small and the competition within the recycling channel (h) intensifies, the recycling rate with blockchain (rr^B) can increase in A and eventually surpasses the recycling rate without blockchain (rr^N). This suggests that, under certain conditions, blockchain adoption can positively impact the recycling rate. Figure 3(b) demonstrates that the recycling rate, regardless of blockchain adoption, increases with the intensity of reverse channel competition and can exceed the target recycling rate set by the regulator when the competition within the recycling channel (h) is sufficiently high. This is because the intensification of competition can lead to price competition, which may attract consumers to recycle, thereby potentially enhancing the recycling rate. Particularly, the recycling rate with blockchain will gradually be higher than that without blockchain when λ is sufficiently low and A is sufficiently large.

Figure 3. The Impact of Blockchain Cost and Competition Intensity on Recycling Rates



4. Summary and Conclusions

As an emerging technology, blockchain can be a potential solution to the challenges posed by unregulated recyclers within the EV battery recycling supply chain, promising enhanced efficiency for CLSC. Despite its potential benefits, blockchain technology has drawbacks such as high costs and concerns related to information sharing. Therefore, we construct a Stackelberg game model encompassing a manufacturer, a retailer, a regulated recycler, and an unregulated recycler, to scrutinize the impact of unregulated recyclers on the EV battery recycling supply chain and the willingness of supply chain members to adopt blockchain technology.

The key findings of this study are summarized as follows: the buyback prices, recycling quantities, and profits of the unregulated recycler can be higher than those of the regulated recycler. The potential of blockchain technology to address these challenges depends on its associated costs. Low blockchain costs prompt increased adoption by supply chain members, resulting in higher buyback prices and quantities for the regulated recycler, overall boosting recycling quantity and demand. Conversely, high blockchain costs lead to decreased adoption, reducing buyback prices, recycling quantities of the regulated recycler, total recycling quantities, and demand. The regulated recycler is more inclined to adopt blockchain technology when costs are low and competition among recycling channels is intense.

The above findings lead to the following managerial insights and implications. Recognizing blockchain as a promising technological innovation, regulators should actively explore the application of blockchain technology in supply chains. Furthermore, acknowledging the challenges associated with battery recycling, particularly in combating unregulated recyclers amid intense industry competition, regulatory initiatives should be geared towards fostering the widespread adoption of blockchain technology. To gain a competitive edge, regulated recyclers should strive to improve recycling technology to narrow the cost disparity in recovery when compared to unregulated recyclers. Blockchain platforms should strive to make their service more affordable, which not only increases the willingness of supply chain members to adopt the technology but also helps to address the environmental challenges associated with EV batteries.

Appendix A: Propositions and Proofs

Derivation of Model B Equilibrium

According to the backward induction method, we first obtain the retail price by solving the retailer's problem. Letting $\frac{d\pi_R^B}{dp} = 0$ and solving for p , we get $p = \frac{\alpha(\lambda+1)+\beta(A+\omega)}{2\beta}$. This is optimal because $\frac{d^2\pi_R^B}{dp^2} = -2\beta < 0$. Second, given $p = \frac{\alpha(\lambda+1)+\beta(A+\omega)}{2\beta}$, we obtain the buyback prices by solving the two recyclers' problems simultaneously. Letting $\frac{d\pi_1^B}{dr_1} = \frac{d\pi_2^B}{dr_2} = 0$ and solving for r_1 and r_2 simultaneously, we get $r_1^B = \frac{f[-2Af+b(2f+h)-hc_2+2fc_1(\eta-1)]-a(2f+h)}{4f^2-h^2}$ and $r_2^B = \frac{f[b(2f+h)-2fk_2-h(A+c_1-c_1\eta)]-a(2f+h)}{4f^2-h^2}$. They are optimal because $\frac{d^2\pi_2^B}{dr_2^2} < 0$ and $\frac{d^2\pi_1^B}{dr_1^2} < 0$. Third, given the above buyback price, we first obtain the wholesale price by solving the manufacturer's problem. Letting $\frac{d\pi_M^B}{d\omega} = \frac{d\pi_M^B}{db} = 0$ and solving for ω and b simultaneously, we get $\omega^B = \frac{\alpha+c_M\beta+\lambda\alpha}{2\beta}$ and $b^B = \frac{2\Delta+c_2+(1-\eta)c_1}{4} - \frac{a}{2(f-h)}$. One can show they are optimal because the associated Hessian matrix is negative definite. Last, we obtain the following optimal decision variables $r_1^B = \frac{f[(2f-3h)c_2-(6f-h)(1-\eta)c_1]}{4(4f^2-h^2)} - \frac{a(3f-2h)}{2(f-h)(2f-h)^2} - \frac{2Af^2}{4(4f^2-h^2)}$, $r_2^B = \frac{f[(2f-3h)(1-\eta)c_1-(6f-h)c_2]}{4(4f^2-h^2)} - \frac{a(3f-2h)}{2(f-h)(2f-h)^2} - \frac{Afh}{4(4f^2-h^2)}$ and $p^B = \frac{3(1+\lambda)\alpha+(2A+c_M)\beta}{4\beta}$. Substituting r_1^B , r_2^B , and p^B into demand function $q^B = (1+\lambda)\alpha - \beta p^B$, recycling quantities $Q_1^B = a + fr_1^B - hr_2^B$ and $Q_2^B = a + fr_2^B - hr_1^B$ and profit function, we obtain the following outcomes:

$$q^B = \frac{(1+\lambda)\alpha-(2A+c_M)\beta}{4},$$

$$Q_1^B = \frac{f[a+(f-h)\Delta]}{2(2f-h)} + \frac{f(2f^2+3fh-h^2)c_2-f(6f^2+fh-3h^2)(1-\eta)c_1}{4(4f^2-h^2)} - \frac{Af(2f^2-h^2)}{4f^2-h^2},$$

$$Q_2^B = \frac{f[a+(f-h)\Delta]}{2(2f-h)} + \frac{f(2f^2+3fh-h^2)(1-\eta)c_1-f(6f^2+fh-3h^2)c_2}{4(4f^2-h^2)} + \frac{Af^2h}{4f^2-h^2},$$

$$\pi_F^B = \frac{f\{(6f^2+fh-3h^2)(1-\eta)c_1-(2f^2+3fh-h^2)c_2-2(2f+h)(f-h)[a+(f-h)\Delta]+4A(2f^2-h^2)\}^2}{16(4f^2-h^2)^2},$$

$$\pi_I^B = \frac{f\{(6f^2+fh-3h^2)c_2-(2f^2+3fh-h^2)(1-\eta)c_1-4Afh-2(2f+h)[a+(f-h)\Delta]\}^2}{16(4f^2-h^2)^2},$$

$$\pi_R^B = \frac{[(1+\lambda)\alpha-(2A+c_M)\beta]^2}{16\beta} \text{ and}$$

$$\pi_M^B = \frac{((1+\lambda)\alpha-\beta(2A+c_M))^2}{8\beta} + \frac{f\{(f-h)(c_2+(1-\eta)c_1)-2[a+(f-h)\Delta]\}^2}{8(2f-h)(f-h)} + \frac{A^2f(2f^2-h^2)}{(2f-h)(2f+h)} - \frac{Af[a+(f-h)\Delta]}{2f-h} - \frac{Af[fhc_2-(2f^2-h^2)(1-\eta)c_1]}{4f^2-h^2}.$$

Derivation of Model N Equilibrium

The solving procedures are similar to that of Model B and results are the same except that $A = \eta = \lambda = 0$. For example, $\omega^N = \omega^B|_{\lambda=0} = \frac{\alpha+c_M\beta+\lambda\alpha}{2\beta}|_{\lambda=0} = \frac{\alpha+c_M\beta}{2\beta}$.

Proof of Proposition 1

Given that $f > h$, we obtain $Q_1^B + Q_2^B - (Q_1^N + Q_2^N) = -\frac{f(f-h)(2A-c_1\eta)}{4f-2h} > 0$ when $A < \frac{c_1\eta}{2}$. $\clubsuit$

Proof of Proposition 2

$Q_1^B - Q_2^B = -\frac{f(f+h)(A+(1-\eta)c_1-c_2)}{2f+h} > 0$ if and only if $A + (1-\eta)c_1 - c_2 < 0$, or equivalently $A < c_2 - (1-\eta)c_1$. Similarly, $r_1^B - r_2^B = -\frac{f(A+(1-\eta)c_1-c_2)}{2f+h} > 0$ if and only if $A < c_2 - (1-\eta)c_1$.

Moreover, $\Pi_1^B - \Pi_2^B = -\frac{f(f+h)(A+(1-\eta)c_1-c_2)\{2a+(f-h)[2\Delta-c_2-(1-\eta)c_1-2A]\}}{8f^2-2h^2}$. Note that $Q_1^N + Q_2^N > 0$ requires that $2a + (f-h)[2\Delta - c_2 - (1-\eta)c_1 - 2A] > 0$ and recall that that $f > h$. Thus, $\Pi_1^B - \Pi_2^B > 0$ if and only if $A < c_2 - (1-\eta)c_1$. $\clubsuit$

Proof of Proposition 3

$\pi_1^B - \pi_1^N = \frac{f\{[2(2f^2-h^2)(3c_1-c_2-2\Delta+2A)+fh(c_1-3c_2+2\Delta)]-4a(2f+h)-(6f^2+fh-3h^2)c_1\eta\}}{16(4f^2-h^2)^2} \times [4A(2f^2 - h^2) - (6f^2 + fh - 3h^2)c_1\eta]$. The recycling quantity of the regulated recycler and the total recycling quantity should be non-negative: $Q_1^N = \frac{f[2\Delta(2f+h)(f-h)+(\eta-1)(6f^2+fh-3h^2)c_1]}{16f^2-4h^2} + \frac{f[2a(2f+h)+4A(h^2-2f^2)+(2f^2+3fh-h^2)c_2]}{16f^2-4h^2} > 0$, $Q_1^N + Q_2^N = \frac{f[2a-(f-h)(2A+c_1+c_2-2\Delta-c_1\eta)]}{4f-2h} > 0$. Thus, $\{[2(2f^2 - h^2)(3c_1 - c_2 - 2\Delta + 2A) + fh(c_1 - 3c_2 + 2\Delta)] - 4a(2f + h) - (6f^2 + fh - 3h^2)c_1\eta\} < 0$.

Now we obtain that the sign of $\pi_1^B - \pi_1^N$ is determined by the sign of $4A(2f^2 - h^2) - (6f^2 + fh - 3h^2)c_1\eta$. By letting this expression equal 0 and solving for A , we have $A = \frac{(6f^2+fh-3h^2)c_1\eta}{4(2f^2-h^2)}$. Therefore, $\pi_1^B - \pi_1^N > 0$ if and only if $A < \frac{(6f^2+fh-3h^2)c_1\eta}{4(2f^2-h^2)}$. $\clubsuit$

Appendix B: Interview Questions

1. Has your company encountered any challenges in the current EV battery recycling process, such as being unable to trace the source of the waste batteries?
2. Does the existence of unregulated recyclers cause issues in your process of recycling EV power batteries? If so, what are the major issues?
3. Do you know any EV or EV battery manufacturers that employ blockchain technology on EV batteries? If so, what are the purposes of using blockchain technology?
4. It is believed that the benefits of implementing blockchain technology include enhancing consumer trust through traceability, strengthening brand reputation, and increasing market potential. Do you think these benefits exist in the EV battery industry?
5. Is it economically feasible to implement blockchain technology in EV battery manufacturing? What are the main costs?
6. Do you know any EV or EV battery manufacturers that employ blockchain technology to help recycle batteries? If so, what are those companies and what are the main reasons for using blockchain technology? If not, why do not EV or EV battery manufacturers adopt blockchain technology?

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