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Decisions on blockchain adoption and echelon utilization in the closed-loop supply chain for electric vehicles under carbon trading policy

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ABSTRACT

The rapid increase in ownership of new energy vehicles has resulted in a surge in retired power batteries, necessitating the development of an efficient recycling system. Given the application of blockchain in recycling, we analyze the blockchain adoption and echelon utilization decisions for the manufacturer in a closed-loop supply chain under the carbon trading policy and offer four distinct models: 1) without echelon utilization and without blockchain, 2) without echelon utilization but with blockchain, 3) echelon utilization without blockchain, and 4) echelon utilization with blockchain. Equilibrium decisions and profits are derived across these models. The results show: adopting blockchain technology is consistently the optimal choice for the manufacturer irrespective of echelon utilization business, and can enhance the recycling quantity. The manufacturer's decision regarding echelon utilization depends on the recycling competition coefficient between the manufacturer and the echelon utilizer. If the competition coefficient falls below a threshold, the manufacturer engages in echelon utilization business; Otherwise, the manufacturer refrains from engaging in echelon utilization activities. The carbon emission reduction level is independent of the manufacturer's involvement in echelon utilization but is improved by the adoption of blockchain. Additionally, conducting Nash negotiation on profit allocation is beneficial for both members.

1. Introduction

To address environmental pollution, energy crises, and global warming, new energy vehicles (NEVs) powered by rechargeable batteries have emerged as an alternative to gasoline-powered vehicles, representing the future direction for the automotive industry. China, the world's largest NEV market for eight consecutive years, achieved remarkable milestones in 2022, with NEV production and sales reaching 7.058 million and 6.887 million units, respectively, marking year-on-year growth rates of 96.9 % and 93.4 %.[1] As of June 2023, the cumulative quantity of new energy electric vehicles in China has surged to an impressive 12.594 million units.[2] In particular, NEVs have gained popularity on major car-sharing platforms in China [1], such as EVCARD, indicating their widespread adoption.

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[1] https://www.gov.cn/xinwen/2023-01/24/content_5738622.htm.
[2] https://www.gov.cn/govweb/lianbo/bumen/202307/content_6890847.htm.

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With the burgeoning growth of the NEV market, China's production and sales of power batteries have been steadily increasing. In March 2023, China's production of power batteries reached a total of 51.2 GWh, including 32.9 GWh of lithium iron phosphate batteries and 18.2 GWh of ternary batteries.[3] The number of retired power batteries in China is also expected to surge rapidly. It is estimated that by 2025, the retired power batteries are projected to reach 803,600 metric tons (approximately 134.49 GWh), including 100.53 GWh of ternary lithium batteries and 33.96 GWh of lithium iron phosphate batteries.[4] Faced with such a large number of retired power batteries, their scientific recycling and proper disposal have become increasingly crucial. Without effective measures, the improper handling of retired power batteries could pose a significant threat to China's ecological environment. Therefore, it is of utmost importance to study and explore recycling and utilization technologies and strategies for retired power batteries, promote scientific recycling and efficient utilization, reduce resource waste, mitigate environmental risks, and foster the sustainable development of the ecological environment.

Retired power batteries from NEVs possess significant economic value. The first aspect is echelon utilization, which is the process of repurposing retired or non-applicable power batteries from NEVs for use in other application areas after appropriate testing and screening. The remaining capacity of the power batteries is the criterion for judging whether the retired power batteries can be echelon utilized. When the power batteries retain 70–80 % of their original capacity, opportunities for reuse can be found in applications with relatively low safety requirements, such as energy storage, communication base stations, power regulation, and low-speed electric vehicles. Once the remaining capacity of the power batteries drops to 20–60 %, they should be disassembled into individual battery cells, and then recombined into multiple batteries, either in series or parallel. These batteries can be used either by end-users or in microgrids. The second aspect is material recycling. When the remaining capacity of the power batteries falls below 20 %, they are no longer suitable for echelon utilization but are suitable for extracting valuable rare metal materials such as lithium, nickel, cobalt, and manganese [2]. Recycling these materials can generate significant economic value.

In recent years, it has been widely believed that the optimal technical route for retired power batteries is echelon utilization followed by recycling [3]. The echelon utilization market for power batteries shows promising prospects [4], and has become a new focal point in the development of the NEV industry. Electric vehicle companies have recognized the importance of echelon utilization, and have made corresponding arrangements [5]. For instance, ABB Group collaborates with General Motors to echelon utilize power batteries retired from Chevrolet vehicles by manufacturing backup power supplies for households and small businesses, as well as peak shaving and valley filling equipment for clean energy generation.[5] In 2016, BYD Co., Ltd. established a 10 MW, 20 MWh echelon utilization project using retired lithium iron phosphate batteries in the BYD Industrial Park in Longgang, Shenzhen.[6] Bosch Group has utilized retired power batteries from BMW i3 and Active E electric vehicles to build a 2 MW, 2 MWh photovoltaic energy storage system.[7] Therefore, whether from the perspectives of resources, the environment, or industrial development, recycling and comprehensive utilization of retired power batteries are urgent and important.

Blockchain technology's transparency and traceability features help monitor battery lifespan, aiding the development of a well-organized recycling system [6]. It ensures power battery authenticity and legality, reducing the circulation of fake products and protecting consumer rights. Blockchain records battery production, supply chain, and usage data, allowing consumers to access detailed information, which enhances trust in battery quality [7]. Some NEV manufacturers or battery suppliers, including BMW, Volvo, and LG Chemical, are already implementing blockchain to track the power batteries of their vehicles in practice.[8] The power battery industry faces significant challenges related to the handling and echelon utilization of retired power batteries, while blockchain can provide an improved solution. By recording key information such as the source, processing method, and reuse of batteries, blockchain enables companies to have accurate knowledge of the status and performance of retired batteries, maximizing their lifespan and reducing the cost of raw materials [8]. In conclusion, blockchain implementation is an auspicious means of alleviating the challenges related to battery traceability and recycling efficiency.

The manufacturing of power batteries is a major source of carbon emissions. To address this issue and promote sustainable development, the cap-and-trade policy has been widely adopted. This policy is favored for its flexibility and robust enforcement mechanisms. By treating carbon emissions as tradable commodities, the policy employs market mechanisms to regulate company emissions. Initially, companies are granted government-allocated free carbon allowances. If their actual emissions exceed or fall below the set limits, they can adjust by purchasing or selling carbon credits in the carbon trading market. This market-driven approach incentives companies to prioritize carbon emissions management and adopt low-carbon technologies for more effective environmental impact reduction. The integration of blockchain technology in the CLSC of NEV power batteries and decisions regarding their echelon utilization within the framework of carbon trading policies are crucial. These endeavors significantly contribute to sustainable development and environmental protection in the NEV industry, fostering the realization of a low-carbon economy and a sustainable future. However, no prior research has specifically examined the influence of blockchain on power battery recycling and echelon utilization under carbon trading policies. Hence, this study aims to address the following research questions, building upon the aforementioned background:

[3] https://ev-a2z.com/news/china-power-battery-installations-grew-29-7-yoy-in-march-2023/.

[4] https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries.

[5] https://new.abb.com/news/detail/13214/gm-and-abb-demonstrate-chevrolet-volt-battery-reuse-worlds-first-use-of-electric-vehicle-batteries-for-homes.

[6] https://new.qq.com/rain/a/20220727A04I0B00.

[7] https://www.digitaltrends.com/cars/bmw-home-energy-storage-system-i3-electric-car/.

[8] https://www.cnet.com/roadshow/news/volvo-electric-car-batteries-blockchain-materials/.

(1) How does the adoption of blockchain benefit manufacturers in the echelon utilization business, and when is it beneficial for manufacturers to engage in or not engage in echelon utilization? How does echelon utilization benefit manufacturers when adopting or not adopting blockchain?

(2) How should supply chain members formulate equilibrium pricing decisions when the manufacturer engages in or does not engage in echelon utilization? Does the adoption of blockchain influence equilibrium pricing decisions?

(3) Can the echelon utilizer and the manufacturer achieve coordination?

This paper focuses on the adoption of blockchain technology and decision-making regarding echelon utilization within the closed-loop supply chain of power batteries under the framework of carbon trading policies. Considering the background of carbon trading policies, we examine a power battery closed-loop supply chain comprising an echelon utilizer and a manufacturer. Four models are constructed and solved for scenarios where the manufacturer has or does not have echelon utilization business and adopts or does not adopt blockchain. We determine the equilibrium pricing decisions, equilibrium carbon emission reduction levels, and equilibrium profits for these scenarios. The manufacturer's blockchain adoption and echelon utilization decisions are obtained through numerical analysis and profit comparison. By analyzing the effects of key parameters on carbon emission reduction levels, market demand, total recycling quantity, and profits of each member, we derive the following management insights:

Firstly, the adoption of blockchain consistently results in an increased profit for the manufacturer. Blockchain enhances the carbon emission reduction level, stimulates market demand, and increases recycling quantity. Therefore, the power battery manufacturer involved in recycling should actively participate in blockchain development.

Secondly, when contemplating echelon utilization, the manufacturer should evaluate the competition coefficient with the echelon utilizer. If the coefficient is low, participation is recommended; If high, abstaining is wise. Therefore, when deciding on echelon utilization, factors such as competition coefficient, cost-effectiveness, resource allocation, and expertise should be considered. Only when the competition coefficient is suitable and the benefits are significant should the manufacturer engage in echelon utilization business.

Thirdly, the equilibrium carbon emission reduction level initially increases, then decreases with the rising carbon trading price. However, increasing the government carbon quota steadily boosts the manufacturer's profit. Hence, solely raising the carbon trading price does not guarantee emission reductions, necessitating an appropriate carbon quota and carbon trading price to benefit the manufacturer.

Finally, in analyzing the coordination between the manufacturer and the echelon utilizer, it is observed across all scenarios that the profits of both CLSC parties are higher after Nash bargaining compared to their profits before bargaining. This suggests that conducting Nash negotiation on profit allocation is beneficial for both the manufacturer and the echelon utilizer. As the game leader, the manufacturer should grant appropriate bargaining power to the echelon utilizer to facilitate acceptance of the integration.

The contributions of this paper: Firstly, prior studies have primarily focused on the EV manufacturer's decisions regarding the recycling of retired power batteries, neglecting the aspect of echelon utilization with blockchain technology. In contrast, our study examines the manufacturer's operational decisions involving both echelon utilization and blockchain, two essential factors commonly present in retired power battery recycling and utilization practices. Specifically, we investigate the manufacturer's optimal blockchain traceability level. Secondly, we address this gap by examining the issue within the context of the carbon trading policy. Specifically, we investigate the manufacturer's optimal decisions regarding carbon emission reduction, considering the integration of echelon utilization and blockchain adoption, and derive novel and significant analytical results that not only contribute to the pertinent literature but also provide suggestions for the government to achieve carbon neutrality. Lastly, we examine the coordination between the manufacturer and the echelon utilizer. We provide a comprehensive understanding of how collaboration between these stakeholders can be optimized to enhance efficiency and sustainability in the management of retired power batteries.

The subsequent sections of this paper are structured as follows: Section 2 offers a comprehensive review of relevant literature. Section 3 outlines the problem, notations, and assumptions. Section 4 develops models, provides solutions, analyzes and compares the equilibrium outcomes for four different modes. Additionally, this section analyzes the coordination between the manufacturer and the echelon utilization enterprise. Section 5 conducts numerical studies and provides managerial insights. Finally, in Section 6, the paper culminates with a conclusion and a discussion of prospects for future research.

2. Literature review

This section provides a comprehensive review from three aspects: power battery CLSC, the application of blockchain in CLSCs, and CLSCs under the carbon trading policy.

2.1. Research on CLSCs

Closed-loop supply chain (CLSC) is a system that manages the entire process from raw material production to product use and remanufacturing, aiming to reduce waste and environmental impact. With increasing environmental awareness and social responsibility, CLSC or green supply chain has garnered growing attention. For example, [9] explored how members of low-carbon CLSCs can effectively achieve carbon neutrality and waste recycling in the era of low-carbon circular economy. The results indicate that under different subsidy conditions, leading enterprises should choose suitable recycling modes to maximize social welfare, while the subsidy rate provided by the government decreases as the altruism level of leading enterprises increases. [10] investigated the information-sharing strategies in a CLSC consisting of three levels and two channels. By employing game theory models, they found that retailers' inclination towards voluntary information sharing and the most effective methods are significantly influenced by the recycling efficiency of suppliers and the nonlinear production costs of manufacturers.

This paper focuses on the CLSC of automotive power batteries, with particular emphasis on two topics: (1) power battery echelon utilization, and (2) recycling mode selection within power battery CLSCs. Regarding power battery echelon utilization, [11] proposed a CLSC model for electric vehicle batteries involving a battery manufacturer and a remanufacturer, and they determined that battery recycling and reuse effectively reduced material consumption and environmental impact, but may not generate economic benefits. Additionally, [5] established a two-stage CLSC model for the utilization of secondary batteries, which encompassed a battery manufacturer, secondary users, and government involvement. Their findings indicated that the government should contemplate offering subsidies in cases where the recycled batteries retained a high residual charge or the remanufacturing rate was low. [12] utilized the Stackelberg model to analyze the recycling and echelon utilization of power batteries, finding that government intervention, especially through the development of mature dismantling technology and increasing carbon tax rates, could effectively reduce the environmental footprint of products and promote an increase in the recycling rate.

In terms of recycling mode selection within power battery CLSCs, [13] evaluated six recycling channel strategies under a reward-penalty mechanism, identifying the simultaneous recovery mode by the manufacturer and retailer as advantageous. [14] investigated profit allocation and pricing strategies for CLSC members under different scenarios of government subsidy absence or presence. [15] conducted a comparative analysis of six recycling modes, assessing their societal, economic, and environmental implications within a reward-penalty framework. Their findings favored the manufacturer and retailer's joint recovery approach as the most effective in achieving the highest recycling rate and overall social welfare. [16] explored optimal recycling strategies across four alliance recycling modes for power batteries, operating within the framework of a deposit refund system. Their analysis revealed the comprehensive mode as the most advantageous alliance recycling approach, particularly in scenarios marked by significant recycling competition. However, in cases with less intense recycling competition, the alliance mode involving the battery manufacturer emerged as the optimal choice. [17] studied optimal pricing strategies for electric vehicle power batteries across three distinct recycling channels, considering varying government subsidy scenarios. Their recommendations emphasized the importance of increasing government subsidies for EV battery recycling to incentivize EV companies to actively participate in and take responsibility for battery recycling endeavors. [18] formulated seven recycling modes under three government policies and considered the secondary utilization of waste power batteries. They compared social welfare and analyzed stakeholder decision-making in CLSCs under different recycling modes, and found that the alliance recycling mode had the ability to achieve the highest social welfare.

Based on the above literature, we observe that previous studies primarily focused on the selection of recycling modes. In contrast, our work makes two distinct contributions. Firstly, we investigate the decision-making process of manufacturers regarding echelon utilization. Manufacturers often adopt this practice to leverage their knowledge about their own batteries and gain cost advantages through echelon utilization.[9] Secondly, we explore the adoption of blockchain technology and derive new findings, such as the superiority of blockchain adoption for manufacturers regardless of whether they engage in echelon utilization.

2.2. Research on the application of blockchain in CLSCs

Blockchain is a sequential chain-like data structure that ensures immutability and tamper-proof characteristics through cryptography [19]. Blockchain technology has been widely applied in fields such as intelligent transportation [20], smart healthcare [21], reinsurance design [22], and supply chain finance [19].

In the domain of supply chain management, blockchain technology has also been explored in recent years. For instance, [8] proposed a novel approach to optimize waste recycling and management processes through blockchain technology, aiming to enhance monitoring, reduce costs, and establish a citizen reward mechanism to improve the efficiency and transparency of the entire solid waste recycling and management process. [23] explored the issue of manufacturers using blockchain technology to verify product recycling information in the presence of both original and green consumers in the market. The results indicate that the adoption pattern of manufacturers depends on blockchain expansion costs and verification rates, and when the verification rate is low, adopting a third-party blockchain platform may be more advantageous. [24] discovered that manufacturers may face differing impacts on grey market entry when adopting blockchain, depending on foreign market costs and product quality. Those with a strong market position and high-quality products are more likely to embrace blockchain technology. [25] examined a global supply chain model involving a manufacturer and a retailer. They found that high consumer distrust discourages companies from adopting blockchain. However, in cases where blockchain technology is adopted, it can help minimize the negative environmental impact. [26] studied the impact of blockchain technology on remanufacturing mode selection in competitive remanufacturing supply chains. They found that blockchain technology enhances sales of remanufactured products in competitive supply chains, particularly when costs are low and information disclosure is minimal.

In CLSCs, blockchain ensures product quality, consumer trust, and risk mitigation. For example, [27] analyzed a remanufacturer that utilizes blockchain technology to collect old products from consumers or allow them to exchange old products for new ones. They discovered that blockchain improves the quality of remanufactured products, benefiting both the remanufacturer and consumers. [28] established a CLSC composed of manufacturers and online platforms and studied the choice of online platform sales format after introducing blockchain technology. They found that blockchain enhances brand reputation and positively impacts demand in CLSCs with manufacturers and online platforms. [29] investigated the optimal integration of blockchain technology with platform sales

[9] https://new.qq.com/rain/a/20220525A05C2000.

models. They revealed that blockchain builds consumer trust in platform recycling, leading to stable cooperation between online platforms and manufacturers. [30] studied the influence of brand advantage, patent licensing fees, and blockchain on the choice of remanufacturing modes for manufacturers and remanufacturers. They observed that brand advantage influences manufacturers' mode selection, while blockchain affects remanufacturers' mode selection. [31] investigated the motivation for the adoption of blockchain by members of the remanufacturing supply chain based on consumer risk aversion and quality distrust in purchasing remanufactured products. They revealed that blockchain adoption by members depends on the level of risk aversion among customers and the quality of remanufactured products. [32] considered the low consumer willingness to pay for remanufactured products and constructed four models of two sales channels for original equipment manufacturers (OEMs) with and without blockchain technology. The study found that OEMs should only adopt blockchain if consumers value remanufactured product evaluations and the cost is reasonable. [33] explored the integration of remanufacturing and blockchain within the framework of carbon trading policies. They found that in scenarios characterized by reselling or market modes, when the carbon emission intensity is low, manufacturers may opt not to adopt blockchain, whereas in high carbon emission intensity situations, blockchain adoption becomes advantageous. [34] focused on the sales model selection issue of electronic platforms in CLSCs. The conclusion shows that the application of blockchain improves the efficiency of CLSCs, and enhances brand reputation, promoting the improvement of economic, environmental, and social performance. [35] developed a game theory model to investigate the incentives for CLSC participants to adopt blockchain technology to mitigate perceived risks of remanufacturing. They examined consumer preferences for new and remanufactured products under different blockchain adoption strategies and found that choosing the appropriate blockchain adoption strategy can increase the remanufacturing rate. [36] studied the impact of blockchain technology adoption on environmental effects and company profitability in CLSCs related to lithium-ion batteries. The conclusion is that the application of blockchain technology in the production and recycling of lithium-ion batteries depends on operational costs and energy-saving benefits.

While prior studies have predominantly concentrated on the utilization of blockchain technology, our research redirects the focus towards the decision-making mechanisms of manufacturers engaged in power battery recycling and echelon utilization, integrating blockchain technology into the framework. Our study produces innovative findings, particularly emphasizing the consistent advantage of adopting blockchain technology within this domain.

2.3. Research on CLSCs under the carbon trading policy

As governments worldwide aim for carbon neutrality, research on the operations of CLSCs under carbon cap-and-trade policies is increasingly important. [37] delved into an investigation of the remanufacturing process within a CLSC operating under a carbon trading policy. Their findings underscored the effectiveness of remanufacturing within a CLSC in terms of reducing carbon emissions and bolstering profits. [38] undertook an exploration of decisions pertaining to carbon emission reduction and end-of-life product recycling within a CLSC operating under the umbrella of a carbon trading policy. Their analysis revealed that, under certain specific conditions, opting for the manufacturer's recovery mode emerged as the optimal choice for simultaneously achieving carbon emission reduction and profit maximization. [39] studied electric vehicle power battery recovery in CLSC and concluded that simultaneous recovery by retailers, recyclers, and echelon utilization businesses is optimal under certain thresholds. [40] studied the impact of battery range and advertising effects on recovery channel selection under carbon trading policy. The results revealed that different recovery channels have no effect on pricing and market demand. The total profit functions of retailers and manufacturers have a "U"-shaped nonlinear relationship with battery range, while they have a positively correlated linear relationship with advertising effects. [41] considered consumer inconvenience regarding recovery channels under carbon trading policy and proposed a multi-recovery structure model to study the manufacturer's optimal reduction strategy. They found that manufacturers adjust their reduction strategies based on carbon quotas, carbon trading prices, and consumer preferences. [42] studied three recovery modes and optimal recovery strategies considering emission reduction and echelon utilization under carbon trading. They found that when the recovery competition coefficient is low, the joint recovery mode is optimal; Otherwise, the single-channel recovery mode is optimal. [43] proposed regulatory solutions for power battery recovery and demonstrated the effectiveness of reward-punishment and deposit refund mechanisms. [44] studied four power battery recovery modes considering carbon trading policy and echelon utilization. The results showed that when the competition intensity is lower but the recycling price sensitivity is greater than some thresholds, manufacturers should choose simultaneous recovery by retailers, echelon utilization businesses, and battery recyclers. [45] investigated the impact of carbon emission reduction tools on blockchain technology in the NEV supply chain. They found that under a carbon tax regime, carbon emission reduction encourages battery suppliers to adopt blockchain technology, while under carbon emission quota trading regulations, manufacturers' investment decisions are influenced by unit outsourcing costs and the performance of blockchain technology. [46] addressed the design of CLSCs under carbon trading policy, aimed at reducing carbon emissions and meeting personalized delivery service demands, by proposing a fuzzy mathematical model for the p-hub median problem with multiple service levels and uncertainties.

This paper investigates the operational decision-making in the CLSC of NEV power batteries, considering carbon emission reduction investments under carbon trading policy. By addressing real-world considerations, the study focuses on the operational decision-making within the CLSC under the carbon trading policy for NEVs, contributing to the existing body of research on NEV supply chains. The introduction of blockchain technology into power battery CLSCs and the exploration of echelon utilization represent important dimensions of this research.

2.4. Research gap

Table 1 illustrates the distinctions between our study and the existing literature.

The existing literature has laid a solid theoretical and model foundation for our study. However, there are still several research gaps that need further exploration, as outlined below.

Firstly, there is a lack of research on blockchain in the CLSCs of NEV power batteries. Previous studies such as [8,27-30,35] have investigated the application of blockchain in CLSCs of general commodities. However, the characteristics of NEV power battery CLSCs differ from traditional ones. Therefore, exploring the impact of blockchain adoption decisions on the performance of NEV power battery CLSCs is worthwhile. Secondly, there is a lack of research on the echelon utilization of power batteries. Echelon utilization of power batteries is crucial for promoting renewable energy and sustainable utilization, reducing reliance on finite resources. For example, [45] studied the impact of blockchain adoption decisions on NEV power battery CLSCs under different carbon policies, but none considered the echelon utilization of power batteries. Therefore, exploring the echelon utilization of power batteries in NEVs holds significant research value. Lastly, there is a lack of relevant research on operational strategies for NEV power battery CSLCs under carbon trading policies. Most existing literature has focused on operational strategies of power battery CLSCs under government subsidies, such as [12,13,15], without considering carbon trading policies. Given the current context of carbon peaking and neutrality targets, studying operational strategies under carbon trading policies is essential.

In contrast, our study examines the manufacturer's operational decisions within the context of carbon trading policies, involving both echelon utilization and blockchain – two essential factors commonly found in retired power battery recycling and utilization practices. Specifically, we investigate the manufacturer's optimal level of blockchain traceability and its decisions regarding carbon emission reduction, and derive novel and significant analytical results.

3. Problem description

This study primarily focuses on NEV companies possessing power battery production technology or collaborating with power battery manufacturers, collectively referred to as "manufacturers." The recycling and utilization of retired power batteries has emerged as a prominent issue, with echelon utilization companies playing a crucial role. However, the echelon utilization phase of power batteries faces challenges such as low efficiency in diagnosing and screening retired batteries, and incomplete storage of battery information and data. Introducing blockchain technology by a manufacturer enables the tracing of the entire lifecycle of power batteries, standardizes consumer recycling behavior, and reduces the cost of retesting and evaluating batteries during the echelon utilization phase. This facilitates rapid and accurate screening and grouping of retired power batteries, promoting their safe and efficient application in subsequent scenarios. Consequently, this enhances their value utilization, prevents resource waste, and allows consumers to verify the authenticity and origin of the batteries used. This, in turn, establishes trust between enterprises and users.

Before modeling, we provide the symbols used throughout the paper in Table 2.

We establish a CLSC system for NEV power batteries. This system comprises several key actors: a manufacturer, an echelon utilizer, consumers, and echelon users (e.g., photovoltaic companies). The holistic structure of the power battery CLSC is visually depicted in Fig. 1.

Under the carbon trading policy, the manufacturer obtains complimentary carbon emission quotas for its manufacturing and engages in carbon emission quota trading. In the forward supply chain, the manufacturer employs raw and recycled materials to produce power batteries, which are subsequently distributed directly to consumers. In the reverse supply chain, if the manufacturer does not have echelon utilization businesses, the responsibility for retired power battery collection falls upon the echelon utilizer. However, in scenarios where the manufacturer has echelon utilization businesses, the manufacturer and the echelon utilizer jointly handle the collection task. After the manufacturer (e.g., NIO) and the echelon utilizer (e.g., CATL) collect retired batteries from consumers, they test the remaining battery capacity to identify those suitable for echelon utilization. These batteries are processed into echelon products and sold in the echelon utilization market. The manufacturer and the echelon utilizer also take responsibility for recycling the echelon utilization products they produce. The batteries that cannot be used in echelon utilization are utilized for material extraction.

Based on this, this paper aims to study the manufacturer's adoption of blockchain technology and decision-making regarding echelon utilization under the carbon trading policy. The specific problems are as follows: (1) Should the manufacturer adopt blockchain when she has or does not have an echelon utilization business, and under what circumstances would adopting blockchain be more advantageous? (2) Should the manufacturer engage in an echelon utilization business when she adopts or does not adopt

Table 1
Comparison of related studies.

Papers	Carbon trading policy	Reverse logistics	Material reusing	Echelon utilization	Blockchain	Endogenous traceability
[33]	√				√	
[8,23,27-30,34,35]		√			√	
[12,13,15]		√	√	√		
[24,39,40,42,43]	√	√	√	√		
[45]	√	√	√		√	√
This paper	√	√	√	√	√	√

Table 2
Notations and descriptions.

Notations	Description
Parameters	
E	Carbon quota (ton CO_2-eq.)
p_c	Carbon trading price (CNY/ton CO2-eq.)
e_m	Carbon emissions per unit of raw material production (ton CO2-eq./unit)
a	Potential market size (unit)
b	Sensitivity of consumers to sales price (unit/CNY)
γ	Sensitivity of consumers to the level of blockchain traceability
c_m	Unit cost of manufacturing power batteries using raw materials (CNY/unit)
c_r	Unit cost of manufacturing power batteries using recycled materials (CNY/unit)
Δ	Unit cost savings for producing new batteries (CNY/unit)
u	Net profit per unit of residual capacity of recycled power batteries in echelon utilization (CNY/unit)
c_s	Unit cost of testing and sorting retired power batteries (CNY/unit)
A	Number of retired power batteries voluntarily returned by consumers (unit)
η	Sensitivity of consumers to the selling price of power batteries (unit/CNY)
δ	Competition coefficient among recycling entities
h	Carbon emission reduction investment cost coefficient
g	Blockchain traceability level investment cost coefficient
k	Proportion of recycled batteries available for echelon utilization
ϕ	Cost-sharing proportion of blockchain traceability investment
Decision variables	
e^j	Carbon emission reduction level (ton CO2-eq./unit)
t^j	Blockchain traceability level, referring to the credibility of the product traceability information [47].
p_n^j	Retail price per unit of power battery (CNY/unit)
p_b^j	Price paid by the manufacturer to consumers for retired power batteries (CNY/unit)
p_m^j	Price paid by the manufacturer to the echelon utilizer for recycling (CNY/unit)
p_u^j	Price paid by the echelon utilizer to consumers for retired power batteries (CNY/unit)
Functions	
D^j	Market demand for power batteries
π_i^j	Profit of different entity i under scenario j
Q_i^j	Quantity of retired power batteries recovered by different entity i under scenario j
Superscripts	
i	Supply chain member, $i = \{m, u\}$, where $i = m$ represents the manufacturer and $i = u$ represents the echelon utilizer.
j	$j = \{O, MO, B, MB\}$, where $j = O$ represents the manufacturer without echelon utilization business and not adopting blockchain, $j = B$ represents the manufacturer without echelon utilization business but adopting blockchain, $j = MO$ represents the manufacturer with echelon utilization business but not adopting blockchain, and $j = MB$ represents the manufacturer with echelon utilization business and adopting blockchain.

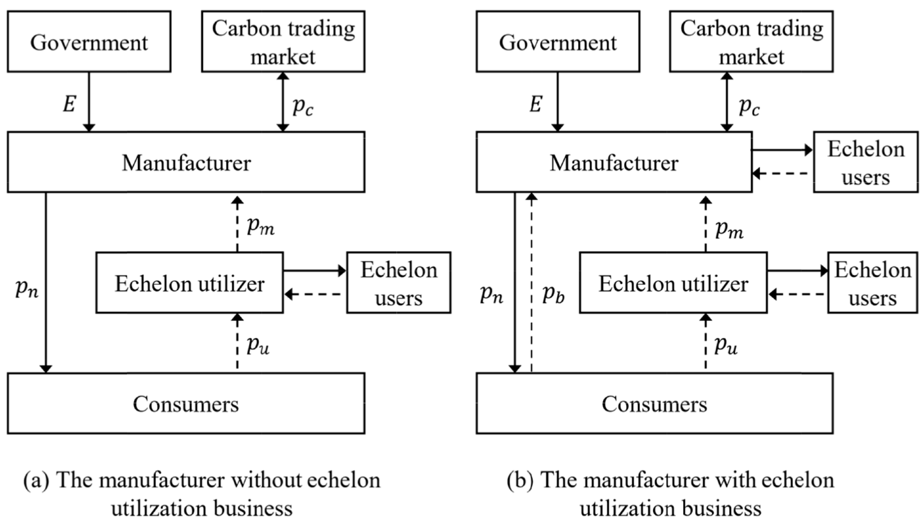

Fig. 1. Power battery CLSC.

blockchain, and under what circumstances would engaging in an echelon utilization business be more advantageous? (3) Can the echelon utilizer and the manufacturer achieve coordination?

For the modeling and analysis in the subsequent sections, we make the following assumptions based on practical considerations:

(1) Power batteries, whether newly manufactured or made from recycled materials, have identical quality and performance, and are sold at uniform prices within the same market [13]. Both the power batteries sold in the market and those collected for recycling are of the same type [15].

(2) Decisions are considered within a stable single period. When the price, demand, and recycling rate of a product stabilize, it is considered the mature stage of the product lifecycle. For power batteries, the manufacturing, sales, recycling, echelon utilization, and reuse processes are considered within one cycle [43].

(3) Consumer demand for power batteries can indirectly substitute the demand for NEVs, and the adoption of blockchain can increase the demand [45]. Therefore, the demand function for power batteries when blockchain is not adopted is given by: $D^j = a - bp_n^j$ ($a > b > 0$); and the demand function for power batteries when blockchain is adopted is given by: $D^j = a - bp_n^j + \gamma t^j$.

(4) Based on the extended producer responsibility (EPR) system, the manufacturer is responsible for the entire lifecycle of her products, including the collection and disposal of waste. The manufacturer invests in carbon emission reduction technologies to reduce carbon emissions during the production process, with an investment cost of $he^2/2$. Additionally, the manufacturer has to bear the adoption cost of blockchain, $gt^2/2$. To ensure a fair distribution of profits among supply chain members, after the manufacturer adopts blockchain, the echelon utilizer should share the blockchain cost, allowing both the manufacturer and the echelon utilizer to bear the investment cost of blockchain, with the manufacturer bearing a proportion ϕ of the blockchain investment cost [32].

(5) To enhance resource utilization efficiency, it is assumed that recycled power batteries undergo echelon utilization before being dismantled, processed, extracted, and recycled. It is further assumed that echelon utilization activities are only applied to power batteries used for power generation and energy storage. In this scenario, echelon utilization profits depend on the remaining capacity of retired power batteries. The net profit per unit of residual capacity of recycled power batteries in echelon utilization is denoted as $u = \lambda\widehat{L}$, where $\widehat{L}$ represents the remaining capacity of the retired power batteries, and $\widehat{L}$ follows a normal distribution with a mean of $\mu\widehat{L}$ and a variance of $\sigma\widehat{L}^2$. λ represents the net profit obtained per unit of residual capacity of retired power batteries in echelon utilization [13].

(6) Recycling quantity of retired power batteries is $Q_i^j = A + \eta p_x^j - \delta p_z^j$ ($\eta > \delta > 0, x = u,b, z = u,b, x \neq z$) [13].

(7) Throughout the lifecycle of power batteries, carbon emissions are mainly concentrated in the manufacturing process. Therefore, this study assumes that the government implements carbon trading policies only for the manufacturer. Power batteries produced using recycled materials have equivalent quality and initial carbon emissions to those produced using new materials [38].

(8) The manufacturer and the echelon utilizer have the ability to sort batteries, and the unit cost of testing and sorting is the same for both entities. In general, the testing cost is not included in the production cost, and after adopting blockchain, the corresponding testing cost is reduced, resulting in improvements to cost, reliability, flexibility, sustainability, and risk reduction, thereby enhancing recycling efficiency. Therefore, it is assumed that the testing cost is reduced after adopting blockchain.

(9) It is assumed that the echelon utilizer and the manufacturer have the same echelon utilization rate $k(0 < k < 1)$ for the retired power batteries.

(10) The echelon utilization market is different from the general reuse market, and the demand for high-energy–density retired power batteries in the echelon utilization market does not affect the demand for new power batteries in the NEV market. Additionally, it is assumed that all discarded echelon utilization products can be fully recycled.

(11) The cost savings per unit of power battery produced using recycled materials compared to using new materials is $\Delta = c_m - c_r > 0$. To ensure the economic feasibility of the retired power battery recovery and echelon utilization process, it is assumed that $\Delta > p_m$, $ku - c_s + p_m^j - p_u^j > 0$ represents a cost advantage for this process.

4. Modeling and analysis

4.1. Blockchain adoption decision of the manufacturer without echelon utilization business

4.1.1. Without blockchain adoption

When the manufacturer without echelon utilization business does not adopt blockchain, the market demand is $D^O = a - bp_n^O$, and the recycling quantity is $Q_u^O = A + \eta p_u^O$. The game is played in the following order: the manufacturer first decides the retail price p_n^O, the carbon emission reduction level e^O, and the recycling price p_m^O. Then, the echelon utilizer decides the recycling price p_u^O based on the manufacturer's decision. The profit functions are:

$$\pi_m^O = (p_n^O - c_m)D^O + (\Delta - p_m^O)Q_u^O - p_c[D^O(e_m - e^O) - E] - \frac{1}{2}h(e^O)^2 \tag{1}$$

$$\pi_u^O = (ku - c_s + p_m^O - p_u^O)Q_u^O \tag{2}$$

In function (1), the term $(p_n^O - c_m)D^O$ represents the net profit from selling all new power batteries $(\Delta - p_m^O)Q_u^O$ signifies the cost savings derived from selling new power batteries made from recycled materials, and $-p_c[D^O(e_m - e^O) - E] - h(e^O)^2/2$ is the net benefit of implementing the carbon emission reduction strategy under the carbon trading policy. In function (2), the term $(ku - c_s + p_m^O - p_u^O)$

Q_u^O is the net profit generated from all retired power batteries collected by the echelon utilizer. By solving (1) and (2) through backward induction, we obtain Proposition 1.

Proposition 1. *Under the carbon trading policy, the optimal decisions for the manufacturer and the echelon utilizer in the case where the manufacturer without echelon utilization business does not adopt blockchain are as follows:*

$$p_n^{O*} = \frac{h(a + bc_m + be_m p_c) - abp_c^2}{b(2h - bp_c^2)},\ e^{O*} = \frac{p_c(bc_m + be_m p_c - a)}{bp_c^2 - 2h},\ p_m^{O*} = \frac{U}{2},$$
$$p_u^{O*} = \frac{\Delta\eta - \eta c_s + k\eta u - 3A}{4\eta},\ \pi_m^{O*} = p_c E - \frac{h(bc_m + be_m p_c - a)^2}{2b(bp_c^2 - 2h)} + \frac{U}{8},\ \pi_u^{O*} = \frac{U}{16},$$

where $U = (A + \Delta\eta + ku\eta - \eta c_s)^2/\eta > 0$.

To ensure non-negative values for the variables, the following conditions must be satisfied: $h > bp_c^2/2$, $bc_m + be_m p_c - a < 0$, $0 < c_m < a/b$, $0 < p_c < (a - bc_m)/be_m$, $h > abp_c^2/(a + bc_m + be_m p_c)$, $\Delta > 2A/\eta$, and $\max\{(3A - \Delta\eta + \eta c_s)/k\eta, 0\} < u < (\Delta\eta + \eta c_s - A)/k\eta$.

Please refer to Appendix A.1 for the proof.

Corollary 1. *(1)* $\frac{\partial e^{O*}}{\partial h} < 0$, $\frac{\partial e^{O*}}{\partial e_m} < 0$; *(2)* $\frac{\partial p_m^{O*}}{\partial k} < 0$, $\frac{\partial p_u^{O*}}{\partial k} > 0$, $\frac{\partial \pi_m^{O*}}{\partial k} > 0$, $\frac{\partial \pi_u^{O*}}{\partial k} > 0$; *(3)* $\frac{\partial p_m^{O*}}{\partial u} < 0$, $\frac{\partial p_u^{O*}}{\partial u} > 0$, $\frac{\partial \pi_m^{O*}}{\partial u} > 0$, $\frac{\partial \pi_u^{O*}}{\partial u} > 0$; *(4)* $\frac{\partial p_m^{O*}}{\partial \eta} > 0$, $\frac{\partial p_u^{O*}}{\partial \eta} > 0$, $\frac{\partial \pi_m^{O*}}{\partial \eta} > 0$, $\frac{\partial \pi_u^{O*}}{\partial \eta} > 0$.

Please refer to Appendix A.2 for the proof.

Corollary 1 (1) suggests that the carbon emission reduction level decreases as the carbon emission reduction investment cost coefficient and the initial carbon emission rise. This is because the manufacturer may face technological feasibility constraints when implementing carbon reduction technologies. As the initial carbon emission increases, the company requires greater investment in carbon reduction to achieve the same level of carbon emission reduction. This leads to an increase in the carbon reduction investment cost. As the carbon reduction investment cost coefficient increases, the manufacturer bears a higher carbon reduction cost, resulting in an increased production cost for the company. Consequently, the motivation for carbon reduction decreases.

Corollaries 1 (2)-(3) illustrate that as the proportion of echelon-utilizable batteries or the net profit obtained per unit remaining capacity increases, the recycling price offered by the manufacturer to the echelon utilizer decreases. Nonetheless, concurrently, the echelon utilizer's recycling price, and profits of the manufacturer and the echelon utilizer increase with the proportion of echelon utilization. As the echelon-utilizable battery proportion or the net profit per unit remaining capacity increases, the value of collected batteries in the hands of the echelon utilizer increases, which motivates the echelon utilizer to pay a higher recycling price to acquire more reusable resources. Meanwhile, the manufacturer may lower the recycling price considering the residual value and cost of the used batteries. The ability to reuse the retired echelon utilization products allows the manufacturer to save on manufacturing costs.

Corollary 1 (4) highlights that as the recycling price sensitivity for consumers increases, recycling prices and profits of both the manufacturer and the echelon utilizer increase. An increase in recycling price sensitivity means that consumers place a higher degree of importance on recycling prices for used power batteries. This heightened consumer concern motivates the echelon utilizer to raise its recycling price to attract greater consumer participation in recycling activities. Consequently, the echelon utilizer can generate more economic benefits from the echelon utilization of spent power batteries. Furthermore, the manufacturer may increase her recycling price to encourage the echelon utilizer to collect more batteries. The ability to reuse retired echelon utilization products allows the manufacturer to reduce the manufacturing cost and enhance her profit.

4.1.2. With blockchain adoption

When the manufacturer without echelon utilization business adopts blockchain, the market demand is $D^B = a - bp_n^B + \gamma t^B$, and the recycling quantity is $Q_u^B = A + \eta p_u^B$. The manufacturer first decides the retail price p_n^B, carbon emission reduction level e^B, blockchain traceability level t^B, and the recycling price p_m^B offered to the echelon utilizer. Then, based on the manufacturer's decision, the echelon utilizer determines the recycling price p_u^B. The profit functions are:

$$\pi_m^B = (p_n^B - c_m)D^B + (\Delta - p_m^B)Q_u^B - p_c[D^B(e_m - e^B) - E] - \frac{1}{2}h(e^B)^2 - \phi\frac{1}{2}g(t^B)^2 \tag{3}$$

$$\pi_u^B = (ku + p_m^B - p_u^B)Q_u^B - (1 - \phi)\frac{1}{2}g(t^B)^2 \tag{4}$$

In function (3), the term $(p_n^B - c_m)D^B$ represents the net profit from selling all new power batteries, $(\Delta - p_m^B)Q_u^B$ signifies the cost savings derived from selling new power batteries made from recycled materials, $-p_c[D^B(e_m - e^B) - E] - h(e^B)^2/2$ denotes the net benefit of implementing the carbon emission reduction strategy under the carbon trading policy, and $-\phi g(t^B)^2/2$ is the investment cost of blockchain technology borne by the manufacturer. In function (4), $(ku + p_m^B - p_u^B)Q_u^B$ is the net profit generated from all retired power batteries collected by the echelon utilizer, and $-(1 - \phi)g(t^B)^2/2$ represents the investment cost of blockchain technology borne by the echelon utilizer. By solving (3) and (4) through backward induction, we obtain Proposition 2.

Proposition 2. *Under the carbon trading policy, the optimal decisions for the manufacturer and the echelon utilizer in the case where the manufacturer without echelon utilization business adopts blockchain are as follows:*

$$p_n^{B^*}=\frac{h(\gamma^2-bg\phi)(c_m+e_mp_c)+ag\phi(bp_c^2-h)}{h(\gamma^2-2bg\phi)+b^2g\phi p_c^2},\ e^{B^*}=\frac{b\phi p_cG}{h(bp_ce_m+bc_m-a)},\ t^{B^*}=\frac{\gamma G}{g(bp_ce_m+bc_m-a)},$$
$$p_m^{B^*}=\frac{\Delta\eta-ku\eta-A}{2\eta},\ p_u^{B^*}=\frac{\Delta\eta+ku\eta-3A}{4\eta},\ \pi_m^{B^*}=p_cE-\frac{\phi G}{2}+\frac{V}{8},\ \pi_u^{B^*}=\frac{h\gamma^2(\phi-1)G}{2\left[h(\gamma^2-2bg\phi)+b^2g\phi p_c^2\right]}+\frac{V}{16},$$

where $V=(A+\Delta\eta+ku\eta)^2/\eta>0$ *and* $G=\frac{gh(bp_ce_m+bc_m-a)^2}{h(\gamma^2-2bg\phi)+b^2g\phi p_c^2}$.

To ensure that the aforementioned variables are non-negative, the following conditions must be satisfied:
1) $h>bp_c^2/2$, $0<c_m<a/b$, $0<p_c<(a-bc_m)/(be_m)$, $\Delta>2A/\eta$, *and* $\max\{(3A-\Delta\eta)/(k\eta),0\}<u<(\Delta\eta-A)/(k\eta)$;

2) $\begin{cases} abp_c^2/(a+bc_m+be_mp_c)<h\leqslant bp_c^2 \\ g>(h\gamma^2c_m+h\gamma^2e_mp_c)/(ah\phi+bh\phi c_m+bh\phi e_mp_c-ab\phi p_c^2)\end{cases}$ *or* $\begin{cases} h>bp_c^2 \\ g>h\gamma^2/(2bh\phi-b^2\phi p_c^2)\end{cases}$.

The proof is analogous to that of Proposition 1 and is omitted for brevity.

Corollary 2. *(1)* $\frac{\partial e^{B^*}}{\partial h}<0$, $\frac{\partial e^{B^*}}{\partial e_m}<0$; *(2)* $\frac{\partial t^{B^*}}{\partial g}<0$, $\frac{\partial t^{B^*}}{\partial \gamma}>0$, $\frac{\partial t^{B^*}}{\partial \phi}<0$; *(3)* $\frac{\partial p_m^{B^*}}{\partial k}<0$, $\frac{\partial p_u^{B^*}}{\partial k}>0$, $\frac{\partial \pi_m^{B^*}}{\partial k}>0$, $\frac{\partial \pi_u^{B^*}}{\partial k}>0$; *(4)* $\frac{\partial p_m^{B^*}}{\partial u}<0$, $\frac{\partial p_u^{B^*}}{\partial u}>0$, $\frac{\partial \pi_m^{B^*}}{\partial u}>0$, $\frac{\partial \pi_u^{B^*}}{\partial u}>0$; *(5)* $\frac{\partial p_m^{B^*}}{\partial \eta}>0$, $\frac{\partial p_u^{B^*}}{\partial \eta}>0$, $\frac{\partial \pi_m^{B^*}}{\partial \eta}>0$, $\frac{\partial \pi_u^{B^*}}{\partial \eta}>0$.

The proof is analogous to that of Proposition 1 and is omitted for brevity.

The carbon emission reduction level decreases as the emission reduction investment cost coefficient and the initial carbon emission increase, for the same reasons as discussed in Corollary 1 (1). Corollary 2 (2) indicates that the traceability level increases with the consumer's sensitivity to traceability level and decreases with the increase in blockchain investment cost coefficient and blockchain cost-sharing ratio. This is because, as consumers demand higher traceability levels for products, the manufacturer may be more inclined to invest more in the development and application of blockchain. However, the application of blockchain requires a certain cost investment. As the investment cost coefficient rises, the manufacturer allocates increasing funds. Additionally, the manufacturer and the echelon utilizer jointly participate in the implementation of blockchain but bear different proportions of the costs. The echelon utilizer bears lower costs but the manufacturer bears higher costs. Considering cost allocation, the manufacturer may reduce her implementation effort in traceability technology to reduce the investment in improving the blockchain traceability level. Corollaries 2 (3)-(5) indicate that the manufacturer's recycling price offered to the echelon utilizer decreases with the increase in the echelon utilization proportion and the net profit obtained per unit residual capacity. On the other hand, as the echelon utilization proportion and the net profit obtained per unit residual capacity rise, both the echelon utilizer's recycling price and the profits of the manufacturer and the echelon utilizer increase. Moreover, the manufacturer's recycling price offered to the echelon utilizer, the echelon utilizer's recycling price, and the profits of both the manufacturer and the echelon utilizer rise with the recycling price sensitivity of consumers. The reasons for these observations are similar to those discussed in Corollary 1 and will not be reiterated here.

4.2. Blockchain adoption decision of the manufacturer with echelon utilization business

4.2.1. Without blockchain adoption

When the manufacturer with echelon utilization business does not adopt blockchain, the market demand is $D^{MO}=a-bp_n^{MO}$, the manufacturer's recycling quantity is $Q_m^{MO}=A+\eta p_b^{MO}-\delta p_u^{MO}$, and the echelon utilizer's recycling quantity is $Q_u^{MO}=A+\eta p_u^{MO}-\delta p_b^{MO}$. The manufacturer first decides the retail price p_n^{MO}, the carbon emission reduction level e^{MO}, the recycling price for consumers p_b^{MO}, and the recycling price for the echelon utilizer p_m^{MO}. Then the echelon utilizer decides the recycling price p_u^{MO} based on the manufacturer's decision. The profit functions are:

$$\pi_m^{MO}=(p_n^{MO}-c_m)D^{MO}+(\Delta-p_m^{MO})Q_u^{MO}+(\Delta+ku-c_s-p_b^{MO})Q_m^{MO}-p_c\left[D^{MO}(e_m-e^{MO})-E\right]-\frac{1}{2}h(e^{MO})^2 \tag{5}$$

$$\pi_u^{MO}=(ku-c_s+p_m^{MO}-p_u^{MO})Q_u^{MO} \tag{6}$$

In function (5), the term $(p_n^{MO}-c_m)D^{MO}$ represents the net profit from selling all new power batteries, $(\Delta-p_m^{MO})Q_u^{MO}+(\Delta+ku-c_s-p_b^{MO})Q_m^{MO}$ includes the cost savings derived from selling batteries made from recycled materials and the net profit generated from retired power batteries collected by the manufacturer, and $-p_c[D^{MO}(e_m-e^{MO})-E]-h(e^{MO})^2/2$ denotes the net benefit of implementing the carbon emission reduction strategy under the carbon trading policy. In function (6), $(ku-c_s+p_m^{MO}-p_u^{MO})Q_u^{MO}$ is the net profit generated from all retired power batteries collected by the echelon utilizer. By solving (5) and (6) through backward induction, we obtain Proposition 3.

Proposition 3. *Under the carbon trading policy, the optimal decisions for the manufacturer and the echelon utilizer in the case where the manufacturer with echelon utilization business does not adopt blockchain are as follows:*

$$p_n^{MO*} = \frac{h(a + bc_m + be_m p_c) - abp_c^2}{b(2h - bp_c^2)},\ e^{MO*} = \frac{p_c(a - bc_m - be_m p_c)}{2h - bp_c^2},\ p_b^{MO*} = \frac{1}{2}\left(\Delta + \frac{A}{\delta - \eta} - c_s + ku\right),$$
$$p_m^{MO*} = \frac{1}{2}\left(\Delta + \frac{A}{\delta - \eta} + c_s - ku\right),\ p_u^{MO*} = \frac{A(\delta - 3\eta) + (\delta^2 - \eta^2)(c_s - \Delta - ku)}{4\eta(\eta - \delta)},$$
$$\pi_m^{MO*} = p_c E - \frac{h(bc_m + be_m p_c - a)^2}{2b(bp_c^2 - 2h)} - \frac{(\delta + 3\eta)R}{8\eta},\ \pi_u^{MO*} = \frac{[A + (\delta - \eta)(c_s - ku - \Delta)]^2}{16\eta},$$

where $R = [A + (\delta - \eta)(c_s - ku - \Delta)]^2/(\delta - \eta) > 0$.

To ensure that the above variables are non-negative, the following conditions must be satisfied:

$h > bp_c^2/2,\ 0 < c_m < a/b,\ 0 < p_c < (a - bc_m)/(be_m),\ h > abp_c^2/(a + bc_m + be_m p_c),\ \Delta > 2A/\eta,\ \max\{(3A - \Delta\eta + \eta c_s)/(k\eta), 0\} < u < (\Delta\eta + \eta c_s - A)/(k\eta)$, *and* $h > bp_c^2/2$.

The proof is analogous to that of Proposition 1 and is omitted for brevity.

Corollary 3. (1) $\frac{\partial e^{MO*}}{\partial h} < 0$, $\frac{\partial e^{MO*}}{\partial e_m} < 0$; (2) $\frac{\partial p_m^{MO*}}{\partial k} < 0$, $\frac{\partial p_u^{MO*}}{\partial k} > 0$, $\frac{\partial \pi_m^{MO*}}{\partial k} > 0$, $\frac{\partial \pi_u^{MO*}}{\partial k} > 0$; (3) $\frac{\partial p_m^{MO*}}{\partial u} < 0$, $\frac{\partial p_u^{MO*}}{\partial u} > 0$, $\frac{\partial \pi_m^{MO*}}{\partial u} > 0$, $\frac{\partial \pi_u^{MO*}}{\partial u} > 0$; (4) $\frac{\partial p_m^{MO*}}{\partial \eta} > 0$, $\frac{\partial p_u^{MO*}}{\partial \eta} > 0$, $\frac{\partial \pi_m^{MO*}}{\partial \eta} > 0$, $\frac{\partial \pi_u^{MO*}}{\partial \eta} > 0$; (5) $\frac{\partial p_m^{MO*}}{\partial \delta} < 0$, $\frac{\partial p_u^{MO*}}{\partial \delta} < 0$, $\frac{\partial \pi_m^{MO*}}{\partial \delta} < 0$, $\frac{\partial \pi_u^{MO*}}{\partial \delta} < 0$.

The proof is analogous to that of Corollary 1 and is omitted for brevity.

Corollaries 3 (1)-(4) indicate that increasing the carbon emission reduction investment cost coefficient and initial carbon emissions leads to a decreased emission reduction level. An increase in the proportion of echelon utilization or the net profit from unit remaining capacity will decrease the recycling price offered by the manufacturer, but increase the recycling price offered by the echelon utilizer and the profits of both the manufacturer and the echelon utilizer. When consumers become more sensitive to recycling prices, the recycling prices and profits of both the manufacturer and the echelon utilizer increase. These results align with those presented in Corollary 1. Corollary 3 (5) reveals that an increased recycling competition coefficient between the manufacturer and the echelon utilizer results in decreased recycling prices and profits of both CLSC parties.

4.2.2. With blockchain adoption

When the manufacturer with echelon utilization business adopts blockchain, the market demand is: $D^{MB} = a - bp_n^{MB} + \gamma t^{MB}$, the manufacturer's recycling quantity is $Q_m^{MB} = A + \eta p_b^{MB} - \delta p_u^{MB}$, and the echelon utilizer's recycling quantity is $Q_u^{MB} = A + \eta p_u^{MB} - \delta p_b^{MB}$. The manufacturer first decides the retail price p_n^{MB}, the carbon emission reduction level e^{MB}, the blockchain traceability level t^{MB}, the recycling price for the echelon utilizer p_m^{MB}, and the recycling price for the consumer p_b^{MB}. Then the echelon utilizer decides the recycling price p_u^{MB} based on the manufacturer's decisions. The profit functions are:

$$\pi_m^{MB} = (p^{MB} - c_m)D^{MB} + (\Delta - p_m^{MB})Q_u^{MB} + (\Delta + ku - p_b^{MB})Q_m^{MB} - p_c[D^{MB}(e_m - e^{MB}) - E] - \frac{1}{2}h(e^{MB})^2 - \phi\frac{1}{2}g(t^{MB})^2 \tag{7}$$

$$\pi_u^{MB} = (ku + p_m^{MB} - p_u^{MB})Q_u^{MB} - (1 - \phi)\frac{1}{2}g(t^{MB})^2 \tag{8}$$

In function (7), the term $(p^{MB} - c_m)D^{MB}$ represents the net profit from selling all new power batteries, $(\Delta - p_m^{MB})Q_u^{MB} + (\Delta + ku - p_b^{MB})Q_m^{MB}$ includes the cost savings derived from selling batteries made from recycled materials and the net profit generated from retired power batteries collected by the manufacturer, $-p_c[D^{MB}(e_m - e^{MB}) - E] - h(e^{MB})^2/2$ denotes the net benefit of implementing the carbon emission reduction strategy under the carbon trading policy, and $-\phi g(t^{MB})^2/2$ is the investment cost of blockchain technology borne by the manufacturer. In function (8), $(ku + p_m^{MB} - p_u^{MB})Q_u^{MB}$ is the net profit generated from all retired power batteries collected by the echelon utilizer, and $-(1 - \phi)g(t^{MB})^2/2$ represents the investment cost of blockchain technology borne by the echelon utilizer. By solving (7) and (8) by backward induction, we get Proposition 4.

Proposition 4. *Under the carbon trading policy, the optimal decisions for the manufacturer and the echelon utilizer in the case where the manufacturer with echelon utilization business adopts blockchain are as follows:*

$$p_n^{MB*} = \frac{h(\gamma^2 - bg\phi)(c_m + e_m p_c) - ag\phi(h - bp_c^2)}{h(\gamma^2 - 2bg\phi) + b^2 g\phi p_c^2},\ e^{MB*} = \frac{b\phi p_c G}{h(bc_m + be_m p_c - a)},\ t^{MB*} = \frac{\gamma G}{g(bc_m + be_m p_c - a)},$$
$$p_b^{MB*} = \frac{1}{2}\left(\Delta + \frac{A}{\delta - \eta} + ku\right),\ p_m^{MB*} = \frac{1}{2}\left(\Delta + \frac{A}{\delta - \eta} - ku\right),\ \pi_m^{MB*} = p_c E - \frac{\phi G}{2} - \frac{(\delta + 3\eta)S}{8\eta},$$
$$p_u^{MB*} = \frac{A(\delta - 3\eta) - (\delta^2 - \eta^2)(ku + \Delta)}{4\eta(\eta - \delta)},\ \pi_u^{MB*} = \frac{(\phi - 1)h\gamma^2 G}{2\left[h(\gamma^2 - 2bg\phi) + b^2 g\phi p_c^2\right]} + \frac{(\delta - \eta)S}{16\eta},$$

where $S = [A - (\delta - \eta)(ku + \Delta)]^2 \Big/ (\delta - \eta) > 0$.

To ensure that the variables are non-negative:

1) $h > bp_c^2/2$, $0 < c_m < a/b$, $0 < p_c < (a - bc_m)/be_m$, $\Delta > 2A/\eta$, *and* $\max\{(3A - \Delta\eta)/(k\eta), 0\} < u < (\Delta - A\eta)/(k\eta)$;

2) $\begin{cases} abp_c^2/(a + bc_m + be_m p_c) < h \leqslant bp_c^2 \\ g > (h\gamma^2 c_m + h\gamma^2 e_m p_c)/(ah\phi + bh\phi c_m + bh\phi e_m p_c - ab\phi p_c^2) \end{cases}$ *or* $\begin{cases} h > bp_c^2 \\ g > h\gamma^2/(2bh\phi - b^2\phi p_c^2) \end{cases}$.

The proof is analogous to that of Proposition 1 and is omitted for brevity.

Corollary 4. (1)$\frac{\partial e^{MB*}}{\partial h} < 0$, $\frac{\partial e^{MB*}}{\partial e_m} < 0$; (2)$\frac{\partial t^{MB*}}{\partial g} < 0$, $\frac{\partial t^{MB*}}{\partial \gamma} > 0$, $\frac{\partial t^{MB*}}{\partial \phi} < 0$; (3)$\frac{\partial p_m^{MB*}}{\partial k} < 0$, $\frac{\partial p_u^{MB*}}{\partial k} > 0$, $\frac{\partial \pi_m^{MB*}}{\partial k} > 0$, $\frac{\partial \pi_u^{MB*}}{\partial k} > 0$; (4)$\frac{\partial p_m^{MB*}}{\partial u} < 0$, $\frac{\partial p_u^{MB*}}{\partial u} > 0$, $\frac{\partial \pi_m^{MB*}}{\partial u} > 0$, $\frac{\partial \pi_u^{MB*}}{\partial u} > 0$; (5)$\frac{\partial p_m^{MB*}}{\partial \eta} > 0$, $\frac{\partial p_u^{MB*}}{\partial \eta} > 0$, $\frac{\partial \pi_m^{MB*}}{\partial \eta} > 0$, $\frac{\partial \pi_u^{MB*}}{\partial \eta} > 0$; (6)$\frac{\partial p_m^{MB*}}{\partial \delta} < 0$, $\frac{\partial p_u^{MB*}}{\partial \delta} < 0$, $\frac{\partial \pi_m^{MB*}}{\partial \delta} < 0$, $\frac{\partial \pi_u^{MB*}}{\partial \delta} < 0$.

The proof is analogous to that of Corollary 1 and is omitted for brevity.

Corollary 4 (1)-(5) indicate that as the carbon emission investment coefficient and the initial carbon emission rise, the carbon emission reduction level decreases. The traceability level increases with an improvement in consumer sensitivity towards traceability but decreases with an increase in the blockchain investment cost coefficient. An increase in the echelon utilization proportion of retired power batteries reduces the recycling price for the echelon utilizer but increases the recycling price for the echelon utilizer, as well as profits of the manufacturer and the echelon utilizer. An increase in the net profit obtained per unit residual capacity diminishes recycling prices and profits for both the manufacturer and the echelon utilizer. An increase in consumer sensitivity towards recycling prices increases recycling prices and profits for both CLSC members. These trends align with Corollary 2. Additionally, Corollary 4 (6) indicates that heightened recycling competition between the manufacturer and echelon utilizer decreases recycling prices and profits for both CLSC members, following the same rationale as in Corollary 3.

4.3. Analysis and comparison of equilibrium outcomes

4.3.1. The manufacturer's blockchain adoption decision without echelon utilization business

Corollary 5. $e^{B*} > e^{O*}$, $D^{B*} > D^{O*}$, $p_m^{B*} < p_m^{O*}$, $p_u^{B*} > p_u^{O*}$, $Q^{B*} > Q^{O*}$.Please refer to Appendix A.3 for the proof.

Corollary 5 indicates that when the manufacturer without echelon utilization business adopts blockchain, the optimal carbon emission reduction level increases, because blockchain can provide a lifecycle traceability and verification mechanism for power batteries, ensuring their environmental friendliness and emission reduction effectiveness. The adoption of blockchain leads to an increase in demand, because blockchain can provide highly transparent data records and traceability, allowing consumers to accurately understand the source, history, and quality of power batteries, thereby enhancing consumer trust and inclination to purchase new energy vehicles and related power batteries. If the manufacturer without echelon utilization adopts blockchain, the recycling price offered by the manufacturer to the echelon utilizer decreases. In contrast, the recycling price set by the echelon utilizer for consumers increases, leading to an overall increase in the recycling quantity within the CLSC. The adoption of blockchain enables more accurate assessment of the value and quality of a retired power battery, and reduces uncertainty in transactions. Consequently, by raising the recycling price of retired power batteries, the echelon utilizer can boost the overall recycling quantity. Additionally, the adoption of blockchain allows the manufacturer to offer a more competitive price when transferring retired power batteries to the echelon utilizer, thereby reducing the recycling price.

Corollary 6. $\pi_m^{B*} > \pi_m^{O*}$.

Please refer to Appendix A.4 for the proof.

Corollary 6 indicates that the manufacturer without echelon utilization business achieves higher profitability through the adoption of blockchain compared to not adopting blockchain. The utilization of blockchain technology benefits the manufacturer for the following reasons. (1) Improved market demand: Blockchain enhances data transparency and reliability, allowing consumers to gain a deeper comprehension of both product quality and environmental performance. The heightened transparency and credibility offered by blockchain technology can potentially stimulate consumer demand for NEVs and power batteries, consequently boosting market demand. (2) Increased carbon emission reduction level: The adoption of blockchain technology enables comprehensive tracking and documentation of the entire lifecycle of power batteries, from raw material sourcing to production, sales, and recycling processes. This heightened level of carbon emission monitoring aligns with environmental regulations and carbon trading mandates, enabling the manufacturer to obtain carbon emission certifications and incentives. Consequently, the manufacturer's products become more competitive in the market. (3) Reduced detection costs: Through blockchain's transparent and traceable data records, the manufacturer can swiftly and accurately verify the authenticity and quality of products. This streamlined verification process leads to decreased labor costs and shorter detection times, ultimately reducing overall detection expenses. As a result, production efficiency improves, leading to higher profitability. (4) Increased recycling quantity: Blockchain technology streamlines the supervision and oversight of power battery recycling operations, which empowers the manufacturer to collaborate more efficiently with the echelon utilizer in collecting and repurposing retired power batteries.

4.3.2. The manufacturer's blockchain adoption decision with echelon utilization business

Corollary 7. $e^{MB*} > e^{MO*}$, $D^{MB*} > D^{MO*}$, $p_m^{MB*} < p_m^{MO*}$, $p_b^{MB*} > p_b^{MO*}$, $p_u^{MB*} > p_u^{MO*}$, *and* $Q^{MB*} > Q^{MO*}$.

The proof is analogous to that of Corollary 5 and is omitted for brevity.

Corollary 7 illustrates that the manufacturer's adoption of blockchain technology enhances both the carbon emission reduction level and the market demand. Hence, the recycling price from the manufacturer to the echelon utilizer decreases, while the prices from both CLSC members to consumers for recycling retired power batteries increase. This leads to an overall rise in the quantity of recycling within the CLSC. The utilization of blockchain enables precise evaluation of the value and potential reuse of retired power batteries by the manufacturer and the echelon utilizer, resulting in higher recycling prices and, hence, a greater overall recycling quantity in the supply chain. This observation is consistent with the rationale presented in Corollary 5.

Corollary 8. $\pi_m^{MB*} > \pi_m^{MO*}$.

The proof is analogous to that of Corollary 6 and is omitted for brevity.

Corollary 8 demonstrates that the manufacturer's implementation of blockchain within the echelon utilization business results in a greater profit compared to the scenario without blockchain. Therefore, blockchain adoption is beneficial for the manufacturer, with similar reasoning to that of Corollary 6.

4.3.3. The manufacturer's echelon utilization decision without blockchain adoption

Corollary 9. $e^{MO*} = e^{O*}$, $D^{MO*} = D^{O*}$, *and* $p_m^{MO*} < p_m^{O*}$.

Please refer to Appendix A.5 for the proof.

Corollary 9 indicates that both the carbon emission reduction level and the market demand remain constant, whether or not the manufacturer participates in the echelon utilization. Concerning carbon emission reduction, the manufacturer can implement similar measures to improve environmental sustainability and decrease the carbon emission, irrespective of their involvement in echelon utilization business. These measures may include utilizing renewable energy sources, optimizing production processes, and advancing product design. As for market demand, the manufacturer's products primarily target the consumer market and are not influenced by echelon utilization business. Hence, successful market sales primarily hinge on consumer demand and acceptance of power batteries, regardless of the manufacturer's participation in the echelon utilization activity. Regarding the recycling price offered by the manufacturer to the echelon utilizer, the involvement of the manufacturer in echelon utilization business usually leads to a decrease in the recycling price offered to the echelon utilizer. This reduction stems from the manufacturer's ability to process suitable power batteries for echelon utilization within their own echelon utilization business, allowing them to sell directly in the echelon utilization market and achieve higher profits. As a result, the manufacturer wields greater negotiating power in setting the recycling price for the echelon utilizer.

Corollary 10. $\pi_m^{MO*} > \pi_m^{O*}$, *if* $X_1 > X_2$; $\pi_m^{MO*} < \pi_m^{O*}$, *if* $X_1 < X_2$. *Here,* $X_1 = (\delta + 3\eta)[A + (\delta - \eta)(c_s - ku - \Delta)]^2$, *and* $X_2 = (\eta - \delta)(A + \Delta\eta + ku\eta - \eta c_s)^2$.

Please refer to Appendix A.6 for the proof.

Corollary 10 indicates that engaging in echelon utilization business without the adoption of blockchain may not always be beneficial for the manufacturer. The threshold for this depends on factors such as the proportion of power batteries suitable for echelon utilization, the unit benefits of echelon utilization, the sensitivity of consumer recycling price during the recycling process, and the level of competition among companies.

4.3.4. The manufacturer's echelon utilization decision with blockchain adoption

Corollary 11. $e^{MB*} = e^{B*}$, $t^{MB*} = t^{B*}$, $D^{MB*} = D^{B*}$, *and* $p_m^{MB*} < p_m^{B*}$.

The proof is analogous to that of Corollary 9 and is omitted for brevity.

Corollary 11 demonstrates that the traceability level remains consistent regardless of the manufacturer's involvement in echelon utilization business. This consistency can be attributed to the manufacturer's capability to employ similar technologies, regardless of whether the echelon utilization activity is implemented. Additionally, the manufacturer's involvement in echelon utilization business does not affect the carbon emission reduction level or the market demand. Concerning the recycling price from the manufacturer to the echelon utilizer, when the manufacturer participates in echelon utilization business, the recycling price for the echelon utilizer generally decreases. This reduction in recycling price primarily arises from the manufacturer's increased bargaining power and their ability to process power batteries suitable for echelon utilization through their own echelon utilization business.

Corollary 12. $\pi_m^{MB*} > \pi_m^{B*}$, *if* $X_3 > X_4$; $\pi_m^{MB*} < \pi_m^{B*}$, *if* $X_3 < X_4$. *Here,* $X_3 = (\delta + 3\eta)[A - (\delta - \eta)(ku + \Delta)]^2$, *and* $X_4 = (\eta - \delta)(A + \Delta\eta + ku\eta)^2$.

The proof is analogous to that of **Corollary 10** and is omitted for brevity.

Corollary 12 indicates that the adoption of blockchain and engagement in echelon utilization business may not always result in higher profits for the manufacturer. The threshold for this depends on factors such as the proportion of power batteries suitable for echelon utilization, the unit benefit of echelon utilization, the sensitivity of consumer recycling prices during the recycling process, and the level of competition among companies.

4.4. Coordination between the manufacturer and the echelon utilizer

Following the collaboration between the manufacturer and the echelon utilizer, both entities establish an identical recycling price for retired power batteries, denoted as p_0^{C-j}, for consumers. The profit functions for the CLSC under centralized decision-making in the four modes are as follows:

$$\pi_c^O = (p_n^{C-O} - c_m)D^{C-O} + (ku + \Delta - p_0^{C-O} - c_s)Q_0^{C-O} - p_c[D^{C-O}(e_m - e^{C-O}) - E] - \frac{1}{2}h(e^{C-O})^2 \tag{9}$$

$$\pi_c^B = (p_n^{C-B} - c_m)D^{C-B} + (ku + \Delta - p_0^{C-B})Q_0^{C-B} - p_c[D^{C-B}(e_m - e^{C-B}) - E] - \frac{1}{2}h(e^{C-B})^2 - \frac{1}{2}g(t^{C-B})^2 \tag{10}$$

$$\pi_c^{MO} = (p_n^{C-MO} - c_m)D^{C-MO} + 2(ku + \Delta - p_0^{C-MO} - c_s)Q_0^{C-MO} - p_c[D^{C-MO}(e_m - e^{C-MO}) - E] - \frac{1}{2}h(e^{C-MO})^2 \tag{11}$$

$$\pi_c^{MB} = (p_n^{C-MB} - c_m)D^{C-MB} + 2(ku + \Delta - p_0^{C-MB})Q_0^{C-MB} - p_c[D^{C-MB}(e_m - e^{C-MB}) - E] - \frac{1}{2}h(e^{C-MB})^2 - \frac{1}{2}g(t^{C-MB})^2 \tag{12}$$

where $D^{C-O} = a - bp_n^{C-O}$, $Q_0^{C-O} = A + \eta p_0^{C-O}$, $D^{C-B} = a - bp_n^{C-B} + \gamma t^{C-B}$, $Q_0^{C-B} = A + \eta p_0^{C-B}$, $D^{C-MO} = a - bp_n^{C-MO}$, $Q_0^{C-MO} = A + \eta p_0^{C-MO} - \delta p_0^{C-MO}$, $D^{C-MB} = a - bp_n^{C-MB} + \gamma t^{C-MB}$, and $Q_0^{C-MB} = A + \eta p_0^{C-MB} - \delta p_0^{C-MB}$.

The equilibrium profits under centralized decision-making in the four modes are:

$$\pi_c^{O^*} = p_c E + W + \frac{U}{4} - \frac{he_m^2}{2},\ \pi_c^{B^*} = p_c E + \frac{V}{4} - \frac{F}{2},$$

$\pi_c^{MO^*} = p_c E - \frac{he_m^2 + S}{2} + W + \frac{(2ku + 2\Delta - c_s)(\delta - \eta) - 2A}{2}c_s$, and $\pi_c^{MB^*} = p_c E - \frac{F+S}{2}$,

where $F = \frac{gh(bc_m + be_m p_c - a)^2}{h(\gamma^2 - 2bg) + b^2 g p_c^2} > 0$, and $W = \frac{h[(a - bc_m)(bc_m + 2be_m p_c - a) - 2bhe_m^2]}{2b(bp_c^2 - 2h)}$.

To achieve the coordination of the manufacturer and the echelon utilizer, we use a Nash bargaining cooperative (NBC) game model to examine their coordination mechanism, following the approach outlined by [48] and [49]. We present the model as follows:

$$\begin{aligned} \max_{\pi_m^{B-j}, \pi_u^{B-j}} \ \mathrm{NBC} &= (\pi_m^{B-j} - \pi_m^j)^{\lambda}(\pi_u^{B-j} - \pi_u^j)^{1-\lambda} \\ \text{s.t. } & \pi_m^{B-j} + \pi_u^{B-j} \leqslant \pi_c^{j^*} \end{aligned} \tag{13}$$

where λ and $1-\lambda$ with $\lambda \in [0,1]$ signify the bargaining power of the manufacturer and the echelon utilizer, respectively. π_m^j and π_u^j denote the respective threat points for the manufacturer and the echelon utilizer, i.e., the profits in case the negotiation breaks down. Additionally, $\pi_c^{j^*}$ represents the maximum profit attainable through the coordination between both CLSC members. The constraint in equation (13) ensures that the combined profits of the two members after Nash bargaining do not surpass the profit achieved through coordination. The equilibrium solutions of the NBC game are elucidated in Lemma 1 as follows:

Lemma 1. *In the NBC game model involving the manufacturer and the echelon utilizer, the equilibrium solutions are given by* $\pi_m^{B-j^*} = \pi_m^j + \lambda(\pi_c^{j^*} - \pi_m^j - \pi_u^j)$ *and* $\pi_u^{B-j^*} = \lambda\pi_u^j + (1-\lambda)(\pi_c^{j^*} - \pi_m^j)$.

Please refer to Appendix A.7 for the proof.

According to Lemma 1, the equilibrium solutions of the NBC game model are influenced by several factors, including the bargaining power λ of the manufacturer, the equilibrium profit after coordination π_c^*, and the threat points π_m^j and π_u^j. Proposition 5 presents the equilibrium profits of both the manufacturer and the echelon utilizer in the four different modes.

Proposition 5. *The NBC game model's equilibrium solutions for the manufacturer and the echelon utilizer are as follows:*

(1) When the manufacturer without echelon utilization business does not adopt blockchain,

$\pi_m^{B-O^*} = p_c E + W + \frac{(\lambda+2)U}{16} - \frac{he_m^2}{2}$ *and* $\pi_u^{B-O^*} = \frac{(2-\lambda)U}{16}$.

(2) When the manufacturer without echelon utilization business adopts blockchain,

$\pi_m^{B-B^*} = p_c E + \frac{(2+\lambda)V - 8[(\lambda-1)\phi G - \lambda F]}{16} + \frac{\lambda h\gamma^2(1-\phi)G/2}{h(\gamma^2 - 2bg\phi) + b^2 g\phi p_c^2}$ *and*

$$\pi_u^{B-B^*} = \frac{(2-\lambda)V + 8(1-\lambda)(\phi G - F)}{16} + \frac{\lambda h\gamma^2(1-\phi)G/2}{h(\gamma^2 - 2bg\phi) + b^2 g\phi p_c^2}.$$

(3) When the manufacturer with echelon utilization business does not adopt blockchain,

$\pi_m^{B-MO^*} = p_c E + \frac{2W - he_m^2}{2} + \frac{TS}{8\eta[A - (\delta-\eta)(\Delta + ku)]} + \frac{Tc_s + [\lambda(\delta-\eta) - 2(\delta+3\eta)]S}{16\eta}$ *and*

$$\pi_u^{B-MO^*} = \frac{(2-\lambda)(\delta-\eta)R}{16\eta}.$$

(4) When the manufacturer with echelon utilization business adopts blockchain,

$\pi_m^{B-MB^*} = p_c E - \frac{\gamma^2 Gh\lambda(\phi-1)/2}{h(\gamma^2 - 2bg\phi) + b^2 g\phi p_c^2} + \frac{G(\lambda-1)\phi - F\lambda}{2} + \frac{[\delta(\lambda-2) - \eta(\lambda+6)]S}{16\eta}$ *and*

$$\pi_u^{B-MB*} = \frac{\gamma^2 Gh\lambda(\phi-1)/2}{b^2 g\phi p_c^2 + h(\gamma^2 - 2bg\phi)} + \frac{(1-\lambda)(G\phi - F)}{2} + \frac{(\lambda-2)(\eta-\delta)S}{16\eta}.$$

where $T = c_s[\delta(\lambda-2) - \eta(\lambda+6)](\delta-\eta)$.

Please refer to Appendix A.8 for the proof.

Proposition 6 below delineates the effects of the manufacturer's bargaining power (λ) on the equilibrium solutions of the NBC game model across the four modes.

Proposition 6. *The effects of the manufacturer's bargaining power on the equilibrium solutions of the NBC game model are as follows: (1)* $\frac{\partial \pi_m^{B-O*}}{\partial \lambda} > 0$ *and* $\frac{\partial \pi_u^{B-O*}}{\partial \lambda} < 0$; *(2)* $\frac{\partial \pi_m^{B-B*}}{\partial \lambda} > 0$ *and* $\frac{\partial \pi_u^{B-B*}}{\partial \lambda} < 0$; *(3)* $\frac{\partial \pi_m^{B-MO*}}{\partial \lambda} > 0$ *and* $\frac{\partial \pi_u^{B-MO*}}{\partial \lambda} < 0$; *(4)* $\frac{\partial \pi_m^{B-MB*}}{\partial \lambda} > 0$ *and* $\frac{\partial \pi_u^{B-MB*}}{\partial \lambda} < 0$.

Please refer to Appendix A.9 for the proof.

Based on Proposition 6, as λ increases in the four modes, the manufacturer's profit rises while the echelon utilizer's profit declines following the bargaining process. Proposition 7 establishes the relationships between the manufacturer's and the echelon utilizer's profits both before and after coordination.

Proposition 7. *(1)* $\pi_m^{B-O*} > \pi_m^{O*}$ *and* $\pi_u^{B-O*} > \pi_u^{O*}$; *(2)* $\pi_m^{B-B*} > \pi_m^{B*}$ *and* $\pi_u^{B-B*} > \pi_u^{B*}$; *(3)* $\pi_m^{B-MO*} > \pi_m^{MO*}$ *and* $\pi_u^{B-MO*} > \pi_u^{MO*}$; *(4)* $\pi_m^{B-MB*} > \pi_m^{MB*}$ *and* $\pi_u^{B-MB*} > \pi_u^{MB*}$.

Please refer to Appendix A.10 for the proof.

Proposition 7 demonstrates that, across all modes, the profits of both the manufacturer and the echelon utilizer are higher following Nash bargaining compared to their profits before bargaining. This indicates that the manufacturer and the echelon utilizer should conduct Nash negotiation on profit allocation, and the manufacturer, as the game leader, should grant appropriate bargaining power to the echelon utilizer to persuade it to accept the integration.

5. Numerical studies

To demonstrate the applicability of the proposed model, we perform simulations to explore how model parameters influence the CLSC member's equilibrium decisions and profits. The parameter values are set based on [13] and [42]: $a = 250$ (unit), $b = 0.9$ (unit/CNY), $\gamma = 3$, $c_m = 50$ (CNY/unit), $c_r = 25$ (CNY/unit), $e_m = 15$ (ton CO2-eq./unit), $A = 0$ (unit), $\eta = 1.1$ (unit/CNY), $\delta = 0.4$, $u = 32$ (CNY/unit), $c_s = 10$ (CNY/unit), $k = 0.4$, $h = 200$, $g = 300$, $\phi = 0.2$, $p_c = 10$ (CNY/ton CO2-eq.), and $E = 300$ (ton CO2-eq.).

5.1. Analysis of carbon emission reduction level, market demand, and recycling quantity

5.1.1. Analysis of carbon emission reduction level

From Corollary 9 and Corollary 11, $e^{MO*} = e^{O*}$ and $e^{MB*} = e^{B*}$. We denote the equilibrium carbon emission reduction level without (with) adopting blockchain as e^O (e^B). Fig. 2 presents the influences of e_m, h, and p_c on the manufacturer's equilibrium carbon emission reduction level.

As depicted in Fig. 2(a), the carbon emission reduction level decreases with an increase in the initial carbon emission level, regardless of the scenario. This can be attributed to the factors explained in Corollary 1(1). For instance, reducing carbon emissions may necessitate energy transformations, equipment modifications, or resource substitutions. However, these transformations can be constrained by technological, economic, or resource limitations, resulting in a decrease in the carbon emission reduction level. Fig. 2 (b) illustrates that the carbon emission reduction level decreases with an increase in the carbon emission investment cost coefficient in both scenarios. This aligns with the analysis in Corollary 1(1), where a higher carbon emission investment cost coefficient signifies a greater investment cost needed to attain a unit carbon emissions reduction. With the increasing emission reduction investment cost, businesses and individuals may assess the economic feasibility of emission reduction projects more carefully. If the cost of emission reduction investment becomes excessively high, it may lead to longer payback periods or lower returns on investment, thereby diminishing the attractiveness of the emission reduction projects. Fig. 2 (c) indicates that, regardless of the mode, the manufacturer's carbon emission reduction level rises and then declines with the carbon trading price. This trend can be explained by the economic

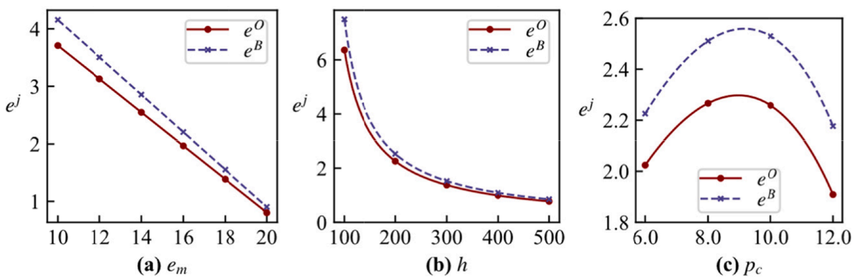

Fig. 2. The influence of e_m, h, and p_c on the manufacturer's equilibrium carbon emission reduction level.

incentives at play: as the carbon trading price increases, the manufacturer is motivated to prioritize cost-effective emission reduction measures to meet carbon emission quotas, ultimately leading to reduced carbon emissions and an increased emission level. However, as the carbon trading price continues to rise, the manufacturer may encounter challenges associated with rising marginal emission reduction costs. Marginal emission reduction cost represents the cost per unit of emission reduction, typically increasing as the emission reduction level rises. When the marginal emission reduction cost surpasses the carbon trading price, the manufacturer may curtail further emission reductions.

Regardless of the mode, the adoption of blockchain leads to a higher carbon emission reduction level compared to non-adoption. While blockchain itself does not directly reduce carbon emissions, it provides a more reliable, transparent, and efficient infrastructure for improving the monitoring, verification, and management processes of carbon emission reduction, thereby elevating the overall carbon emission reduction level.

5.1.2. Analysis of market demand

From Corollary 9 and Corollary 11, $D^{MO^*} = D^{O^*}$ and $D^{MB^*} = D^{B^*}$. We denote the market demand without (with) adopting blockchain as D^O (D^B). Fig. 3 analyzes the effects of γ, g, and h, on the market demand.

As observed in Fig. 3(a), the market demand for adopting blockchain rises in correlation with the sensitivity of consumers to traceability, because consumers who are sensitive to the traceability level of products are more interested in relevant information and data about the products. They want to understand the production process, raw material sources, environmental impact, and other related information. When consumers can obtain accurate and transparent traceability information, they have more confidence in purchasing and supporting these products. Fig. 3(b) shows that the market demand for adopting blockchain decreases with the increase in blockchain investment cost coefficient, because the investment cost of blockchain typically leads to an increase in product prices. When the product price rises, consumers' purchasing power may be limited, resulting in a decrease in market demand. Fig. 3(c) demonstrates that, irrespective of the mode, the market demand diminishes as the carbon emission reduction investment cost increases. This phenomenon occurs because elevated carbon emission reduction investment costs typically result in higher production expenses for businesses, subsequently causing an uptick in the product price. Notably, the market demand is higher when the blockchain adoption is in place compared to scenarios without blockchain adoption.

5.1.3. Analysis of total recycling quantity

Fig. 4 analyzes the influence of k, u, η, δ, and c_s, on total recycling quantity of each mode.

As depicted in Fig. 4(a), the total recycling quantity rises across all modes as the echelon utilization ratio increases. This increase in the echelon utilization ratio implies a greater capacity to efficiently recycle and reuse a larger number of retired power batteries. Fig. 4 (b) shows that in all modes, the total recycling quantity increases with the unit echelon utilization benefit. This is because a heightened unit echelon utilization benefit signifies that echelon utilization businesses can derive greater returns from processing each retired power battery. Higher unit echelon utilization benefit provides greater economic rewards, motivating stakeholders to participate in echelon utilization activities. Fig. 4(c) shows that the total recycling quantity rises in all modes with increasing consumer sensitivity to recycling prices. This outcome occurs because heightened consumer sensitivity to recycling prices encourages the manufacturer or the echelon utilizer to raise recycling prices, thereby attracting greater consumer participation in recycling efforts.

Fig. 4(d) shows that in the mode where the manufacturer operates with echelon utilization business, the total recycling quantity declines as the competition coefficient between the manufacturer and the echelon utilizer increases. However, when the manufacturer operates without an echelon utilization business, the total recycling quantity remains unaltered regardless of the competition coefficient. It's noteworthy that when the competition coefficient exceeds a specific threshold, the total recycling quantity in the mode where the manufacturer engages in echelon utilization business becomes lower than that in the mode without echelon utilization business. This trend is attributed to the fact that an increase in the competition coefficient signifies intensified competition between the manufacturer and the echelon utilizer. In the mode with echelon utilization business, both CLSC members may encounter difficulties in acquiring a sufficient number of retired power batteries for echelon utilization, leading to competition for market share in recycling and the acquisition of recycling resources.

As depicted in Fig. 4(e), in the mode where the manufacturer does not implement blockchain technology, the total recycling quantity decreases as the unit detection and classification cost rises. This is because, without blockchain adoption, an increase in the unit detection and classification cost imposes a higher financial burden on the recycling of retired batteries, leading to reduced profit

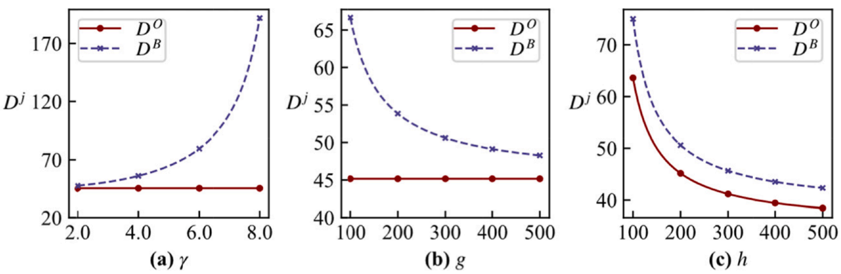

Fig. 3. The influence of γ, g, and h on the market demand in different modes.

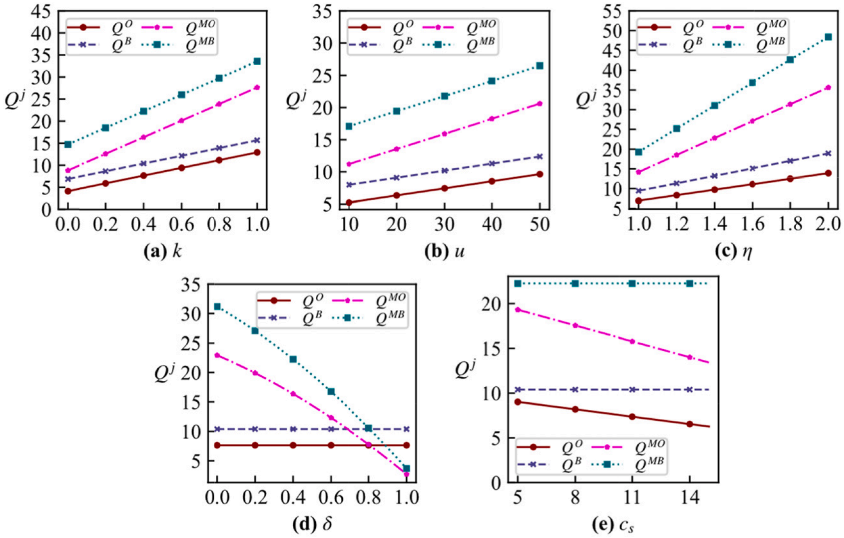

Fig. 4. The influence of k, u, η, δ, and c_s on the total recycling quantity in different modes.

margins. Conversely, in the mode with blockchain adoption, the total recycling quantity is not influenced by the unit detection and classification cost. This is attributed to the transparency and traceability provided by blockchain, which ensures accurate and reliable detection and classification outcomes during the recycling process. Stakeholders can trust the blockchain-recorded data, eliminating the need for additional detection and classification expenses. Blockchain adoption incentivizes the echelon utilizer to actively engage in recycling, thereby fostering an increase in the overall recycling quantity. In summary, Fig. 4(a)-(e) demonstrate that, irrespective of the mode, adopting blockchain leads to a higher total recycling quantity compared to when it is not adopted.

5.2. Analysis of the manufacturer's blockchain adoption decision

To explore the manufacturer's decision to adopt blockchain, we compare the manufacturer's profit in different modes. Fig. 5 presents the influence of g, ϕ, and c_s on the manufacturer's profit.

Fig. 5(a) illustrates that when blockchain is adopted, the manufacturer's profit declines as the blockchain traceability investment cost coefficient increases. This reduction can be attributed to the investments required for system development, data storage, and maintenance associated with blockchain adoption. A higher blockchain traceability investment cost coefficient implies a larger allocation of funds for establishing and maintaining a robust traceability system. Fig. 5(b) reveals that when adopting blockchain, the manufacturer's profit decreases as the blockchain traceability cost-sharing ratio increases. This outcome arises from the cost-sharing arrangement between the manufacturer and downstream stakeholders in implementing and operating blockchain traceability technology: a greater proportion of cost sharing exerts a more pronounced influence on the manufacturer's profit. Fig. 5(c) shows that without blockchain adoption, the manufacturer's profit decreases as the unit detection and classification cost rises in both modes. However, with blockchain adoption, the manufacturer's profit remains unaffected by variations in the unit detection and classification cost, resulting in an overall higher profit compared to scenarios without blockchain adoption. This is because, without blockchain, the manufacturer incurs higher costs for battery detection and classification to ensure proper processing and utilization. As the unit detection and classification cost increases, the manufacturer's expenses rise. Conversely, with blockchain adoption, the manufacturer can access real-time information on the recycling and classification of power batteries without incurring additional detection and classification costs. In summary, Fig. 5 indicates that the manufacturer's profit is higher when adopting blockchain, highlighting the strong recommendation for manufacturers to embrace blockchain technology.

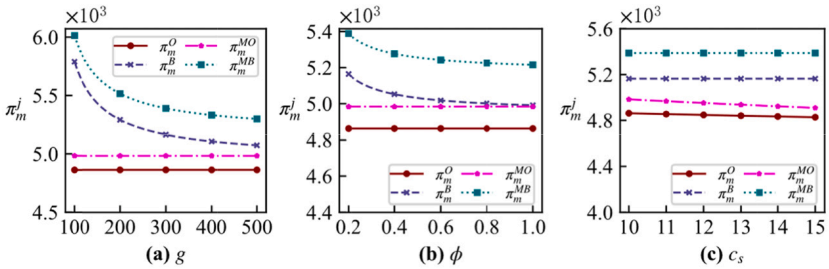

Fig. 5. The influence of g, ϕ, and c_s on the manufacturer's profit in different modes.

5.3. Analysis of the manufacturer's echelon utilization decision

To explore the manufacturer's echelon utilization decision, we compare the manufacturer's profits in different modes. Fig. 6 depicts the influence of k, u, η, and δ on the manufacturer's profit.

As shown in Fig. 6(a), in both modes, the manufacturer's profit increases with the echelon utilization ratio, suggesting a tendency for the manufacturer to participate in echelon utilization activities. This is due to the higher utilization ratio enabling the recovery and reuse of a greater amount of waste materials, leading to reduced costs associated with raw material procurement. Through the echelon utilization of power batteries, the manufacturer can transform waste materials into new echelon products, which creates new market opportunities, expands product lines and sales channels, and ultimately boosts sales volume and profit. Fig. 6(b) indicates that in both modes, the manufacturer's profit increases with the unit benefit of echelon utilization. This is because, on the one hand, the manufacturer obtains higher net profits from echelon utilization, and on the other hand, the high unit benefit of echelon utilization motivates recyclers to collect more retired power batteries, allowing the manufacturer to acquire more recycled materials, reduce reliance on new raw materials, and save more costs in manufacturing new products. Fig. 6(c) illustrates that in either mode, the manufacturer's profit rises with an increase in the consumer sensitivity coefficient to recycling prices. A higher consumer sensitivity coefficient implies that a one-unit increase in recycling prices leads to more recycling volume, increasing the net profits from echelon utilization and the utilization of recycled materials from retired power batteries. Fig. 6(d) unveils that in the echelon utilization mode, the manufacturer's profit decreases with an increase in the competition coefficient. By contrast, under the non-utilization mode, the manufacturer's profit remains unaffected with the change of the competition coefficient. This is because a higher competition coefficient intensifies the competition between the echelon utilizer and the manufacturer in acquiring retired power batteries, resulting in a reduction in the manufacturer's share of collected batteries. When the competition coefficient remains below a specific threshold ($\delta < 0.8$), the manufacturer's profit in the non-utilization mode is lower than that in the echelon utilization mode. This incentivizes the manufacturer to participate in echelon utilization operations. Conversely, when the competition coefficient surpasses a certain threshold ($\delta > 0.8$), the profit in the echelon utilization mode falls below that in the non-utilization mode, leading the manufacturer to refrain from engaging in echelon utilization.

5.4. Managerial insights

(1) Regarding the adoption of blockchain, it's noteworthy that the manufacturer consistently achieves higher profits when opting for blockchain adoption in contrast to not adopting blockchain. Blockchain adoption not only increases the carbon emission reduction level but also enhances market demand and recycling quantity. The multiple benefits associated with blockchain adoption make it a favorable choice for the manufacturer.

(2) Regarding the echelon utilization decision, in situations where the competition coefficient between the manufacturer and the echelon utilizer is low, it is advisable for the manufacturer to opt for engagement in echelon utilization business. However, when the competition coefficient is high, the manufacturer should refrain from such business. Therefore, when making decisions on whether to engage in echelon utilization, the manufacturer should consider factors such as the competition coefficient, cost-effectiveness, resource allocation, and expertise. Only when the competition coefficient is appropriate and the benefits are significant, should the manufacturer opt for echelon utilization to optimize resources and maximize profits.

(3) Concerning the carbon trading policy, it's important to note that the optimal carbon emission reduction level for the manufacturer exhibits an initial increase followed by a decrease with the carbon trading price increases. Nevertheless, the manufacturer's profit steadily increases as the government carbon quota rises. Solely increasing the carbon trading price does not guarantee an enhancement in the manufacturer's carbon emission reduction level. Therefore, it is advisable for the government to set an appropriate carbon quota and promote the formation of suitable carbon trading prices in the market. Additionally, increasing the carbon quota is always beneficial for the manufacturer.

(4) In terms of coordinating between the manufacturer and the echelon utilizer, it is evident across all scenarios that the profits of both parties increase after Nash bargaining compared to their profits before bargaining. This indicates that conducting Nash negotiations on profit allocation benefits both the manufacturer and the echelon utilizer. As the leader in the game, the manufacturer should allocate appropriate bargaining power to the echelon utilizer to facilitate the acceptance of integration.

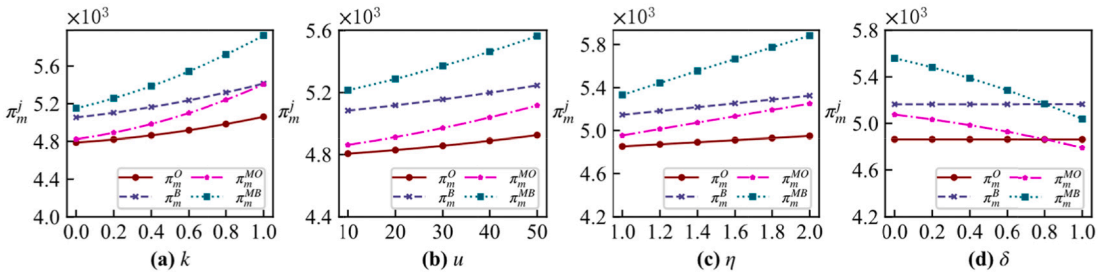

Fig. 6. The influence of k, u, η, and δ on the manufacturer's profit in different modes.

6. Conclusions

This study investigated the adoption of blockchain and echelon utilization for the manufacturer within a power battery CLSC for NEVs operating under the carbon trading policy. By considering the manufacturer's carbon emission reduction action, we formulated profit-maximization models for the power battery CLSC consisting of a manufacturer and an echelon utilizer. Through reverse solving, we derived equilibrium decisions and profits for four distinct scenarios, and provided comprehensive analyses. This comparison provided valuable insights into the manufacturer's adoption of blockchain and echelon utilization under the carbon cap-and-trade policy. The primary findings of this study are summarized as follows.

(1) The carbon emission reduction level decreases with an increase in the initial carbon emission and the carbon emission investment cost coefficient, while it initially increases and then decreases with an increase in the carbon trading price. This reduction level is independent of the manufacturer's involvement in echelon utilization but is improved by the adoption of blockchain. (2) The market demand increases with the consumer sensitivity to traceability level, but decreases with the blockchain investment cost coefficient and the carbon emission investment cost. Adopting blockchain increases market demand. (3) The total recycling quantity increases with the echelon utilization ratio and the unit benefit of echelon utilization, but decreases with the unit detection and classification cost and the consumer sensitivity coefficient to recycling prices. In the non-utilization mode, variations in the competition coefficient between the manufacturer and the echelon utilizer do not affect the total recycling quantity. However, in the echelon utilization mode, the total recycling quantity decreases as the competition coefficient increases. Once this competition coefficient exceeds a specific threshold, the total recycling quantity in the echelon utilization mode becomes lower than that in the non-utilization mode. Adoption of blockchain technology can enhance the recycling quantity. (4) From a profit maximization standpoint, the manufacturer always chooses to adopt blockchain. Irrespective of blockchain adoption, the manufacturer's decision regarding echelon utilization is influenced by the competition coefficient. When the competition coefficient is below a certain threshold, the manufacturer engages in echelon utilization business. Conversely, when the competition coefficient exceeds a specific threshold, the manufacturer abstains from echelon utilization business. (5) The manufacturer and the echelon utilizer should conduct Nash negotiation on profit allocation, and the manufacturer should grant appropriate bargaining power to the echelon utilizer to persuade its acceptance of integration.

This study provides recommendations and theoretical support for manufacturers' decisions on blockchain adoption and echelon utilization in different scenarios. Furthermore, it contributes to the research on operational strategies and echelon utilization in power battery CLSCs under the carbon trading policy. There is room for further study, considering the uncertainty of power battery demand and the impact of multiple stakeholders such as manufacturers, retailers, and echelon utilization entities on low-carbon supply chains and power battery CLSCs. Future research could explore decision-making and profit variations across multiple periods and optimize decisions for power battery recycling, echelon utilization, and blockchain application within different periods. This would provide a more comprehensive reflection of real-world situations and offer long-term, sustainable strategies and decision-making support for businesses.

CRediT authorship contribution statement

Chuan Zhang: Supervision, Funding acquisition. **Jian-Chi Li:** Writing – original draft, Investigation. **Yu-Xin Tian:** Writing – review & editing, Writing – original draft, Software, Methodology, Data curation. **He-Shuang Li:** Writing – original draft, Software, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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