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Research on Closed-Loop Supply Chain Decision Making of Power Battery Considering Subsidy Transfer under EPR System

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Abstract: With new energy vehicles becoming the mainstream of new vehicles sold, the surge in user ownership has triggered a wave of power battery scrapping, and the environmental problems caused by improper power battery recycling are becoming more serious. It is essential to promote the development of the closed-loop supply chain (CLSC) of power batteries effectively through government subsidies under the extended producer responsibility (EPR) regime. Combining the EPR system with the battery manufacturer as the leader and the vehicle manufacturer and the retailer as the subordinates, this paper constructs and solves four models of different CLSC subsidy objects and analyzes the pricing of power batteries by different subsidy objects by using the Stackelberg game, as well as the profit change and profit distribution ratio of each CLSC participant. The results of the study showed: (1) when the unit subsidy is limited, the government should subsidize all the CLSC subjects as much as possible. (2) When the government subsidizes the remanufacturing of power batteries, the recycling rate of power batteries is higher, and the benefits of the CLSC are better than those of subsidizing other actors. (3) The change in government subsidy objects will not affect the profit distribution ratio of CLSC, mainly because the subsidy not only improves the recovery rate, but also improves the profitability of each entity.

Keywords: CLSC; Stackelberg game; EPR system; power battery

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1. Introduction

As China's transportation business has been soaring in recent years, the accompanying issues of climate change, environmental pollution, and energy depletion have become an urgent problem. Road transportation accounts for 86% of the carbon emissions of transportation, accelerating energy consumption and greenhouse gas emissions; therefore, improving and establishing a green low-carbon cyclical motor vehicle economic system [1] is now essential to the industrialization and popularization of new energy vehicles (NEVS). China has led the globe in producing and selling new energy cars for six straight years since 2015, making it the biggest producer and owner of such vehicles in the world [2] Power batteries are components of NEVS, for which business has been expanding fast alongside the new energy vehicle sector. However, the extensive uncontrolled development has also brought out some problems [3,4]. First, long-term power batteries contain the heavy metals Ni, Co, and electrolytes that pollute the environment. Furthermore, if the government takes no additional steps, these may eventually irreparably harm the environment [5,6]. Secondly, when a power battery's capacity deteriorates to roughly 80% of its original level, it must be replaced [7]. According to the China Automotive Technology Research Center, China retired more than 200,000 tons (about 25 GWh) of power batteries from NEVS by 2020. If 70% of them can be used for cascade utilization, about 60,000 tons of batteries need to be scrapped. Moreover, the total scrapped power batteries will reach about 780,000 tons (about 116 GWh) in 2025, and there will be about 234,000 tons of batteries to be disposed of at the end-of-life stage [8]. Adopting a circular economy strategy to enhance the resilience and sustainability of the power battery supply chain can reduce the demand

for primary resources such as lithium, cobalt, and nickel, and reduce the mining of primary raw materials [9]. It is estimated that China's power battery market will account for 45% of the world's global market by 2030, so it is very important to study the closed-loop supply chain based on China's power batteries [10]. Therefore, handling end-of-life batteries in a suitable, safe, and environmental way has become a research hotspot to achieve the goal of carbon neutrality. It is also the core content of circular economy theory.

The study of how to build a better closed-loop green supply chain for power batteries is also one of the new important challenges in the future development of the circular economy [11]. To handle this challenge, different countries have undertaken diverse actions. The United States already has a complete legal system for power battery recycling, Germany has established a relatively complete recycling system, and Japan has a good national awareness of environmental protection and the infrastructure of waste recycling, China, which owns the largest number of new energy vehicles, urgently needs to improve the sound power battery CLSC. Currently, China is attempting to implement an extended producer responsibility [12] (EPR) system in diverse fields to promote the green development of industry, resource conservation, and recycling. The fundamental concept of the EPR system is to extend the environmental responsibility of producers from the production link to all links in the product life cycle, including the recovery and final disposal of products, and including encouraging or restricting producers in product design. Recycling and reusing discarded products are effective in conserving the environment [13–16].

In May 2021, The Notice on Issuing the Pilot Implementation Plan for EPR of Automotive Products was released by the Ministries of Industry and Information Technology, Science and Technology, Finance, and Commerce (henceforth referred to as the "Pilot Plan"), clearly implementing the EPR system to ensure the orderly progress of power battery recovery. The Pilot Programmer aims to initially address the basic input for power battery recycling through enacting and implementing subsidy policies and effectively mobilizing relevant entities to engage in recycling. The application of the EPR system to the power battery recycling process is realizing the transformation from "end-of-pipe treatment" to "front prevention" [17,18]. Green supply chains promote economic development on a global scale and bring more opportunities for trade, especially in pro-environmental countries to attract foreign investors through green policies such as tariff reductions [19,20]. Current research demonstrates that EPR systems are implemented mostly through tax and subsidy policies [21]. In addition, numerous studies have demonstrated that government subsidies can provide substantial support for the development of industry, reducing environmental pollution and promote sustainable production of the company, which can influence the decisions of firms and the behavior of consumers, and play a more significant part in CLSC pricing decisions [22–24]. In this situation, the government wants to help the whole CLSC run more smoothly by providing subsidies. As China's recycling system for power batteries is imperfect, the recycled batteries are informally disposed of, raising serious environmental problems [25]. In light of this, the government should change the situation by providing suitable subsidies to CLSC members. This step will leave a far-reaching impact in establishing a consummate power battery-recycling management system and a more green, environmentally friendly and low carbon environment in its recycling process.

With all the above, it can be seen that the EPR system needs to be formulated in combination with the characteristics of the industry's CLSC structure and industry characteristics [26,27]. However, there are few studies on the combination of EPR systems and power battery recycling, and the recycling is not fully integrated with specific industries. The research direction of many scholars focuses on channel selection [27–29] and there is less research on specific subsidy policies of "co-building a recycling network model with car companies". Secondly, in the recycling process, most research has focused on the recycling method dominated by retailers; the recycling method dominated by the main bearers of the EPR system is less common. Currently, researchers mainly focus on the pricing decisions of the secondary CLSC under the sales and recycling channels and rarely extend to the

three-level CLSC, which ignores the internal relationships of a specific industry to a certain extent. Therefore, in this article, we will explore the following questions:

(1) What is the optimal decision for each subject under different subsidy models? What are the conditions under which different subsidy strategies are applicable?
(2) What is the impact of subsidies on the decision making and profitability of the power battery CLSC, product pricing and product recovery rates, as well as the distribution of CLSC profits?

There are three main contributions of this paper. Firstly, this paper considers the characteristics of the power battery industry, combines EPR system with recycling decisions, constructs and solves a Stackelberg Competition game model of CLSC for power batteries under EPR system, and derives equilibrium solutions for each node enterprise in the CLSC regarding the optimal economic benefits of the secondary utilization of used power batteries. Secondly, this paper compared and analyzed CLSC members' equilibrium solution and profit distribution under different subsidy subjects, which can figure out the transfer path of profits and the effect of various targets of government subsidies on the competitiveness of the CLSC to obtain the optimal subsidy strategy. Finally, we simulated the economic efficiency and recovery rate graphs of each node firm in the CLSC by using numerical simulation to offer theoretical support for the government's subsidy policy execution and enterprise price decisions.

The following chapters are organized in this article. The second section contains a review of relevant literature to this work. Section 3 discusses the paper's key assumptions and model building. Section 4 investigates four models and determines the best choices. Section 5 carries out a numerical analysis. Section 6 summarizes the paper, its implications for management, and future avenues for research.

2. Literature Review

2.1. Analysis of the Economic and Environmental Benefits of Power Battery Recycling

When the capacity of the power battery is reduced by about 20%, its battery power will not meet the standard of new energy vehicles and needs to be replaced [30]. China's power battery retirement volume has already reached more than 20 GWh by 2020 and will increase rapidly in the next few years. The recovery and treatment of retired batteries will directly or indirectly affect the ecological environment, resources, and the development of the NEVS industry. Therefore, correct disposal of retired batteries has become the focus of current research [31,32].

The existing literature mainly studies the recycling technology for power batteries and the impact of recycled power batteries on the environment and economy [33,34]. Power battery recycling is the basis for achieving battery gradient use and material regeneration and is a prerequisite for ensuring the sustainable development of the NEVS ecosystem. Ensuring effective battery recycling cannot be achieved without policy guidance. Gradient utilization refers to the economical use of the residual value of used electric vehicle batteries [35]. Regarding the feasibility analysis of gradient utilization mode, Lv Y et al. [36] used instruments to detect the chemical properties of decommissioned batteries and found that the deep cycle life of decommissioned batteries could reach more than 750 times the current usage. Regarding the cost analysis of gradient utilization, Sandia National Laboratory (SNL) [37] studied and analyzed the re-application cost of retired power batteries and constructed a corresponding economic analysis model.

The study found that the secondary utilization of power batteries is not inevitable, and there are technical hurdles to overcome. The efficient recovery of power batteries is significant for resource development and social security. From the demand side, China's cobalt, lithium, and other power battery production necessary elements are scarce in reserves, and the extraction cost is high. Obtaining valuable metals required for material production by recycling and processing waste batteries can save on raw material costs and have a greater economic impact. From a social perspective, power battery recycling is in line with the concept of a sustainable development strategy to protect the environment

and reduce energy consumption, and has great social significance. The recycling and reuse of power batteries conform to the national policy orientation. They have a huge role in promoting the growth of a low-carbon economy and a more environmentally friendly society [38,39]. So, this research focuses on how to recover and recycle used power batteries effectively.

2.2. Research Related to CLSC Operation Decisions under Government Subsidies

Gu X et al. [40] used power batteries for NEVS as a background to demonstrate that government subsidies boosted remanufacturers' profits and promoted the development of the power battery remanufacturing industry. Chen et al. [41] thought that manufacturers and remanufacturers in a CLSC might be more likely to recycle if the government gave them money. Gu X et al. [42] further optimized the total CLSC profit for different battery life cycles by studying the optimal pricing strategy between manufacturers and remanufacturers. Ma et al. [43] compared the decision-making behavior of CLSC members with or without government subsidies by studying the impact of government subsidies on dual-channel CLSC and found that all CLSC members would benefit from government subsidies to various degrees. He P et al. [44] examined the government's subsidy approach for new and remanufactured items to determine the ideal channel layout and pricing decision for the producer and the optimal government subsidy level in each of these three channels. Hh Zhao et al. [45] analyzed how retailers' CSR efforts affected CLSC members' optimal decision making and coordination and analyzed the effect of different government incentives on CLSC coordination. The analysis shows that the improvement of total profit in the channel could be massive. Each member is incentivized to participate in recycling, and a tariff contract is designed to solve the problem of channel coordination. Vorasayan et al. [46] constructed a mathematical programming model, analyzed the relationship between the recycling price of waste products and their recycling quantities, and deeply studied the impact of the recycling quality and recycling cost of waste products on their CLSC. Pazoki & Zaccour et al. [47] explored the impact of different government subsidies on corporate CLSC decisions. By establishing an analytical model, Huaying Gu et al. [48] studied the impact of government subsidies, battery recycling, and wear aversion on the optimal production decisions of electric vehicle manufacturers. Mitra et al. [49] studied the incentive government subsidies' influence on the recycling pricing of manufacturers and remanufacturers in CLSC. Sun et al. [28] used the game method to study the choice of power battery recycling channels combined with carbon trading policy, power battery endurance and advertising influence. Considering the impact of the uncertainty of battery remaining capacity on CLSC in existing research, Liu developed two different models for manufacturer and retailer recycling to describe the uncertainty by the level of battery capacity required for remanufacturing [50]. Zheng et al. [29] discuss the manufacturers' back-channel selection and coordination mechanisms for designing CLSCs in dual-competitive sales channels and designs a revenue-sharing price contract that can effectively coordinate dual-channel CLSCs under different recycling channel structures.

This paper looks at the pricing decision problem of a three-level CLSC with multiple subsidy subjects based on previous research.

2.3. Research Related to CLSC Operation Decisions under EPR System

Many scholars have researched the CLSC based on the idea of the EPR system. Lin He 42 talked about the role of the EPR system in the game of each subject in the process of recycling power batteries. He concluded that if companies want to reduce the recycling cost of each subject, recycling raw battery materials into high-value-added products increases the profitability of remanufacturing and contributes to the sustainability of the recycling industry. De Giovanni et al. [51] proposed a CLSC model with operational and marketing advantages, using incentive strategies to implement coordinated solutions in the CLSC. Chen et al. [41] looked at cascade utilization from the point of view of CLSC coordination. They built a three-party game CLSC model based on the market environment and devel-

oped a new coordination contract. Current research shows that the operation of a CLSC under EPR is influenced by several different factors. Zan et al. [52] showed that producers are responsible for the whole life cycle of lead batteries. This significantly alleviates the environmental pollution caused by the illegal disposal of used lead batteries and contributes to the sustainable development of leadership resources. Zhong et al. [53] concentrated on the e-waste recycling model under an EPR deposit refund system, concentrating on the concerns of e-waste recycling channels and government subsidy policies, giving a fresh viewpoint for supply chain analysis. Yan et al. [54] used an evolutionary game model to analyze the effectiveness of the EPR system's reward and punishment mechanisms and constructed a producer-led reverse CLSC model to construct an effective producer-led reverse CLSC model under the conditions. Compared to that, they analyzed the channel choice of producers to carry out a reverse CLSC under different reward and punishment mechanisms. He and Sun constructed a system dynamics model to study the recycling mechanism of power batteries under the EPR regime using the supply side as the entry point [55]. Li et al. [21] found through the literature that the EPR system is mainly realized through tax and subsidy policies. Government subsidies can provide strong support for the development of NEVS, influence the choices of enterprises and the behavior of consumers, and play a significant role in the pricing decisions of the CLSC.

From Table 1 it can be seen that on the basis of the previous studies, this paper looks at the subsidy strategy for the CLSC of power batteries under extended producer responsibility and puts forward the corresponding strategy. In summary, there are few studies on the CLSC of power batteries under the existing EPR system and few on the pricing decisions of the three-tier CLSC considering multiple subsidies. Therefore, this paper considers the problem of pricing decisions and profit transfer in the CLSC of power batteries under the concept of EPR with multiple subsidies and different subsidy strategies. The results can be used to plan to recycle and remake power batteries under the EPR system and set up government subsidy policies.

Table 1. The related literature.

Author(s)	CLSC?	Subsidy?	EPR?	Power Battery?	Echelon Utilization?
Gu et al. (2021) [40]	√			√	√
Zhao et al. (2022) [41]	√		√	√	√
Gu et al. (2018) [42]	√			√	√
Ma et al. (2013) [43]	√	√			
Le et al. (2018) [21]	√	√			
He et al. (2019) [44]	√	√			
Pazoki et al. (2018) [47]		√			√
Gu et al. (2017) [48]		√		√	√
Mitra et al. (2008) [49]	√	√			
He et al. (2022) [55]		√	√	√	√
Sun et al. (2022) [28]	√			√	
Liu et al. (2022) [50]	√			√	√
Zheng et al. (2021) [29]	√	√			
Giovanni et al. (2016) [51]	√				
Zan et al. (2022) [52]		√	√	√	√
Zhong et al. (2012) [53]	√	√	√		
This paper	√	√	√	√	√

3. Problem Description and Assumption

In this paper, a single-cycle, three-stage CLSC system is constructed with the power battery manufacturer as the leading party and the vehicle manufacturer and retailer as the subordinate parties, the four models have different subsidy methods. The CLSC operation mode is as follows: the new power battery reaches the consumer through the forward CLSC and is returned to the battery manufacturer through the reverse CLSC after the battery

performance fails to meet the everyday driving needs of electric vehicles or is dismantled and no longer used for other reasons, as shown in Figure 1. Considering the nature of recycled used power batteries for secondary use, this paper divides the recycled power batteries into two types. The first power batteries are those with less than 80% capacity and can be directly reused, which can be sold as energy storage devices at P_1 after technical modifications. Power batteries of type 1 are recycled by the secondary recycler, a long-term partnership between the power battery manufacturer and the secondary recycler, with no upper limit on recycling capacity. Power batteries of type 2 can be recycled for precious metals, which are generally physically intact and easily recycled for precious metals.

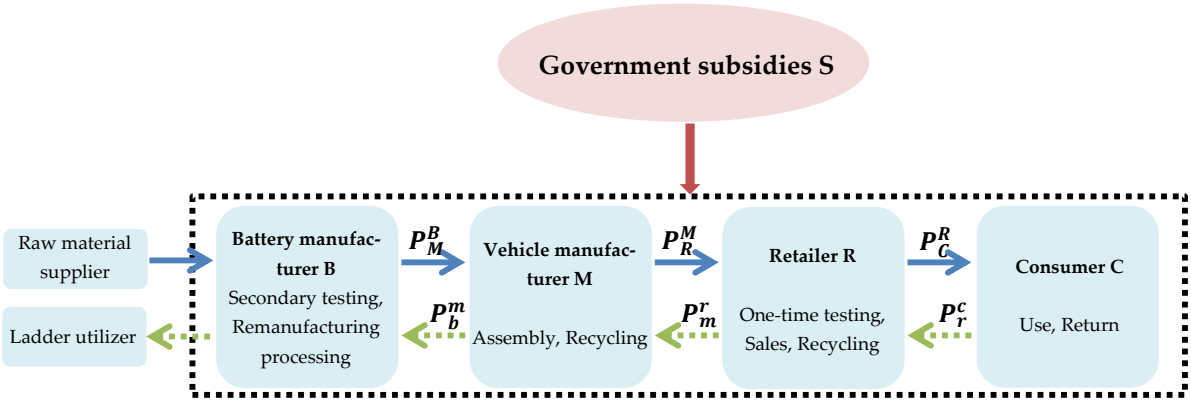


Figure 1. CLSC model for power batteries.

3.1. Description of Symbols

Referring to the model created by Heydari et al. [56] parameters are specified in Table 2.

Table 2. Model parameters.

Parameters			
C_n^B	New brake battery manufacturing cost	C_M	Complete vehicle manufacturer operation and cost recovery
C_r^B	Recycled battery manufacturing cost	C_R	Retailer operating and recovery costs
a	Environmental awareness of consumers	b	Consumer Recycling Price Sensitivity
k	Consumer Price Sensitivity Coefficient	D	The biggest demand in the market
θ	Market Recovery Price Sensitivity	α	Class I power battery proportion
Q_d^N	Power battery sales	$Q_r^N = a + bP_r^c$	Power battery recycling
P_1	Cascade utilization price	β	Distribution ratio of S_1
S_1	Recycling allowance	S_2	Remanufacturing subsidies
$\Delta = C_n^B - C_r^B$ Cost savings for battery manufacturers due to recycling			
Decision variables			
P_M^B	Wholesale pricing of power battery to automakers	P_b^m	Battery dealer recycling price
P_C^R	Retailer selling price	P_R^M	Retailer Wholesale Price
P_m^r	Battery recycling prices for complete vehicle manufacturers	P_r^c	Retailer Recovery Price

3.2. Model Assumption

The model in this paper discusses only the single cycle case. To better describe the model, with reference to the literature of Savaskan et al. [26], the following assumptions were made.

Assumption 1. *The production of power battery manufacturers is continuous, and their remanufacturing capacity is not limited. Furthermore, there are end-of-life power batteries on the market that can be remanufactured and sold with recycling value.*

Assumption 2. *Remanufactured power batteries are the same quality as new power batteries and are sold at the same price, and consumers cannot perceive the difference [57].*

Assumption 3. *Assumptions are made on the recycling of used batteries: firstly, retailers conduct a primary inspection, recycle old power batteries with recycling value and pay the corresponding recycling amount to consumers; then after recycling through the vehicle manufacturer, the power batteries are passed to the battery manufacturer for secondary inspection; finally, the type 1 power batteries that meet the requirements are sold to the gradient utilizer, and the power batteries that do not meet the requirements are remanufactured, where the selling price of type 1 power batteries is higher than the remanufacturing cost of type 2 power batteries, i.e.,* $P_1 > C_r^B$.

Assumption 4. *Under normal circumstances, battery testing, recycling and remanufacturing of used power by battery manufacturers, vehicle manufacturers, and retailers are all profitable, i.e.,*$P_r^c > P_m^r > P_b^m$*is satisfied.*

Assumption 5. *The proportion of type 1 powerbatteries in the recycling process is α.*

Assumption 6. *The recycling price has a catalytic effect on market demand and helps boost power battery sales, expressed as* $Q_d = D - KP_C^R + \theta P_r^c$ [58].

Assumption 7. *Considering that government subsidies for a single industry are limited, it is assumed that the total amount of government subsidies for each unit of recycling behavior in the CLSC is fixed, with remanufacturing subsidies for battery manufacturers and recycling and dismantling subsidies for vehicle manufacturers and retailers.*

4. Model and Analysis

In this section, different subsidy subjects may lead to completely different optimal decisions and determine which kind of subsidy is the best fit. Product pricing and optimal decision-making issues are examined under each model, exploring the impact of government subsidies on the distribution of benefits and the decisions of the various actors in the CLSC under the EPR regime.

4.1. No Government Subsidy Model N

According to the inverse solution method of Stackelberg's game theory, the profit analyzed under the no-subsidy model is as follows.

Battery manufacturer profits:

$$\pi_B^N = \left(P_M^B - C_n^B\right)Q_d^N + (\Delta - P_b^m)Q_r^N + \alpha P_1 Q_r^N \tag{1}$$

Complete vehicle manufacturer profits:

$$\pi_M^N = \left(P_R^M - P_M^B - C_M\right)Q_d^N + (P_b^m - P_m^r)Q_r^N \tag{2}$$

Retailer profits:

$$\pi_R^N = \left(P_C^R - P_R^M - C_R\right)Q_d^N + (P_m^r - P_r^c)Q_r^N \tag{3}$$

Conclusion 1. In the no-subsidy model, the results at game equilibrium are, respectively:

Optimal sales volume of power batteries:

$$Q_d^N = \frac{-k\left(a\theta - 2bD + 2kbC_n^B + 2kbC_M + 2kbC_R - b\theta\Delta - \theta\alpha bP_1\right)}{16kb - 4\theta^2} \tag{4}$$

Best wholesale prices for power batteries from the power battery manufacturer:

$$P_M^B = \frac{bD - a\theta - kbC_M + kbC_R + kbC_n^B}{2kb} \tag{5}$$

The best wholesale prices for power batteries from the complete vehicle manufacturer:

$$P_R^M = \frac{3bD - 3a\theta + kbC_M - 3kbC_R + kbC_n^B}{4kb} \tag{6}$$

Best selling price for power batteries sold by the retailer:

$$P_C^R = \frac{\left(2k^2b^2 - kb\theta^2\right)\left(C_n^B + C_M + C_R\right) + 3a\theta^3 + 14kb^2D - 3\theta^2bD - 13kab\theta + k\theta\alpha b^2P_1}{4kb(4kb - \theta^2)} \tag{7}$$

Optimal recycling volume of old power batteries:

$$Q_r^N = \frac{-a\theta^2 + 2kab + b\theta D + 2kb^2\Delta + 2k\alpha b^2P_1 - kb\theta\left(C_n^B + C_M + C_R\right)}{4(4kb - \theta^2)} \tag{8}$$

Optimal recycling price for old power batteries:

$$P_r^c = \frac{3a\theta^2 - 14kab + b\theta D + 2kb^2\Delta + 2k\alpha b^2P_1 - kb\theta\left(C_n^B + C_M + C_R\right)}{4b(4kb - \theta^2)} \tag{9}$$

The best recycling price paid by the vehicle manufacturer to the retailer:

$$P_m^r = \frac{\Delta b - 3a + \alpha bP_1}{4b} \tag{10}$$

Battery manufacturers pay vehicle manufacturers the best recycling price:

$$P_b^m = \frac{\Delta b - a + \alpha bP_1}{2b} \tag{11}$$

The optimal profits for battery producers:

$$\pi_B^N = \frac{b\left(kC_n^B + kC_M + kC_R - D\right)^2 + \left(ka\theta - k\alpha b\theta P_1 - kb\theta\Delta\right)\left(C_n^B + C_M + C_R\right) + \alpha bDP_1}{16kb - 4\theta^2} \tag{12}$$

Best margins for the complete vehicle manufacturer:

$$\pi_M^N = \frac{b\left(kC_n^B + kC_M + kC_R - D\right)^2 + \left(ka\theta - k\alpha b\theta P_1 - kb\theta\Delta\right)\left(C_n^B + C_M + C_R\right) + \alpha bDP_1}{32kb - 8\theta^2} \tag{13}$$

The optimal profit for the retailer:

$$\pi_R^N = \frac{b\left(kC_n^B + kC_M + kC_R - D\right)^2 + \left(ka\theta - k\alpha b\theta P_1 - kb\theta\Delta\right)\left(C_n^B + C_M + C_R\right) + \alpha bDP_1}{64kb - 16\theta^2} \tag{14}$$

The optimal total profit for a CLSC under the N model:

$$\pi_N = \frac{7b\left(kC_n^B + kC_M + kC_R - D\right)^2 + 7\left(ka\theta - k\alpha b\theta P_1 - kb\theta\Delta\right)\left(C_n^B + C_M + C_R\right) + 7\alpha bDP_1}{64kb - 16\theta^2} \tag{15}$$

Theorem 1. *when* $0 < \theta < \sqrt{4kb}$, *Optimal profit exists for CLSC.*

Proof. See Appendix A. Similar to Theorem 1, the following proof process of all of the Theorem and the propositions will be omitted in this paper. See the Appendix A for the specific proof process. □

In model N, the profit distribution ratios of the CLSC are Battery manufacturer: $R_B^N = \frac{4}{7}$, vehicle manufacturer: $R_M^N = \frac{2}{7}$ and retailer: $R_R^N = \frac{1}{7}$.

Equation (15) shows that the profits of the battery manufacturer, vehicle manufacturer and retailer in the power battery CLSC are positively correlated with the proportion of Type 1 power batteries and increasing the proportion of Type 1 power batteries can effectively improve the benefits of each main body in the CLSC. The results of Equations (4) and (8) show that under the model without government subsidies, both recycling and sales volumes are influenced by the market price sensitivity coefficient k, and companies have greater risk in the event of market fluctuations. Therefore, to ensure market stability and increase the motivation of enterprises in the CLSC to participate in recycling, the next section will explore the CLSC model for power batteries under government-subsidized retailers.

4.2. Subsidized Retailer Model R

In order to motivate retailers to participate in power battery recycling, this section considers the CLSC for government-subsidized retailers, i.e., the government provides a recycling subsidy per unit of product to the retailer, based on the assumption that the profit of each entity is expressed as:

Battery manufacturer profits:

$$\pi_B^R = \left(P_M^B - C_n^B\right)Q_d^R + (\Delta - P_b^m)Q_r^R + \alpha P_1 Q_r^R \tag{16}$$

Complete vehicle manufacturer profits:

$$\pi_M^R = \left(P_R^M - P_M^B - C_M\right)Q_d^R + (P_b^m - P_m^r)Q_r^R \tag{17}$$

Retailer profits:

$$\pi_R^R = \left(P_C^R - P_R^M - C_R\right)Q_d^R + (S_1 + P_m^r - P_r^c)Q_r^R \tag{18}$$

Conclusion 2. The results in the CLSC of the subsidized retailer, when the game is in equilibrium, are respectively:

Optimal sales volume of power batteries:

$$Q_d^R = \frac{k\left(2bD - a\theta - 2kbC_n^B - 2kbC_M - 2kbC_R + b\theta S_1 + b\theta\Delta + \alpha b\theta P_1\right)}{16kb - 4\theta^2} \tag{19}$$

Best wholesale prices for power batteries from the power battery manufacturer:

$$P_M^B = \frac{bD - a\theta - kb\left(C_M + kbC_R - kbC_n^B\right)}{2kb} \tag{20}$$

The best wholesale prices for power batteries from the complete vehicle manufacturer:

$$P_R^M = \frac{3bD - 3a\theta + kb\left(C_n^B + C_M - 3C_R\right)}{4kb} \tag{21}$$

Best selling price for power batteries sold by the retailer:

$$P_C^R = \frac{\left(2k^2b^2 - kb\theta^2\right)\left(C_n^B + C_M + C_R\right) + bk\theta(bS_1 + b\Delta - 13\mathrm{a}) - 3\theta^2(a - bD) + 14kb^2D + K\theta\alpha b^2\mathrm{P}_1}{4kb(4kb - \theta^2)} \tag{22}$$

Optimal recycling volume of old power batteries:

$$Q_r^R = \frac{-a\theta^2 + 2kab + b\theta D + 2kb^2S_1 + 2kb^2\Delta + 2k\alpha b^2P_1 - kb\theta\left(C_n^B + C_M + C_R\right)}{16kb - 4\theta^2} \tag{23}$$

Optimal recycling price for old power batteries:

$$P_r^c = \frac{3a\theta^2 - 14kab + b\theta D + 2kb^2\Delta + 2kb^2S_1 + 2k\alpha b^2P_1 - kb\theta\left(C_n^B + C_M + C_R\right)}{4b(4kb - \theta^2)} \tag{24}$$

The best recycling price paid by the vehicle manufacturer to the retailer:

$$P_m^r = \frac{\Delta b - 3a + \alpha bP_1 - 3bS_1}{4b} \tag{25}$$

Best recycling price of battery manufacturers that pay the vehicle manufacturer:

$$P_b^m = \frac{-a - bS_1 + b\Delta + \alpha bP_1}{2b} \tag{26}$$

The optimal profits for the battery producer:

$$\pi_B^R = \frac{ak^2 + bA_3 - \theta(D - kA_2)a - bA1 - a\theta^2A_1}{16kb - 4\theta^2} \tag{27}$$

$$A_1 = S_1 + \Delta + \alpha P_1$$

$$A_2 = C_n^B + C_M + C_R$$

$$A_3 = D^2 - 2kDA_2 + k\left(kA_2{}^2 + 2aA_1 + bA_1{}^2\right)$$

Best margins for the complete vehicle manufacturer:

$$\pi_M^R = \frac{ak^2 + bA_3 - \theta(D - kA_2)a - bA1 - a\theta^2A_1}{32kb - 8\theta^2} \tag{28}$$

The optimal profit for the retailer:

$$\pi_R^R = \frac{ak^2 + bA_3 - \theta(D - kA_2)a - bA1 - a\theta^2A_1}{64kb - 16\theta^2} \tag{29}$$

The optimal total profit for a CLSC under the R model:

$$\pi_R = \frac{7ak^2 + bA_3 - 7\theta(D - kA_2)a - bA1 - 7a\theta^2A_1}{64kb - 16\theta^2} \tag{30}$$

Theorem 2. *when* $0 < \theta < \sqrt{4kb}$, *Optimal profit exists for CLSC.*

In model R, the profit distribution ratios of the CLSC are battery manufacturer: $R_B^R = \frac{4}{7}$, vehicle manufacturer: $R_M^R = \frac{2}{7}$ and retailer: $R_R^R = \frac{1}{7}$.

From conclusion 2, it can be seen that the profits of all three entities increase with the increase in remanufacturing cost savings. The results of Equations (19) and (23) show that the sales and recycling volumes of power batteries are positively correlated with the savings in remanufacturing costs, suggesting that cost savings are beneficial to the improvement of CLSC performance. At the same time, government subsidies to retailers positively affect the sales and recycling of power batteries. Therefore, the amount of cost savings from remanufacturing and the increase in government subsidies to retailers are both relevant to the motivation of companies in the CLSC to participate in recycling. So, the CLSC model of subsidized retailers and vehicle manufacturers will be explored in the next section.

4.3. Subsidized Retailer and Complete Vehicle Manufacturer Model RM

In order to motivate the retailer and vehicle manufacturer to participate in recycling, this section considers a CLSC that subsidizes both retailers and vehicle manufacturers.

Since the recycling subsidy S_1 is fixed, we assume that β is the share of subsidized M vehicle manufacturers and $1-\beta$ is the share of subsidized R retailers, i.e., $S_1 = \beta S_1 + (1-\beta)S_1$. Based on the assumptions, the profit of each entity is expressed as:

Battery manufacturer profits:

$$\pi_B^{RM} = \left(P_M^B - C_n^B\right)Q_d^M + (\Delta - P_b^m)Q_r^M + \alpha P_1 Q_r^M \tag{31}$$

Complete vehicle manufacturer profits:

$$\pi_M^{RM} = \left(P_R^M - P_M^B - C_M\right)Q_d^M + (\beta S_1 + \mathrm{P_b^m} - \mathrm{P_m^r})Q_r^M \tag{32}$$

Retailer profits:

$$\pi_R^{RM} = \left(P_C^R - P_R^M - C_R\right)Q_d^M + [1 - \beta S_1 + \mathrm{P_m^r} - \mathrm{P_r^c}]Q_r^M \tag{33}$$

Conclusion 3. Optimal sales volume of power batteries:

$$Q_d^{RM} = \frac{bD + a\theta - kb\left(C_n^B + C_M + C_R\right)}{8b} + \frac{\theta\left(3a\theta^2 - 7kab + \alpha b^2 kP_1 + kb^2 S_1 + kb^2\Delta\right)}{4b(2kb - \theta^2)} \tag{34}$$

Best wholesale prices for power batteries from the power battery manufacturer:

$$P_M^B = \frac{Db + a\theta - kb\left(C_M + C_R - C_n^B\right)}{2kb} \tag{35}$$

The best wholesale prices for power batteries from the complete vehicle manufacturer:

$$P_R^M = \frac{-2a\theta^3 + 6kb^2\mathrm{D} - 3\mathrm{b}\theta^2\mathrm{D} + 5kab\theta^{-}kb^2\theta A_1 + \left(2k^2b^2 - kb\theta^2\right)\left(C_n^B + C_M - 3C_R\right)}{4kb(2kb - \theta^2)} \tag{36}$$

Best selling price for power batteries sold by the retailer:

$$P_C^R = \frac{7bD - a\theta + kb\left(C_n^B + C_M + C_R\right)}{8kb} \tag{37}$$

Optimal recycling volume of old power batteries:

$$Q_r^{RM} = \frac{-a\theta^2 + kab + \alpha b^2 kP_1 + kb^2 S_1 + kb^2\Delta}{4(2kb - \theta^2)} \tag{38}$$

Optimal recycling price for old power batteries:

$$P_r^c = \frac{3a\theta^2 - 7kab + \alpha b^2 kP_1 + kb^2 S_1 + kb^2\Delta}{4b(2kb - \theta^2)} \tag{39}$$

The best recycling price paid by the vehicle manufacturer to the retailer:

$$P_m^r = \frac{5a\theta^2 - 6kab - b\theta D + 2\alpha b^2 kP_1 - 6kb^2 S_1 + 2kb^2\Delta + 8ksb^2\beta + kb\theta\left(C_n^B + C_M + C_R\right)}{8kb^2} \tag{40}$$

Battery manufacturers pay the vehicle manufacturer the best recycling price:

$$P_b^m = \frac{a\theta^2 - kab + \alpha b^2 kP_1 - kb^2 S_1 + kb^2\Delta}{2kb^2} \tag{41}$$

Optimal profits for the battery producer:

$$\pi_B^{RM} = \frac{(bA_3 + a\theta)^2\left(2kb - \theta^2\right) + 4\alpha b^2 k P_1 A_4 + 2{A_4}^2}{16kb^2(2kb - \theta^2)} \tag{42}$$

$$A_3 = D - kA_2$$

$$A_4 = bk(a + bA_1) - a\theta^2$$

Best margins for the complete vehicle manufacturer:

$$\pi_M^{RM} = \frac{b(bA_3 + a\theta)[\theta(ak - \theta A_3) - bk(-2A_3 + \theta A_2)]}{32kb^2(2kb - \theta^2)} \tag{43}$$

Optimal profit for the retailer:

$$\pi_R^{RM} = \frac{(A_5 + A_6)^2 + 2A_4(A_7 + bA_8)}{64kb^2(2kb - \theta^2)^2} \tag{44}$$

$$A_5 = 5\mathrm{a}\theta^3 + b\theta(-12ak - \theta D + kA_2 D)$$

$$A_6 = 2kb^2 A_3 + \theta A_1$$

$$A_7 = \mathrm{a}\left(2k^2b^2 + 10\mathrm{bk}\theta^2 - 5\theta^4\right)$$

$$A_8 = 2k^2b^2A_1 + \theta^3 A_3 - 2kb\theta(\theta A_1 + A_3)$$

Optimal total profit for a CLSC under the RM model:

$$\pi_{RM} = \frac{28b^5k^3{A_1}^2 - 126a^2kb\theta^4 + 29a^2\theta^6 + 4k^2b^4A_9 + 2kb^3A_{10} + b^2\theta^2A_{11}}{64kb^2(2kb - \theta^2)^2} \tag{45}$$

$$A_9 = 7\mathrm{D}^2 + 7k^2\ {A_2}^2 + 14\mathrm{akA_1} - \mathrm{k}\theta A_1 * A_2 - 3\theta^2{A_1}^2 + d(-14A_2 + \theta A_1)$$

$$A_{10} = 14a^2k^2 - 2ak\theta(A_3 + 27\theta A_1 - \theta^2 A_3(14A_3 + \theta A_1))$$

$$A_{11} = 124a^2k^2 + 7\theta^2{A_3}^2 + 2ak\theta(A_3 + 19\theta A_1)$$

Theorem 3. *when* $0 < \theta < \sqrt{4\mathrm{kb}}$, *Optimal profit exists for CLSC.*

In model RM, the profit distribution ratios of the CLSC are:
Battery manufacturer:

$$R_B^{RM} = \frac{4[A_{12}\left(2kb - \theta^2\right) + a^2\theta^4 + 2ab\theta^2(-ak - \theta D + k\theta\mathrm{A_2}) + b^2A_{13}]}{28b^5k^3{A_1}^2 - 126a^2kb\theta^4 + 29a^2\theta^6 + 4k^2b^4A_9 + 2kb^3A_{10} + b^2\theta^2A_{11}} \tag{46}$$

Complete vehicle manufacturer:

$$R_M^{RM} = \frac{2\left[A_{12}\left(2kb - \theta^2\right) + a^2\theta^4 + 2ab\theta^2(-ak - \theta D + k\theta\mathrm{A_2}) + b^2A_{13}\right]}{28b^5k^3{A_1}^2 - 126a^2kb\theta^4 + 29a^2\theta^6 + 4k^2b^4A_9 + 2kb^3A_{10} + b^2\theta^2A_{11}} \tag{47}$$

Retailer:

$$R_R^{RM} = \frac{A_{12}\left(2kb - \theta^2\right) + a^2\theta^4 + 2ab\theta^2(-ak - \theta D + k\theta\mathrm{A_2}) + b^2A_{13}}{28b^5k^3{A_1}^2 - 126a^2kb\theta^4 + 29a^2\theta^6 + 4k^2b^4A_9 + 2kb^3A_{10} + b^2\theta^2A_{11}} \tag{48}$$

$$A_{12} = 2k^2b^4{A_1}^2 + 2kb^3\left(\mathrm{D}^2 - 2\mathrm{kDA_2} + k^2{A_2}^2 + 2\mathrm{akA_1}\right)$$

$$A_{13} = 2a^2k^2 - \theta^2(D - kA_2)^2 - 4ak\theta(-D + \theta A_1 + kA_2)$$

Conclusion 3 shows that the profit of each entity is positively correlated with the cost savings, indicating that the increase in remanufacturing cost savings Δ leads to higher profits for retailers and further increases in power battery sales and recycling volumes. In other words, the higher the remanufacturing cost savings, the more motivated the CLSC nodes are to participate in reverse recycling. However, in addition to the vehicle manufacturers and retailers, the power battery manufacturers are the primary bearers of the EPR system; whether the subsidies imposed on them can more effectively influence the utility of the CLSC will be explored in the next section of this paper.

4.4. Subsidized All Themes Model A

Power battery manufacturers are the most important members of the power battery CLSC, responsible for product development, production and after-sales service. In the CLSC, power battery manufacturers must also take on the task of recycling and manufacturing used power batteries in cooperation with vehicle manufacturers. Batteries are one of the core components of electric vehicles, yet the scarcity of resources drives up the price of batteries. As a result, governments often implement tax credits for power battery manufacturers to stimulate continued investment in the power battery manufacturing and remanufacturing process, indirectly increasing the profitability of producing and recycling vehicles. This section introduces S_2 separate subsidies for power battery manufacturers based on subsidized RM for both the manufacturing and recycling segments of the power battery manufacturer. The profit of each entity is expressed as:

Profits of the battery manufacturer:

$$\pi_B^A = \left(P_M^B - C_n^B\right)Q_d^M + (\Delta - P_b^m + S_2)Q_r^M + \alpha P_1 Q_r^M \tag{49}$$

Profits of the complete vehicle manufacturer:

$$\pi_M^A = \left(P_R^M - P_M^B - C_M\right)Q_d^M + (\beta S_1 + P_b^m - P_m^r)Q_r^M \tag{50}$$

Profits of the retailer:

$$\pi_R^A = \left(P_C^R - P_R^M - C_R\right)Q_d^M + [1 - \beta S_1 + P_m^r - P_r^c]Q_r^M \tag{51}$$

Conclusion 4. Optimal sales volume of power batteries:

$$Q_d^A = \frac{2kbD - ak\theta - 2k^2b\left(C_n^B + C_M + C_R\right) + kb\theta(S_1 + S_2 + \Delta + \alpha P_1)}{4(4kb - \theta^2)} \tag{52}$$

Best wholesale prices for power batteries from the power battery manufacturer:

$$P_M^B = \frac{-a\theta + bD - k\left(C_M + C_R - C_n^B\right)}{2kb} \tag{53}$$

The best wholesale prices for power batteries from the complete vehicle manufacturer:

$$P_R^M = \frac{3Db - 3a\theta + k\left(C_n^B + C_M - 3C_R\right)}{4kb} \tag{54}$$

Best selling price for power batteries sold by the retailer:

$$P_C^R = \frac{3a\theta^3 + 14kb^2D - 3b\theta^2D - 13kab\theta + \left(2k^2b^2 - kb\theta^2\right)A_1 + kb^2\theta(S_1 + S_2 + \Delta + \alpha P_1)}{4kb(4kb - \theta^2)} \tag{55}$$

Optimal recycling volume of old power batteries:

$$Q_r^A = \frac{2kab - a\theta^2 + b\theta D - kb\theta A_1 + 2kb^2(S_1 + S_2 + \Delta + \alpha P_1)}{4(4kb - \theta^2)} \tag{56}$$

Optimal recycling price for old power batteries:

$$P_r^c = \frac{3a\theta^2 - 14kab + b\theta D + 2kb^2(S_1 + S_2 + \Delta + \alpha P_1) - kb\theta A_1}{4b(4kb - \theta^2)} \tag{57}$$

The best recycling price paid by the vehicle manufacturer to the retailer:

$$P_m^r = \frac{bS_1 + bS_2 + b\Delta - 3a + \alpha bP_1 - 2b\beta S_1}{4b} \tag{58}$$

Battery manufacturers pay vehicle manufacturers the best recycling price:

$$P_b^m = \frac{-a + b\Delta - bS_1 + bS_2 + \alpha bP_1}{2b} \tag{59}$$

Optimal profits for battery producers:

$$\pi_B^A = \frac{bA_3{}^2 - A_{14}A_2 + D\theta A_{15} + A_{16} + k(bS_1 + bS_2)^2 + 2kbA_{17} + k(a + \Delta b)^2 - a\theta^2 A_{18}}{16kb - 4\theta^2} \tag{60}$$

$$A_{14} = k\alpha b\theta P_1 + kb\theta S_1 + kb\theta S_2 - ka\theta + kb\Delta\theta$$

$$A_{15} = \alpha bP_1 + bS_1 + bS_2 + \Delta b - a$$

$$A_{16} = k\alpha bP_1(\alpha bP_1 + 2bS_1 + 2bS_2 + 2a + 2\Delta b)$$

$$A_{17} = aS_1 + \Delta bS_1 + aS_2 + \Delta bS_2$$

$$A_{18} = \alpha P_1 + S_1 + S_2 + \Delta$$

Best margins for complete vehicle manufacturers:

$$\pi_M^A = \frac{bA_3{}^2 - A_{14}A_2 + D\theta A_{15} + A_{16} + k(bS_1 + bS_2)^2 + 2kbA_{17} + k(a + \Delta b)^2 - a\theta^2 A_{18}}{32kb - 8\theta^2} \tag{61}$$

Optimal profit for retailers:

$$\pi_R^{\mathrm{A}} = \frac{bA_3{}^2 - A_{14}A_2 + D\theta A_{15} + A_{16} + k(bS_1 + bS_2)^2 + 2kbA_{17} + k(a + \Delta b)^2 - a\theta^2 A_{18}}{64kb - 16\theta^2} \tag{62}$$

Optimal total profit for a CLSC under the A model:

$$\pi_A = 7\left(\frac{bA_3{}^2 - A_{14}A_2 + D\theta A_{15} + A_{16} + k(bS_1 + bS_2)^2 + 2kbA_{17} + k(a + \Delta b)^2 - a\theta^2 A_{18}}{64kb - 16\theta^2}\right) \tag{63}$$

Theorem 4. *when* $0 < \theta < \sqrt{4kb}$, *Optimal profit exists for CLSC.*

Theorem 5. *In model A, the profit distribution ratios of the CLSC are Battery manufacturer:* $\mathrm{R}_B^{\mathrm{A}} = \frac{4}{7}$, vehicle manufacturer: $\mathrm{R}_M^A = \frac{2}{7}$ and retailer: $R_R^A = \frac{1}{7}$.

Theorem 6. $\forall\ b, k, \theta \in R,\ \frac{\partial P_{rN}^c}{\partial \Delta}, \frac{\partial P_{rR}^c}{\partial \Delta}, \frac{\partial P_{rA}^c}{\partial \Delta}, \frac{\partial Q_{rN}^c}{\partial \Delta}, \frac{\partial Q_{rR}^c}{\partial \Delta}, \frac{\partial Q_{rA}^c}{\partial \Delta}, \frac{\partial Q_{dN}^c}{\partial \Delta}, \frac{\partial Q_{dR}^c}{\partial \Delta}, \frac{\partial Q_{dA}^c}{\partial \Delta} > 0.$

By analyzing the optimal sales volume, power battery sales price, power battery recycling price and optimal recycling volume in the four models, this indicates that the more is saved by the closed-loop supply chain remanufacturing under the subsidy model of N, R and A, the greater the recovered quantity and market sales will be. This is because with the increase in cost savings from remanufacturing, the optimal recycling price of products increases, which leads consumers to be more inclined to participate in purchasing and recycling behaviors under the influence of the reverse recycling price sensitivity coefficient and the positive recycling price sensitivity coefficient. Recycling and sales will therefore rise.

5. Numerical Analysis

In order to make the research more practical, and also to verify the previous conclusions and theorems, it is necessary to further explore the impact of different subsidy models and scale effect coefficients on the optimal profits of the power battery retailer, the vehicle manufacturer and the echelon power battery manufacturer, as well as consumers. The impact of sensitivity to the recycling price per unit of waste produced on the optimal solution. In this paper, taking used lithium power batteries as an example, let the cost of producing a new product for a power battery manufacturer be 70, the cost of assembly and operation for a whole vehicle manufacturer to participate 40, and the cost of sales and recycling operation for a retailer to participate in 25, the unit utilization value of type 1 power batteries be 30 and the remaining parameters be $k = 100$; $a = 80$; $D = 20000$; $\theta = 70$; $b = 40$; $\Delta = 30$.

5.1. Internal Analysis of Each Model

(1) Only subsidized retailers

The changes in the recovery rate and profit of each subject with recovery subsidy under Model R are shown in Figures 2 and 3. From the figures, it can be seen that when the government only subsidizes retailers, the amount of recovery subsidy per unit significantly contributes to the growth of both recovery rate and profit, which is positively correlated with the growth in profits. In contrast, the contribution to the recovery rate keeps slowing until it plateaus. The fluctuation of the recycling subsidy will not affect the profit distribution of each main body in the CLSC, which is manifested in that the proportion of profit distribution in the CLSC is not equal. Following the change, it is still 4:2:1. Therefore, to promote the development of the CLSC industry, the government should try to avoid over- or under-subsidizing retailers. At this time, the retailer's recovery rate has the fastest growth rate, achieving a multiplier effect with half the effort.

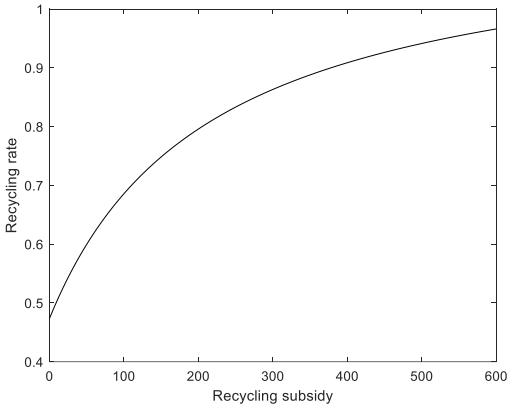


Figure 2. Variation in recovery rate with recovery subsidy under Model R.

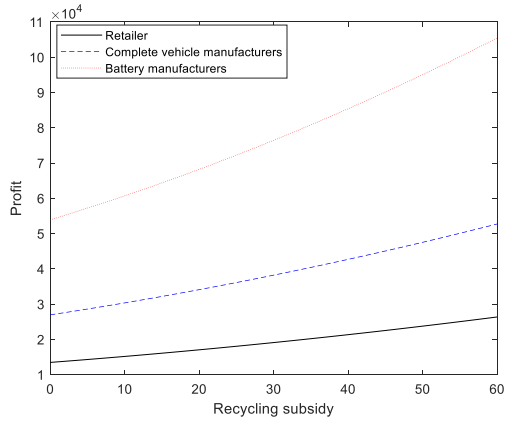


Figure 3. Variation in profit with recovery subsidy for each entity under Model R.

(2) Both retailers and complete vehicle manufacturers are subsidized

Figures 4 and 5 show the change in the recovery rate and profit of each entity with recovery subsidies under Model RM. It can be seen from the figures that when the government subsidizes retailers and vehicle manufacturers at the same time, the recovery subsidy affects the recovery rate and profits. There are promotion effects, in which the profit growth is linear, and the promotion effect of recovery rate is slowing down until stable. Under this model, subsidies significantly boost retailer's profits, as evidenced by the fact that as subsidies increase, the retailer's profits grow at a higher rate than those of the vehicle manufacturer until their profits reverse that of the vehicle manufacturer. At this time, vehicle manufacturers and power battery manufacturers have the fastest profit growth, while power battery manufacturers, as the main bearers of the EPR system, have the highest profits. This can promote the recycling of power batteries.

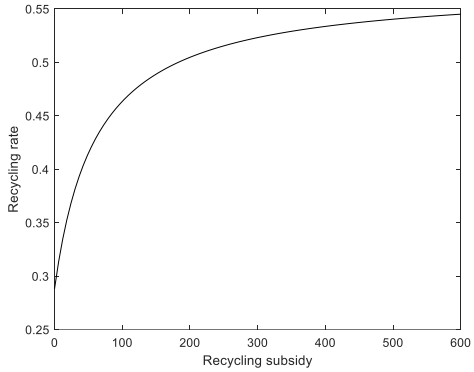


Figure 4. Variation in recovery rate with recovery subsidy under Model RM.

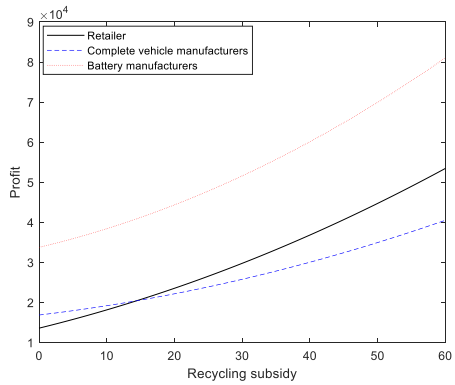


Figure 5. Variation in profit with recovery subsidy for each entity under Model RM.

(3) Subsidized retailers, vehicle manufacturers and power battery producers

Figures 6 and 7 represent the variation of recovery rate and profit of each subject with recovery subsidy under Model A. It can be seen from the figure that when the government subsidizes the three at the same time, the recycling subsidy and the remanufacturing subsidy have both effects on the recycling rate and profit.

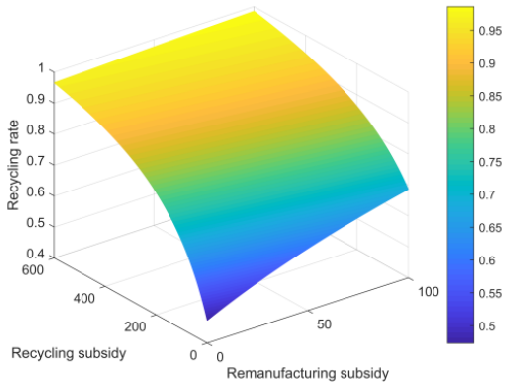


Figure 6. Variation in recovery rate with subsidy under Model A.

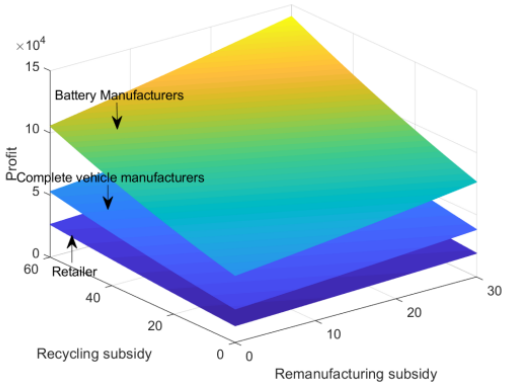


Figure 7. Variation in profit with subsidy for each entity under Model A.

With the promotion effect, the growth of profits is linear, and the effect of remanufacturing subsidies on the profits of power battery manufacturers is obvious. The promotion effect of recycling subsidies on the recycling rate has slowed until stable. The promoting effect of remanufacturing subsidies on the recycling rate is linear, and the effect is obvious. Power battery manufacturers have the highest profits, followed by vehicle manufacturers and retailers. With the increase in unit power battery subsidies, the profits of all entities under the three models have shown an upward trend. The profits of power battery manufacturers have risen more significantly than vehicle manufacturers and retailers. When the recycling subsidy fluctuates, the profit distribution ratio in the CLSC remains unchanged at 4:2:1. The government's remanufacturing subsidies to power battery manufacturers significantly affect their profits, while the changes in the profits of vehicle manufacturers and retailers are relatively modest.

Therefore, the government should adopt a medium level of subsidy for retailers and vehicle manufacturers while providing a small amount of remanufacturing subsidy to power battery manufacturers when the profit growth rate of the three entities is the fastest. Power battery manufacturers, as the primary bearers of the EPR system, earn the highest profits within the model, which contributes to the promotion of power battery recycling and enhancing the utility of the entire CLSC.

5.2. Comparative Analysis of the Models

The changes in total CLSC profit and power battery recycling rate with subsidies under each model are shown in Figures 8 and 9. Under the four models, the total CLSC profit and recycling rate of Model A, Model R and Model RM are all on an upward trend as the number of subsidies increases. Among them, the promotion effect of recycling subsidies on the recycling rate of each main body continuously slows down until it plateaus, while the promotion effect of remanufacturing subsidies on the recycling rate of Model A is linear and has a significant effect.

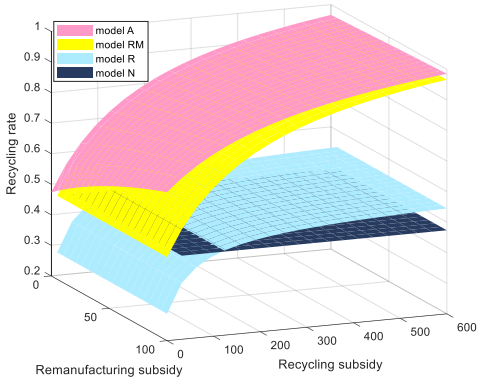


Figure 8. Variation in power battery recycling rates with subsidy for each model.

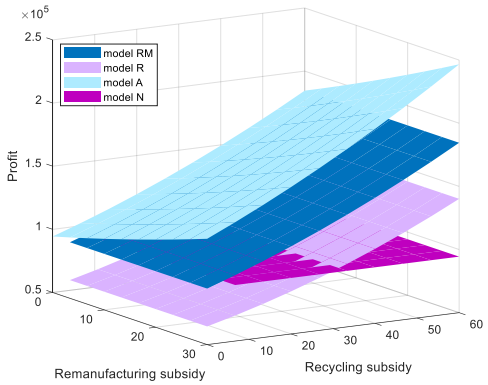


Figure 9. Variation in total supply chain profit with subsidy for each model.

The above show that appropriate government subsidies significantly affect the CLSC's overall profit stimulation. Compared with other models, Model A has the highest total CLSC profit and power battery recovery rate, followed by Model RM. The total CLSC profit and power battery recovery rate of the above two models are always higher than those of Model N. In comparison, it can be found that Model A has obvious advantages. When the subsidy amount is small, the profit under the subsidy-only retailer model is lower than that under the unsubsidized model, and the subsidy effect is not ideal. At the same time, the recovery rate of Model R is always lower than that of Model N, indicating that only subsidizing retailers cannot improve the utility of reverse CLSCs. It is suggested that the government should try its best to subsidize all subjects of the CLSC when the total amount of subsidies is limited.

Figures 10 and 11 show the changes in the total profit of CLSC and the amount of power battery recycling in each mode. In the four models, with the improvement of the echelon utilization rate, the total CLSC profit and the recycling volume of the four models show an upward trend. Among them, the promotion effect on the CLSC total profit recovery of the four models is linear, and the effect is more obvious.

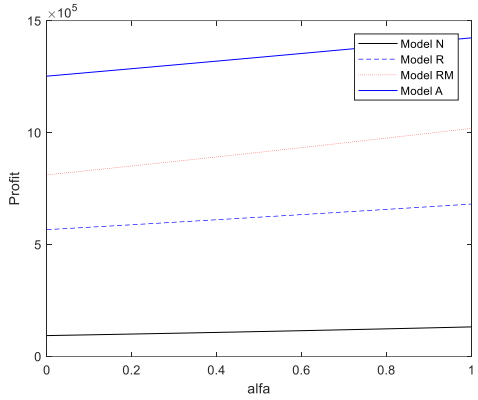


Figure 10. Variation in total supply chain profit with ladder utilization for each model.

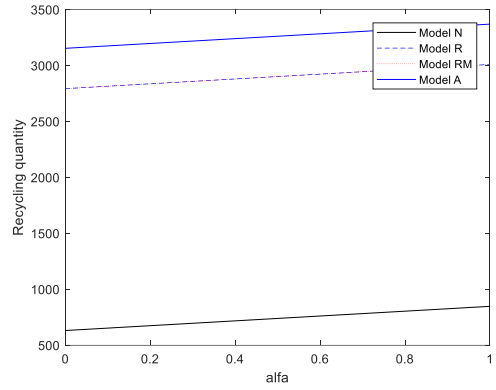


Figure 11. Variation in power battery recycling with ladder utilization for each model.

The above situation shows that echeloned utilization has a significant stimulating effect on the overall profit of CLSC. Compared with other modes, mode A has the highest total profit of CLSC and the recovery of power batteries, and the increase in the echeloned utilization rate has a significantly stronger effect on Model RM and Model A than Model R and Model N, which proves that under these two subsidy conditions, the increased echeloned utilization can help improve the overall profit of the supply chain. In addition, the recycling volume of Model A, Model R, and Model RM is significantly higher than that of the unsubsidized model N, indicating that the effect of subsidies is conducive to the recovery of power batteries.

6. Discussion and Management Implications

With the acceleration of industrialization and urbanization, the contradiction between resource shortage and environmental pollution has become increasingly acute. Governments around the world have attached great importance to participating in the recycling process of CLSC. This paper considers the decision-making problems of subsidizing retailers, subsidizing retailers, and vehicle manufacturers, and subsidizing all subjects of CLSC. By analyzing these three models, this paper draws a series of conclusions, some of which can be confirmed by previous related research. In the process of recycling power batteries, Lin He [55] talked about the role of the EPR system in the game of each subject. He concluded that if companies want to reduce the recycling cost of each subject, recycling raw battery materials into high-value-added products increases the profitability of remanufacturing and contributes to the sustainability of the recycling industry. Zhong et al. [53] concentrated on the e-waste recycling model under an EPR deposit refund system, concentrating on the concerns of e-waste recycling channels and government subsidy policies, giving a fresh viewpoint for supply chain analysis. Zhao et al. [45] analyzed how retailers' CSR efforts affected CLSC members' optimal decision making and coordination and analyzed the effect of different government incentives on CLSC coordination. The analysis

shows that the improvement of total profit in the channel can massively improve. Each member is incentivized to participate in recycling, and a tariff contract is designed to solve the problem of channel coordination. This is consistent with this conclusion, and similar conclusions can be found in the above studies. As described in Section 5, we replace the various parameters of CLSC with numerical quantities. When the government subsidy S is 0, CLSC can be regarded as no government subsidy. Therefore, from Figures 8 and 9, we can clearly find that the profit of CLSC and the recovery rate of power batteries increase with the increase of government subsidies. In addition, Figure 6 shows that a small amount of remanufacturing subsidies given to power battery manufacturers, the main bearers of the EPR system, has a significant effect on the recovery rate of power batteries. The bearers of the EPR system for different products, such as mobile phones and household appliances, are different. Therefore, this study can also guide the decision making of different industries, which is helpful for the promotion of the EPR system in the recycling industry chain. In Figure 2, the economic benefit and recovery rate of each node enterprise in CLSC are simulated by numerical simulation, which provides theoretical support for the implementation of government subsidy policy and enterprise price decision making.

7. Conclusions and Outlook

Based on the current era of vigorously promoting the EPR system in China, this paper designs and solves the CLSC member models under four different subsidy strategies for the design of government subsidy strategies in the CLSC, determines the most efficient optimal sales channel pricing and recycling channel pricing, and finally compares the impact of the profit range of each member of the CLSC and the profit distribution ratio of the CLSC under different subsidy objects. Through the comparative analysis and discussion of the models, the following main conclusions are drawn:

(1) A change in government subsidy objects will not impact the CLSC's profit distribution ratio. Under the premise that the CLSC's overall utility will increase, each subject's enthusiasm will be effectively improved. This is mainly because subsidies increase the recovery rate and the profitability of each entity. Therefore, the CLSC of subsidized power batteries has certain necessity and feasibility.

(2) To describe the real power battery CLSC, this paper considers a three-phase supply chain. Under the premise that the unit subsidy amount is limited while the government subsidizes all objects in the CLSC, and the promotion effect on the benefit of the CLSC is significantly higher than the effect of the subsidy of a single entity. Therefore, the government should try to subsidize all the objects in the CLSC. The main body fully mobilizes the enthusiasm to participate in recycling.

(3) When the government provides subsidies to power battery manufacturers, which is called remanufacturing subsidy, as recycling subsidies to vehicle manufacturers and retailers. When the government provides remanufacturing subsidies to power battery manufacturers, the recovery rate is the highest, which is most beneficial to the entire CLSC.

(4) Power battery manufacturers and sellers not only need to build an efficient CLSC but also advocate for consumers to participate in power battery recycling actively. Moreover, it further obtains better economic benefits.

In conclusion, although this paper has some innovations, it still has some shortcomings. This paper combines the EPR system and government subsidies and considers the industry's characteristics to establish a three-stage CLSC. However, it only considers the game process under complete information, which has some limitations, in contrast to the existing studies that rarely consider the CLSC of power batteries under the EPR system. In addition, this paper only considers the optimal decisions of different subsidy agents under the single subsidy method of piecewise subsidy and does not study the impact of other subsidies, such as one-off subsidies, on the CLSC decision and profit transfer of power batteries. Finally, this paper analyzes the CLSC decision making under different government subsidies but lacks information on the coordination and incentives of the

power battery CLSC under the EPR system from the perspective of maximizing the benefit level of the EPR system.

The future research directions of this paper will focus on the following aspects. This article does not consider the limitations of patent factors on the recycling of power batteries, nor does it consider the fairness of various elements in the recycling process. In the future, we will introduce revenue-sharing contracts while considering patent factors in further research, and further explore the impact of government subsidies on power battery CLSC decision making under the EPR system.

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Appendix A

Proof of Theorem 1. For the optimal profit π_N to exist in a CLSC, i.e., to prove that Equation (15) is meaningful, the Hesse matrix of Equation (15) can be obtained.

$$H = \begin{bmatrix} \frac{\partial^2 \pi_N}{\partial^2 P_C^R} & \frac{\partial^2 \pi_N}{\partial P_C^R \partial P_r^c} \\ \frac{\partial^2 \pi_N}{\partial P_C^R \partial P_r^c} & \frac{\partial^2 \pi_c}{\partial^2 P_r^c} \end{bmatrix} = \begin{bmatrix} -2k & \theta \\ \theta & -2b \end{bmatrix}$$

When $\theta > 0, b > 1, k > 0$, we have $\theta^2 - 4kb < 0$, at which point the Hessian matrix of π_N is a negative definite, implying the existence of a unique optimal solution, i.e., when $0 < \theta < \sqrt{4kb}$, optimal profit exists in a centralised decision CLSC, and the proof is complete. □

Proof of Theorems 2–4. Same as Theorem 1. □

Proof of Theorem 5 Analysis of the four models and comparison of the profit expressions for each subject leads to a profit distribution ratio of 4:2:1 for power battery manufacturers, vehicle manufacturers and retailers in the CLSC. □

Proof of Theorem 6. For each model, P_r^c,Q_r and Q_d to find the partial derivative with respect to Δ, we obtain $\frac{\partial P_{rN}^c}{\partial \Delta}, \frac{\partial P_{rR}^c}{\partial \Delta}, \frac{\partial P_{rA}^c}{\partial \Delta} = \frac{bK}{8bK-2\theta^2}, \frac{\partial P_{rRM}^c}{\partial \Delta} = \frac{bK}{8bK-4\theta^2}, \frac{\partial Q_{rN}^c}{\partial \Delta}, \frac{\partial Q_{rR}^c}{\partial \Delta}, \frac{\partial Q_{rA}^c}{\partial \Delta} =$

$\frac{b^2K}{8bK-2\theta^2}, \frac{\partial Q^c_{rRM}}{\partial \Delta} = \frac{b^2K}{8bK-4\theta^2}, \frac{\partial Q^c_{dN}}{\partial \Delta}, \frac{\partial Q^c_{dR}}{\partial \Delta}, \frac{\partial Q^c_{dA}}{\partial \Delta} = \frac{bK\theta}{16bK-4\theta^2}, \frac{\partial Q^c_{dRM}}{\partial \Delta} = \frac{bK\theta}{8bK-4\theta^2}$. This is because $8bK - 2\theta^2 > 0$, so $\frac{\partial P^c_{rN}}{\partial \Delta}, \frac{\partial P^c_{rR}}{\partial \Delta}, \frac{\partial P^c_{rA}}{\partial \Delta}, \frac{\partial Q^c_{rN}}{\partial \Delta}, \frac{\partial Q^c_{rR}}{\partial \Delta}, \frac{\partial Q^c_{rA}}{\partial \Delta}, \frac{\partial Q^c_{dN}}{\partial \Delta}, \frac{\partial Q^c_{dR}}{\partial \Delta}, \frac{\partial Q^c_{dA}}{\partial \Delta}$ is ever greater than 0. □

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