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Original Research

Research on Optimal Recycling and Reprocessing Strategies for End-of-Life NEV Power Batteries under the EPR System

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Abstract

In China, the number of newly registered electric vehicles (EVs) has been growing steadily each year, especially since the issuance of the Implementation Plan for the Extended Producer Responsibility (EPR) System. However, the country has not yet established clear standards for the recycling rate and management of retired new energy vehicle (NEV) batteries. Therefore, under the EPR system, how to select appropriate recycling and reuse methods to improve the efficiency of retired battery recycling and disposal is not only a current technical challenge but also an unavoidable environmental issue in the future. This paper discusses the key issues related to the recycling and reuse of used batteries within the EPR framework, such as the unclear delineation of recycling responsibility, poor recycling rates, and varying consumer preferences. The core of the paper lies in the analysis of stakeholder behavioral choices and a comparison of the efficiency of different recycling methods. It proposes four distinct recycling modes: the manufacturer's independent recycling, commissioned recycling (outsourced to retailers and third-party recyclers), and joint recycling. The results of the model show that independent recycling results in a significantly higher waste power battery recycling rate compared to commissioned recycling. However, joint recycling proves to be the most effective method for achieving an optimal recycling rate. In terms of corporate profitability, joint recycling appears to be the most advantageous for NEV power battery manufacturers, even though retailers and third-party recyclers may not reap the same benefits. The influence of the market share of remanufactured products on the recycling and remanufacturing of NEV power batteries is contingent on the substitution effects of the two types of products. When product substitutability is low, an increased market share of remanufactured products can boost corporate profits; conversely, it can diminish profits. This study offers fresh perspectives for related research and provides a theoretical foundation for the development of efficacious NEV power battery recycling policies.

Keywords: extended producer responsibility, recycling, remanufacturing, retired electric vehicle batteries

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Introduction

The uptake of electric vehicles (EVs) has been rapidly increasing globally in recent years, with 95% of these having been sold in ten countries, particularly throughout Europe, China, and the USA [1, 2]. Particularly in China, new energy vehicles (NEVs) have constituted around 60% of the global EV sales, resulting in a total of 13.1 million NEVs in circulation. Projections indicate that the global electric vehicle fleet alone will reach 253 million units by 2030 [3]. The forecasted demand for EVs is set to significantly impact both the energy market and climate targets, given the existing policy frameworks [4]. Current policies predict that the demand for petroleum in road transport will reach its zenith around 2025. Moreover, it is anticipated that by 2030, EVs will supplant over 5 million barrels of petroleum per day. This shift towards EVs could potentially prevent emissions equivalent to nearly 700 million metric tons of CO_2 by 2030. At present, NEV power batteries have an average life expectancy of between 5 and 8 years [5]. As such, the retirement rate of NEVs is expected to progressively increase. In China alone, disregarding scrapped registrations, the number of retired NEVs rose by 5.26 million vehicles in 2022 when compared to 2021. Due to the global increase in battery usage, the end-of-life batteries are projected to reach 314 GWh by 2030 [6]. A 2020 research report by Greenpeace, "Resource Continuity: Potential of the Circular Economy for New Energy Vehicle Batteries in 2030", estimates that from 2021 to 2030, the global total of retired passenger EV power batteries will reach 12.85 million tons. The market for recycling and reuse of these batteries is projected to exceed 15 billion USD. In June 2023, the European Parliament passed a New EU regulatory framework for batteries, focusing on an EPR system to regulate and supervise the entire life cycle of all types of batteries sold in the European Union [7]. Specifically, battery power manufacturers will need to disclose information on the recycled content in their (industrial, electric vehicle, LMT, and SLI) batteries. For example, such batteries shall be accompanied by documentation containing information about the percentage share of cobalt, lithium, nickel or lead that has been recovered from waste [8]. Consequently, with the significant growth in the production and sales of new energy vehicles worldwide, the retirement of power batteries is steadily becoming a global concern [9]. Recycling wasted power batteries not only aids in reducing metal resource extraction but also lowers the costs of battery production. However, it's important to note that waste power batteries are populated with a substantial amount of metal elements such as lithium and cobalt, in addition to toxic electrolytes. This raises their value for recycling, while also posing potential hazards. Circular Energy Storage has estimated that by 2030, recovery facilities would be able to recover 35 thousand tons of cobalt, 125 thousand tons of lithium, and 86 thousand tons of nickel. Based on the current prices of these materials, this will increase the market by $6 billion [10]. It has emerged as an urgent issue to align the full-lifecycle performance of power batteries with environmental objectives, especially in terms of their recycling and disposal. However, if effective measures fail to be adopted for the treatment and management of these massive quantities of waste batteries, they will inevitably give rise to a series of severe problems, such as environmental pollution, health hazards, and the depletion of natural resources [11].

To address these concerns, China's General Office of the State Council launched the "Implementation Plan for the Extended Producer Responsibility System" in 2017. This plan explicitly declares the need to enhance and extend producers' environmental responsibilities beyond the production phase. It advocates for environmental consideration during the entire product lifecycle, which includes stages of manufacturing, distribution, retail, recycling, disposal, and waste utilization. To build on this, the 2020 revised "Law on the Prevention and Control of Environmental Pollution by Solid Waste" has assimilated the extended producer responsibility (EPR) system into its legislation [12]. The state implements a target responsibility system and a performance evaluation system, with the completion of solid waste recycling targets incorporated into the performance evaluation. Efficiency within the power battery recycling process is a critical metric for assessing the effectiveness of recycling initiatives. An elevated recycling efficiency portends a reduction in the production costs for enterprises, concurrently optimizing environmental sustainability [13]. Furthermore, the establishment of a rational and efficient closed-loop supply chain system is instrumental in augmenting the rate of battery reclamation [14].

Therefore, this paper aims to develop a rational recycling strategy for NEV power batteries within a closed-loop supply chain, adhering to the EPR system. To achieve this, we aim to answer the following questions:

(1) How can manufacturers of NEV power batteries comply with the EPR system, and what recycling methods are most beneficial for them?

(2) Under what conditions is the recycling rate of waste power batteries at its peak?

(3) How do fluctuations in the market share of remanufactured products and substitution effects influence the recycling and remanufacturing of waste power batteries?

This study offers three significant contributions. Firstly, it integrates factors such as product substitution effects and the market share of remanufactured products into the model, allowing for a diverse range of consumer preferences. Secondly, it provides insights into the optimal method for NEV power battery manufacturers to comply with the EPR system during the recycling process, a topic previously unexplored. Lastly, this study also accounts for how the market share of remanufactured products and substitution effects impact the corporate profits of supply chain businesses, thus offering theoretical guidance for choosing waste power battery recycling strategies.

Literature Review

Thomas Lindhquist, an environmental economist at Lund University in Sweden, was the first to propose the concept of EPR as early as 1988 [15]. EPR is a system that broadens the producer's accountability for the environmental and resource impact of their products throughout their entire lifecycle, including phases such as product design, distribution, consumption, recycling, and waste disposal [16]. As of now, the EPR system is extensively implemented in the NEV power battery recycling sector [17-19]. Recycling and reuse are phenomena with positive aspects, such as lowering manufacturing costs and mitigating waste produced by direct disposal, as well as negative aspects, such as battery collection, storage, handling, and recycling [20]. From the literature, we find that the design of the recycling network involves two important aspects: the first is the recycling mode, the second is the determination of the responsible entity [21]. Recycling activities of power batteries have progressively evolved into three primary modes. The first mode involves the NEV manufacturers taking on the recycling responsibility [22-25]. The second mode sees the power battery retailers taking charge of the recycling process [26, 27]. Lastly, the third mode is characterized by third-party recycling companies shouldering the recycling responsibility [28-30]. To provide a comprehensive overview of the current research on NEV power battery recycling and remanufacturing, Table 1 encapsulates some of the recent studies worth noting and contrasts them with the findings of this study.

As can be seen from Table 1, the current research primarily investigates the impact of battery recycling on operational decisions within the closed-loop supply chain of power batteries. While certain studies acknowledge the part played by entities involved in the recycling and remanufacturing of depleted power batteries from new energy vehicles, the quasi-externality associated with power battery recycling results in substantial technological research and development investments at the outset of the recycling process. The development of the recycling network and framework remains unrefined, and conventional recycling companies are often unable to bear the full responsibility for recycling [42]. Consequently, there is a scarcity of research addressing recycling schemes compatible with the three predominant recycling approaches currently implemented within the industry. To facilitate the efficient recycling of power batteries, there is an imperative need to enhance the recycling rate significantly through the collaboration of multiple stakeholders. The study shows that when multiple companies in the closed-loop supply chain participate in the recycling process together, the recycling rate of batteries and corporate benefits will be improved [43]. The divergence of this paper from prior work is principally evident in the following areas:

(1) This study takes into account both the differences in consumer payments and the supply of waste power batteries in the market. These considerations offer realistic conditions for the execution of recycling and remanufacturing activities by NEV power battery manufacturers.

Table 1. Related research review.

Literature	Subject of recovery			Mixed recycling	Retail price of remanufactured and new products	
	Manufacturer	Retailer	Third-party recyclers		Same price	Different price
Long et al. [31]	√	–	–	–	–	√
Li et al. [32]	–	√	–	–	–	√
Xu and Wang [33]	–	√	–	–	–	√
Yang et al. [34]	–	–	–	√	√	–
Zhang et al. [35]	√	√	√	√	√	–
Huang et al. [36]	–	–	√	–	√	–
Du et al. [37]	√	–	√	–		√
Ranjbar et al. [38]	√	√	–	–	√	–
Wang et al. [39]	–	–	√	–	√	–
Zhang et al. [40]	√	–	–	–	√	–
Taleizadeh et al. [41]	√	√		–	√	–

Notes: – indicates content not covered, √ indicates content covered.

(2) To further alleviate the recycling burden on individual NEV power battery manufacturers and effectively enhance the recycling rate of waste power batteries, this study introduces a novel joint recycling mode involving multiple responsible parties.

Materials and Methods

Description of the Problem

In this paper, a game-theoretic approach is employed to develop a comprehensive closed-loop supply chain game model consisting of three core node enterprises: a new energy vehicle (NEV) power battery manufacturer (e.g., CATL), a retailer (encompassing both NEV manufacturers and 4S stores, henceforth collectively referred to as an NEV power battery retailer), and a third-party recycler (e.g., Guangdong Shengxiang New Material Technology Co., Ltd). In this mode, the manufacturer assumes the role of channel leader and is tasked with converting waste power batteries into new products for market sale. This paper pivots around three distinct recycling modes, all operating under the parameters set by the EPR system. Firstly, the manufacturer's independent recycling mode (denoted by the superscript MM) involves the NEV power battery manufacturer independently collecting waste power batteries from consumers. Secondly, the manufacturer's commissioned recycling mode (denoted by the superscript MR and MT) assigns the recycling responsibility to the retailer or the third-party recycler who collects battery waste from consumers and subsequently sells these batteries to the NEV power battery manufacturer. Lastly, the joint recycling mode (denoted by the superscript MRT) sees the NEV power battery manufacturer collaborating with both the retailer and the third-party recycler in the recycling operation. The joint recycling companies involved include Tesla (Shanghai) Co., Xiamen Golden Dragon Station Wagon Co., and Sichuan Xinzhu Tonggong Automobile Co., LTD.

Model Assumptions

Assumption 1: Assume that new and remanufactured products are substitutable (new products refer to power batteries produced with new materials, remanufactured products refer to power batteries produced from waste materials). The market demand function of the new product here is $q_n = (1-\varphi)g - p_n + kp_r$, the market demand function of remanufactured products is $q_r = \varphi g - p_r + kp_n$ [44]. The meaning of each parameter is shown in Table 2.

Assumption 2: The market supply function of used power batteries is linear $S(P_c) = S_0 + bp_c$, S_0 represents the market supply of waste power batteries. When the recycling price is 0, its size depends on the

Table 2. Symbol descriptions.

Parameters			
c_n	Unit cost of producing a power battery using a new material	q_n	Market demand for new products
c_r	Unit production cost of the remanufactured product $c_r < c_n$	q_r	Market demand for remanufactured products
Δ	Cost savings from remanufacturing activities	k	Substitution utility of the two products
φ	Market share of remanufactured products	v	Coefficient of consumer sensitivity to recycling price
b	The price of the transfer payment ($b < \Delta$)	c_l	The cost of fixed investment
g	Capacity of the market	p_c	The price of used power batteries recovered from consumers
I	The cost of investment in recovery activities	S_0	The market supply of used power batteries when the recycling price is 0
π_m	NEV power battery maker's profit	π_r	NEV power battery retailer's profit
π_τ	NEV power battery third-party recycler's profit	π	Total profit of the supply chain
Decision variables			
ω_n	The wholesale price of the new product $\omega_n > \omega_r$	ω_r	Wholesale price of remanufactured products
p_n	Retail price of the new product $p_n > p_r$	p_r	Retail price of remanufactured products
τ	Recovery rate ($0 < \tau < 1$)	–	–

environmental awareness of consumers. The larger S_0 is, the stronger the environmental awareness of consumers is [45, 46].

Assumption 3: Recyclers need to provide fixed investment such as recycling sites and equipment for the recycling of waste power batteries. The cost function is denoted as, $I(\tau)=c_l\tau^2$ [47].

Assumption 4: It is assumed that the NEV power battery manufacturer is always in the position of the Stackelberg leader in the closed-loop supply chain.

Symbol Definitions

All parameters of the article are shown in Table 2.

Model Construction and Solution

Manufacturer's Recycling and Remanufacturing Model

In the MM mode, the NEV power battery manufacturer first collects waste batteries from consumers, offering them a predetermined price p_c. These used batteries are then processed and refurbished alongside new materials, creating a hybrid product. This product is then wholesaled to the NEV power battery retailer, who integrates the refurbished batteries with newly created ones into new energy vehicles, which are then sold to consumers. For the purposes of this paper, our analysis is singularly focused on the recycling and remanufacturing processes within the NEV power battery industry. In this mode, the interaction between the manufacturer and retailer unfolds as follows: (i) The manufacturer sets the wholesale prices ω_n and ω_r for the two types of products, as well as the price p_c for collecting waste batteries. (ii) The retailer determines its retail prices based on the wholesale prices ω_n and ω_r. Considering consumer preference variations for the two types of products, the retail prices for them are denoted as p_n and p_r. Given the above analysis, we can derive the profit functions for both the NEV power battery manufacturer and retailer within the MM model:

$$\pi_m^{MM} = (\omega_n - c_n)q_n + (\omega_r - c_r)q_r - I(\tau) + \tau(\Delta - p_{c1})(S_0 + vp_{c1}) \tag{1}$$

$$\pi_r^{MM} = (p_n - \omega_n)q_n + (p_r - \omega_r)q_r \tag{2}$$

Proposition 1. The equilibrium solution of the MM model is as follows:

$$\pi_r^{MM*} = \frac{1}{16}\left(c_n^2 + c_r^2 - 2c_r g\varphi - 2c_n y + \frac{g^2\left(2x\varphi(\varphi-1)-1\right)}{-1+k^2}\right) \tag{3}$$

$$\pi_m^{MM*} = \frac{1}{8}\left(\frac{(c_n - y)\left(g + c_n\left(-1+k^2\right) + gx\varphi\right)}{-1+k^2} + \frac{2\left(\Delta - p_{c2}\right)^2\left(S_0 + p_{c2}v\right)^2}{c_l} + \frac{(c_r - c_n k - g\varphi)\left(c_r\left(-1+k^2\right) + g\left(k + \varphi - k\varphi\right)\right)}{-1+k^2}\right) \tag{4}$$

The equilibrium results of τ^{MM*}, ω_n^{MM*}, ω_r^{MM*}, p_n^{MM*} and p_r^{MM*} are shown in Table 3, where $x = k - 1$, $y = g + c_r k - g\varphi$.

Manufacturer's Remanufacturing and Retailer's Commissioned Recycling Model

In the MR model, which shares similarities with the MM model, the NEV power battery manufacturer repurposes waste power batteries to produce refurbished products. These remanufactured items, along with batteries newly manufactured, are then wholesaled to the retailer within the NEV industry. In this scenario, the task of waste battery collection from consumers is not shouldered by the manufacturer but is entrusted to the retailer. The interplay between the NEV power battery manufacturer and retailer in this mode unfolds in this sequence: (i) The manufacturer sets the wholesale prices ω_n and ω_r for the two types of products, as well as the price b to collect waste batteries from the retailer. (ii) The retailer determines its collection price p_{c2} for waste batteries from consumers and the retail prices p_n and p_r for the two types of products, basing this decision on the wholesale prices ω_n and ω_r, the collection price b provided by the NEV power battery manufacturer. Drawing from the analysis above, we can derive the profit functions for both the NEV power battery manufacturer and retailer within the MR model.

$$\pi_m^{MR} = (\omega_n - c_n)q_n + (\omega_r - c_r)q_r + (\Delta - b)\tau(S_0 + vp_{c2}) \tag{5}$$

$$\pi_r^{MR} = (p_n - \omega_n)q_n + (p_r - \omega_r)q_r - I(\tau) + (b - p_c)\tau(S_0 + vp_{c2}) \tag{6}$$

Proposition 2. The equilibrium solution of the MR model is as follows:

$$\pi_r^{MR*} = \frac{(c_n - y)\left(g + c_n\left(-1+k^2\right) + gx\varphi\right) + (c_r - c_n k - g\varphi)\left(c_r\left(-1+k^2\right) + g\left(k - k\varphi + \varphi\right)\right)}{16\left(-1+k^2\right)} + \frac{4\left(b - p_{c2}\right)^2\left(S_0 + p_{c2}v\right)^2}{16c_l} \tag{7}$$

$$\pi_m^{MR*} = \frac{1}{8}\left(\frac{(c_n - y)\left(g + c_n\left(-1+k^2\right) + gx\varphi\right)}{-1+k^2} + \frac{4\left(\Delta - b\right)\left(b - p_{c2}\right)\left(S_0 + p_{c2}v\right)^2}{c_l} + \frac{(c_r - c_n k - g\varphi)\left(c_r\left(-1+k^2\right) + g\left(k + \varphi - k\varphi\right)\right)}{-1+k^2}\right) \tag{8}$$

The equilibrium outcomes for τ^{MR*}, ω_n^{MR*}, ω_r^{MR*}, p_n^{MR*} and p_r^{MR*} are shown in Table 3, where $x = k - 1$, $y = g + c_r k - g\theta$.

Manufacturer's Remanufacturing and Third-Party Commissioned Recycling Model

In the MT model, similarly to the MM and MR models, the NEV power battery manufacturer repurposes waste power batteries to create remanufactured products. Alongside batteries made from new materials, these remanufactured products are wholesaled to the NEV power battery retailer. In this mode, the NEV power battery manufacturer does not directly collect waste batteries from consumers. This task is undertaken by the third-party recycler. This mode involves a three-stage game involving the NEV power battery manufacturer, retailer, and third-party recycler. The sequence of the game is as follows: (i) The manufacturer sets the wholesale prices ω_n and ω_r for the two types of products, as well as the price b to collect waste batteries from the third-party recycler. (ii) The retailer determines the retail prices p_n and p_r for the two types of products, basing this decision on the wholesale prices ω_n and ω_r provided by the NEV power battery manufacturer. (iii) The third-party recycler decides on the price p_{c3} at which it will collect waste batteries from consumers; this decision will be based on the collection price b set by the manufacturer.

Building upon the above analysis, we can establish the profit functions for the NEV power battery manufacturer, retailer, and third-party recycler within the MT model:

$$\pi_m^{MT} = (\omega_n - c_n)q_n + (\omega_r - c_r)q_r + (\Delta - b)\tau(S_0 + vp_{c3}) \quad (9)$$

$$\pi_r^{MT} = (p_n - \omega_n)q_n + (p_r - \omega_r)q_r \quad (10)$$

$$\pi_t^{MT} = (b - p_{c3})\tau(S_0 + vp_{c3}) - I(\tau) \quad (11)$$

Proposition 3. The equilibrium solution of the MT model is as follows:

$$\pi_t^{MT*} = \frac{(b - p_c)^2 (S_0 + p_c v)^2}{4c_l} \quad (12)$$

$$\pi_r^{MT*} = \frac{1}{16}\left(c_n^{\ 2} + c_r^{\ 2} - 2c_r g\varphi - 2c_n y + \frac{g^2\left(2x\varphi(\varphi-1)-1\right)}{-1+k^2} \right) \quad (13)$$

$$\pi_m^{MT*} = \frac{(c_n - y)\left(g + c_n\left(k^2-1\right) + gx\varphi\right) + (c_r - c_n k - g\varphi)\left(c_r\left(k^2-1\right) + g\left(k(1-\varphi)+\varphi\right)\right)}{8\left(k^2-1\right)} + \frac{4(\Delta - b)(b - p_{c3})(S_0 + p_c v)^2}{8c_l} \quad (14)$$

The equilibrium outcomes for τ^{MT*}, ω_n^{MT*}, ω_r^{MT*}, p_n^{MT*} and p_r^{MT*} are shown in Table 3, where $x = k - 1$, $y = g + c_r k - g\theta$.

Analysis and Comparison of Mode Results

In order to make the above three modes have equilibrium solutions, when $\frac{1}{2} < \varphi < \frac{c_n k^2 - c_n + g}{g(1-k)}$, the condition that needs to be satisfied is $\frac{6g\varphi - 3g - c_n + c_r}{c_n - c_r} < k < 1$; when $\varphi < \frac{1}{2}$ or $\varphi > \frac{c_n k^2 - c_n + g}{g(1-k)}$, the condition that needs to be satisfied is $1 > k > \frac{2g\varphi - c_n + c_r - g}{c_n - c_r}$.

Corollary 1. From Table 3, we obtain the following: $\omega_n^{MM*} = \omega_n^{MR*} = \omega_n^{MT*}$; $\omega_r^{MM*} = \omega_r^{MR*} = \omega_r^{MT*}$; $p_n^{MM*} = p_n^{MR*} = p_n^{MT*}$; $p_r^{MM*} = p_r^{MR*} = p_r^{MT*}$.

The results of Corollary 1 show that in the two-stage game dominated by the NEV power battery manufacturer, since both new products and remanufactured products are produced by the NEV power battery manufacturer, the manufacturer has the right to control and guide the wholesale price and the retail price of the two products (which is also in line with the actual product sales in the current new energy vehicle industry). Therefore, no matter how the recycling subject of the waste power battery changes, the wholesale price and retail price of the two products can remain consistent in the pricing process.

Corollary 2. From the optimal recovery rate, we obtain the following: $\tau^{MM*} > \tau^{MR*} = \tau^{MT*}$.

The results of Corollary 2 show that NEV power battery manufacturers have lower recycling rates of used batteries than in the case of independent recycling, whether they commission retailers or third-party recyclers to recycle.

Corollary 3. From the manufacturer's optimal profit, we obtain the following: $\pi_m^{MM*} > \pi_m^{MR*} = \pi_m^{MT*}$.

The results of Corollary 3 show that among the three modes mentioned above, for NEV power battery manufacturers, the benefits of independent recycling and remanufacturing are the highest.

Corollary 4. From the optimal profit of the retailers, we obtain the following: $\pi_r^{MM*} = \pi_r^{MT*} > \pi_r^{MR*}$.

The results of Corollary 4 show that among the three modes mentioned above, the profit for NEV power battery retailers is the lowest when they choose to be responsible for recycling used batteries themselves. In other cases, such as NEV battery manufacturer recycling or third-party recycling, this will not affect their interests.

Table 3. Equilibrium outcomes under the four models.

Variable	MM	MR	MT	MRT
ω_n	$\frac{c_n(k^2-1)-g(\varphi x+1)}{2(k^2-1)}$	$\frac{c_n(k^2-1)-g(\varphi x+1)}{2(k^2-1)}$	$\frac{c_n(k^2-1)-g(\varphi x+1)}{2(k^2-1)}$	$\frac{c_n(k^2-1)-g(\varphi x+1)}{2(k^2-1)}$
ω_r	$\frac{c_r(k^2-1)-g(k+\varphi x)}{2(k^2-1)}$	$\frac{c_r(k^2-1)-g(k+\varphi x)}{2(k^2-1)}$	$\frac{c_r(k^2-1)-g(k+\varphi x)}{2(k^2-1)}$	$\frac{c_r(k^2-1)-g(k+\varphi x)}{2(k^2-1)}$
p_n	$\frac{c_n(k^2-1)-3g(\varphi x+1)}{4(k^2-1)}$	$\frac{c_n(k^2-1)-3g(\varphi x+1)}{4(k^2-1)}$	$\frac{c_n(k^2-1)-3g(\varphi x+1)}{4(k^2-1)}$	$\frac{c_n(k^2-1)-3g(\varphi x+1)}{4(k^2-1)}$
p_r	$\frac{c_r(k^2-1)-3g(k+\varphi x)}{4(k^2-1)}$	$\frac{c_r(k^2-1)-3g(k+\varphi x)}{4(k^2-1)}$	$\frac{c_r(k^2-1)-3g(k+\varphi x)}{4(k^2-1)}$	$\frac{c_r(k^2-1)-3g(k+\varphi x)}{4(k^2-1)}$
τ	$(\Delta-p_c)(S_0+p_c v)/2c_l$	$(b-p_c)(S_0+p_c v)/2c_l$	$(b-p_c)(S_0+p_c v)/2c_l$	$[2c_l-(b-p_c)(S_0+p_c v)]/2c_l$
π_m	$\frac{1}{8}\left(\frac{E_1+E_2}{k^2-1}+\frac{2(\Delta-p_c)^2 E_5^2}{c_l}\right)$	$\frac{1}{8}\left(\frac{E_1+E_2}{k^2-1}+\frac{4(\Delta-b)(b-p_c)E_5^2}{c_l}\right)$	$\frac{1}{8}\left(\frac{E_1+E_2}{k^2-1}+\frac{4(\Delta-b)(b-p_c)E_5^2}{c_l}\right)$	$\frac{1}{8(k^2-1)}\left(\begin{array}{l}E_3+E_4-g^2-S_0\\+8(\Delta-b)((k^2-1)p_c v)\end{array}\right)$
π_r	$\frac{1}{16}\left(\begin{array}{l}c_n^2+c_r^2-2c_r g\varphi-2c_n y\\+\frac{g^2(2x\varphi(\varphi-1)-1)}{-1+k^2}\end{array}\right)$	$\frac{1}{16}\left(\frac{E_1+E_2}{k^2-1}+\frac{4(b-p_c)^2 E_5^2}{c_l}\right)$	$\frac{1}{16}\left(\begin{array}{l}c_n^2+c_r^2-2c_r g\varphi-2c_n y\\+\frac{g^2(2x\varphi(\varphi-1)-1)}{k^2-1}\end{array}\right)$	$\frac{1}{16}\left(\begin{array}{l}E_1+E_2-\frac{4(-2c_l+(b-p_c)E_5)^2}{c_l}\\+\frac{8(b-p_c)E_5(2c_l-(b-p_c)E_5)}{c_l}\end{array}\right)$
π_t	–	–	$\frac{(b-p_c)^2 E_5^2}{4c_l}$	$\frac{(b-p_c)^2 E_5^2}{4c_l}$

Note: $E_1=(c_n-y)(g+c_n(-1+k^2)+gx\varphi)$, $E_2=(c_r-c_n k-g\varphi)(c_r(-1+k^2)+g(k+\varphi-k\varphi))$, $E_3=(k^2-1)[(c_n^2+c_r^2)-2c_n(g+c_r k-g\varphi)]$,

$E_4=2\varphi(g^2(k-1)(\varphi-1)-g(k^2-1)c_r)$, $E_5=2\varphi(g^2(k-1)(\varphi-1)-g(k^2-1)c_r)$.

Corollary 5. From the overall optimal profit of the supply chain, we obtain the following: $\pi^{MM*} > \pi^{MT*} > \pi^{MR*}$.

The results of Corollary 5 show that for the overall profit of the supply chain, the NEV power battery manufacturer has the highest profit when it is recycled, and the retailer has the lowest profit when it is the opposite choice.

Corollary 6. The prices of the two products satisfy: $\frac{\partial \omega_n}{\partial \varphi} < 0$; $\frac{\partial \omega_r}{\partial \varphi} < 0$; $\frac{\partial p_n}{\partial \varphi} < 0$; $\frac{\partial p_r}{\partial \varphi} < 0$; $\frac{\partial \omega_n}{\partial k} > 0$; $\frac{\partial \omega_r}{\partial k} > 0$; $\frac{\partial p_n}{\partial k} > 0$; $\frac{\partial p_r}{\partial k} > 0$.

The results of Corollary 6 show that the price of power battery products is greatly affected by the market share of remanufactured products. As the market share of remanufactured products increases, both the wholesale prices and retail prices of both new products and remanufactured products will decrease. In addition, the power battery market is also affected by the substitution effect, and always maintains a positive correlation with it, that is, the prices of the two products will continue to rise with the enhancement of the substitution effect.

Corollary 7. The profits of NEV power battery manufacturers and retailers meet the following conditions:

(1) When $k > \frac{g(1-2\varphi)-\Delta}{\Delta}$, $\frac{\partial \pi_m^{MM*}}{\partial \varphi} > 0$, $\frac{\partial \pi_m^{MR*}}{\partial \varphi} > 0$, $\frac{\partial \pi_m^{MT*}}{\partial \varphi} > 0$; $\frac{\partial \pi_r^{MM*}}{\partial \varphi} > 0$, $\frac{\partial \pi_r^{MR*}}{\partial \varphi} > 0$, $\frac{\partial \pi_r^{MT*}}{\partial \varphi} > 0$; on the contrary, $\frac{\partial \pi_m^{MM*}}{\partial \varphi} < 0$, $\frac{\partial \pi_m^{MR*}}{\partial \varphi} < 0$, $\frac{\partial \pi_m^{MT*}}{\partial \varphi} < 0$; $\frac{\partial \pi_r^{MM*}}{\partial \varphi} < 0$, $\frac{\partial \pi_r^{MR*}}{\partial \varphi} < 0$, $\frac{\partial \pi_r^{MT*}}{\partial \varphi} < 0$.

(2) When $k < \frac{g - 2g\varphi + 2g\varphi^2 + \sqrt{g^2(1-2\varphi)^2 - 4c_n c_r(-1+\varphi)\varphi}}{2g(-1+\varphi)\varphi}$, $\frac{\partial \pi_m^{MM*}}{\partial k} > 0$, $\frac{\partial \pi_m^{MR*}}{\partial k} > 0$, $\frac{\partial \pi_m^{MT*}}{\partial k} > 0$; $\frac{\partial \pi_r^{MM*}}{\partial k} > 0$, $\frac{\partial \pi_r^{MR*}}{\partial k} > 0$, $\frac{\partial \pi_r^{MT*}}{\partial k} > 0$; on the contrary, $\frac{\partial \pi_m^{MM*}}{\partial k} < 0$, $\frac{\partial \pi_m^{MR*}}{\partial k} < 0$, $\frac{\partial \pi_m^{MT*}}{\partial k} < 0$; $\frac{\partial \pi_r^{MM*}}{\partial k} < 0$, $\frac{\partial \pi_r^{MR*}}{\partial k} < 0$, $\frac{\partial \pi_r^{MT*}}{\partial k} < 0$.

The results of Corollary 7 show that when the market share of remanufactured products is large, the retailer's profit increases with the increase in the market share of remanufactured products. On the contrary, when the market share of remanufactured products is small, the retailer's profit will decrease. But the opposite is true for makers of NEV power batteries.

Mode Extension: Joint Recycling

In practical terms, the complexity of waste battery recycling can differ due to the distinct recycling activities and environments encountered by different recycling companies. This suggests that a single recycling channel might not fully exploit the potential of a closed-loop supply chain mode. To mitigate this, our study investigates the concept of joint recycling involving the manufacturer, the retailer, and the recycler. For instance, Contemporary Amperex Technology Co. Limited (CATL) has engaged in partnerships with industry players such as Mercedes-Benz and GEM Co., Ltd., culminating in the establishment of a recycling infrastructure dedicated to advancing the reclamation and hierarchical deployment of power batteries within various projects. Correspondingly, BYD Company Ltd. has amplified the recyclability and utilization efficacy of batteries via collaborations with third-party recycling entities, including Huayou Cobalt, thereby achieving the progressive utilization and regenerative cycle of power battery materials. These exemplary cases elucidate the enthusiastic commitment and pivotal role of power battery manufacturers in conjunction with other stakeholders within the battery recycling domain. In the MRT recycling model, the NEV power battery manufacturer, holding a central role in the supply chain, initially sets the wholesale and recycling prices. These decisions then guide the retailer in determining the retail and recycling prices, after which the third party sets the third-party recycling price. By scrutinizing these components, we can derive the profit functions for the NEV power battery manufacturer, retailer, and third-party recycler within the MRT model:

$$\pi_m = (\omega_n - c_n)q_n + (\omega_r - c_r)q_r + (\Delta - b)(S_0 + vp_c) \tag{15}$$

$$\pi_r = (p_n - \omega_n)q_n + (p_r - \omega_r)q_r - c_l\tau^2 + (b - p_c)\tau(S_0 + vp_c) \tag{16}$$

$$\pi_\tau = (b - p_c)(1-\tau)(S_0 + vp_c) - c_l(1-\tau)^2 \tag{17}$$

Proposition 4. The equilibrium solution of the MRT model is as follows:

$$\tau^{MRT*} = \frac{\left(2c_l - (b - p_c)(S_0 + p_c v)\right)}{2c_l} \tag{18}$$

$$\pi_\tau^{MRT*} = \frac{(b-p_c)^2(S_0 + p_c v)^2}{4c_l} \tag{19}$$

$$\pi_r^{MRT*}=\frac{1}{16}\left(\frac{\left(c_n-c_rk+g\left(\varphi-1\right)\right)\left(g+c_n\left(k^2-1\right)+g\left(k-1\right)\varphi\right)}{-1+k^2}+ +\frac{8\left(b-p_c\right)\left(S_0+p_cv\right)\left(2c_l-\left(b-p_c\right)\left(S_0+p_cv\right)\right)}{c_l}- +\frac{E_4\left(c_r\left(k^2-1\right)+g\left(k+\varphi-k\varphi\right)\right)}{-1+k^2}-\frac{4\left(-2c_l+\left(b-p_c\right)\left(S_0+p_cv\right)\right)^2}{c_l}\right) \tag{20}$$

$$\pi_m^{MRT*}=\frac{\left(k^2-1\right)\left(\left(c_n^{\ 2}+c_r^{\ 2}\right)-2c_n\left(g+c_rk-g\varphi\right)\right)-g^2+2\varphi\left(g^2\left(k-1\right)\left(\varphi-1\right)-g\left(k^2-1\right)c_r\right)+8\left(\Delta-b\right)\left(\left(k^2-1\right)p_cv-S_0\right)}{8\left(-1+k^2\right)} \tag{21}$$

The equilibrium outcomes for ω_n^{MRT*}, ω_r^{MRT*}, p_n^{MRT*} and p_r^{MRT*} are shown in Table 3. The method of proof is exactly consistent with Proposition 3. It will not be repeated here.

Corollary 8. The recycling rate of waste power batteries satisfies $\tau^{MRT*}>\tau^{MM*}>\tau^{MR*}=\tau^{MT*}$.

The results of Corollary 8 show that the recycling rate of NEV waste power batteries is the highest in the MRT model.

Corollary 9. The profit of waste power battery recycling enterprises satisfies

$\pi_m^{MRT*}>\pi_m^{MM*}>\pi_m^{MR*}=\pi_m^{MT*}$;

$\pi_r^{MM*}=\pi_r^{MT*}>\pi_r^{MR*}>\pi_r^{MRT*}$; $\pi_\tau^{MRT*}=\pi_\tau^{MT*}$;

$\pi^{MM*}>\pi^{MT*}>\pi^{MR*}>\pi^{MRT*}$.

The results of Corollary 9 show that the NEV power battery manufacturer's profit is optimal in the MRT model. The NEV power battery retailer's profit is optimal under the MM and MT models, but the third-party recycling firm's profit is optimal under the MR model when the third party participates in recycling.

Results and Discussion

Using recycled and recovered materials is considered an important method. In fact, EV recycling can help eliminate about 35% of the energy consumption and GHG emissions during its manufacturing phase [48]. In order to better prove the above inferences, we will illustrate through an example below. We assume that the market capacity of new energy vehicles in the market is 300,000 units, of which 200,000 units are produced with new raw materials, that is, q_n = 200,00, and 100,000 units are produced by remanufacturing used batteries, that is, q_r = 100,00. Referring to the research of Jiao et al. [49] taking Tesla's Model S as an example, the battery capacity is 85 kWh/vehicle. Model S uses the 2020 CATL power battery system, with an average unit price of about 6,500 yuan. In addition, the cost of the power battery side increased by about 20%-25% due to the increase in raw material prices in 2021. Therefore, we assume that the unit production cost of power batteries is c_n = 0.8×6,500×(1 + 25%) = 6900 yuan. The production cost of remanufacturing is 85% of the production cost of new materials, that is c_r = 0.85×6,900 = 5800 yuan. See Table 4 for specific parameter assignments.

Substituting the data in Table 4 into the above model, the optimal solutions under the four recovery modes can be obtained (see Table 5).

As can be seen from Table 5,

(i) From the price of the two products,

$\omega_n^{MM*}=\omega_n^{MR*}=\omega_n^{MT*}=\omega_n^{MRT*}=18,645$,

$\omega_r^{MM*}=\omega_r^{MR*}=\omega_r^{MT*}=\omega_r^{MRT*}=16,277$,

$p_n^{MM*}=p_n^{MR*}=p_n^{MT*}=p_n^{MRT*}=24,517$,

$p_r^{MM*}=p_r^{MR*}=p_r^{MT*}=p_r^{MRT*}=21,515$.

Table 4. Parameter assignment results for each variable.

φ	g	p_c	b	S_0	c_l	k	v	Δ
0.35	20,000	500	800	140	600,000	0.65	0.8	1,100

Table 5. Comparison of the results of the four models.

Model Type	ω_n	ω_r	p_n	p_r	τ	π_r	π_m	π_τ	π
MM	18645	16277	24517	21515	0.27	26289049	43913948	-	70202996
MR	18645	16277	24517	21515	0.13	21946039	43892078	-	65838117
MT	18645	16277	24517	21515	0.13	26289049	43892078	10935	70192061
MRT	18645	16277	24517	21515	0.86	21626299	44032208	10935	65669442

The result of Corollary 1 is verified.

(ii) From the recycling rate of waste power batteries, $\tau^{MRT*} = 0.86 > \tau^{MM*} = 0.27 > \tau^{MR*} = 0.13 = \tau^{MT*} = 0.13$. The results of Corollaries 2 and 8 are verified.

(iii) From the profits of waste power battery recycling enterprises,

$$\pi_r^{MM*} = \pi_r^{MT*} = 2.628\times10^7 > \pi_r^{MR*} = \pi_r^{MRT*} = 2.162\times10^7;$$

$$\pi_m^{MRT*} = 4.403\times10^7 > \pi_m^{MM*} = 4.391\times10^7 > \pi_m^{MR*} = \pi_m^{MT*} = 4.389\times10^7;$$

$$\pi_\tau^{MRT*} = \pi_\tau^{MT*} = 10{,}935.$$

(iv) From the total profit of the whole supply chain,

$$\pi_m^{M*} = 7.020\times10^7 > \pi_m^{MT*} = 7.019\times10^7 > \pi_m^{MR*} = 6.583\times10^7 > \pi_m^{MRT*} = 6.566\times10^7.$$

Synthesis (iii) and (iv) together validate the results of Corollary 3, 4, 5, and Corollary 9.

Impact of Remanufactured Market Share on NEV Power Battery Price

To further verify the impact of the market share φ of remanufactured products on the price of NEV power batteries, Fig. 1 can be derived through the method of numerical simulation based on the data in Table 4.

As can be seen from Fig. 1, with the rise in the market share of remanufactured products, the wholesale and retail prices of both new and remanufactured products exhibit a declining trend, with the magnitude of price reduction identical for the two product categories. The underlying reason is that an expansion in the market share of remanufactured products compels manufacturers of power batteries for new energy vehicles to increase investments in the recycling, reuse, and remanufacturing of waste batteries to match market demand. This process, however, involves sophisticated technologies and high input costs, which would exert a certain upward pressure on the wholesale price (ω_r) and retail price (p_r) of remanufactured batteries. Despite this, the prices of both product types still trend downward under the overall effect of market competition. Meanwhile, constrained by the rigid costs of recycling and remanufacturing, the price reduction potential of remanufactured products forms a check and balance with that of new products, ultimately resulting in the same magnitude of price decline for the two.

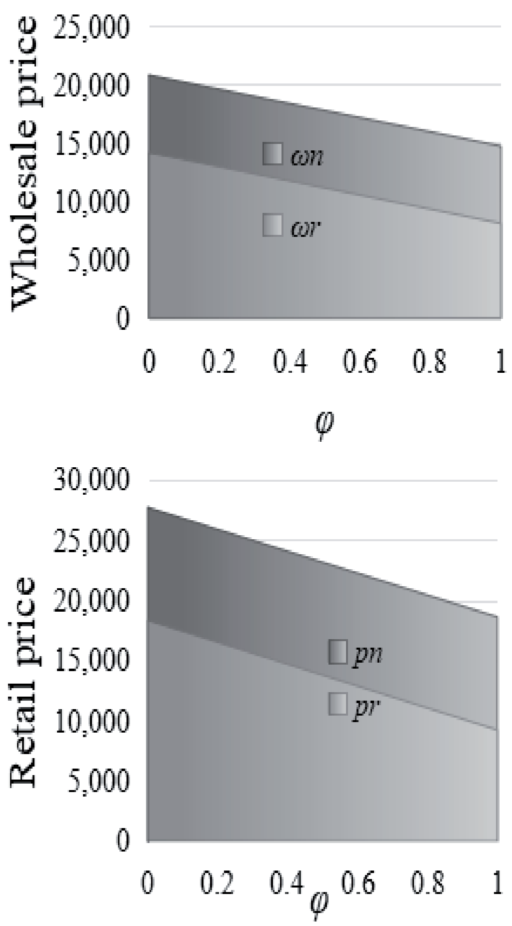

Fig 1. a) φ affects the power battery wholesale price. *b*) φ affects the power battery retail price.

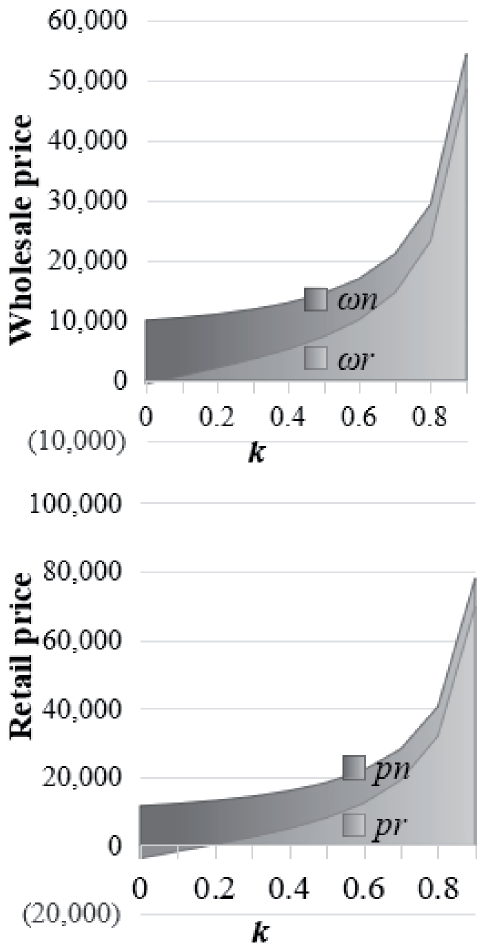

Fig. 2. a) *k* affects the power battery wholesale price. b) *k* affects the power battery retail price.

Impact of the Substitution Effect on NEV Power Battery Price

In order to further verify the impact of the substitution effect of the two products on NEV power battery price, according to the data in Table 4, Fig. 2 can be obtained.

It can be seen from Fig. 2 that as the substitution utility of the new product and the remanufactured product increases, the wholesale price and retail price of the two products also increase. The reason is that as the substitution utility of the two products increases, the difference between consumers' preferences for the two products shrinks. When k = 1, it means that the two products have complete substitution differences. At this time, the NEV power battery manufacturer is always in a dominant position, and in order to pursue higher profits, the NEV power battery manufacturer will increase the wholesale prices ω_r and ω_n of its products. Therefore, the retail prices p_r and p_n will increase accordingly. Here, the results of Corollary 6 are jointly verified by combining the analysis of Fig. 1.

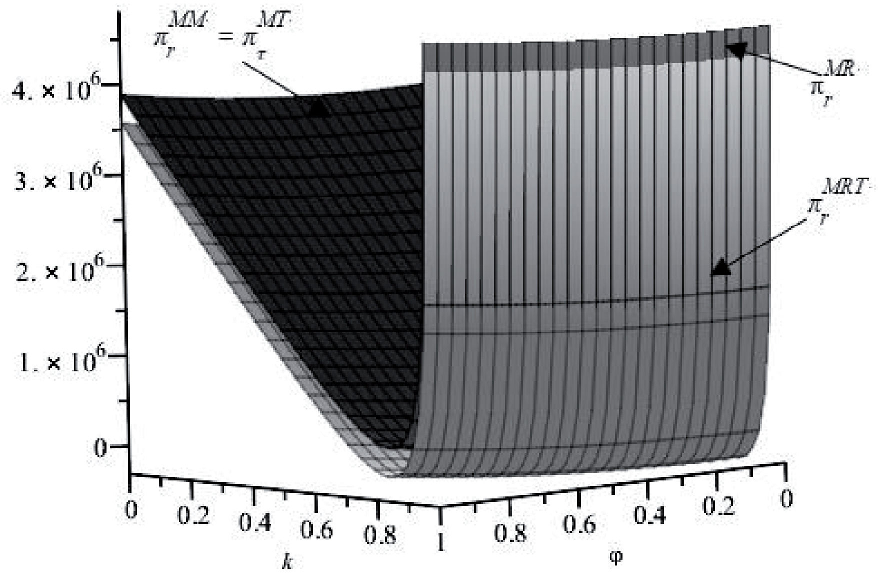

Fig. 3. Impact of remanufactured market share *φ* and substitution effect *k* on retailer profits.

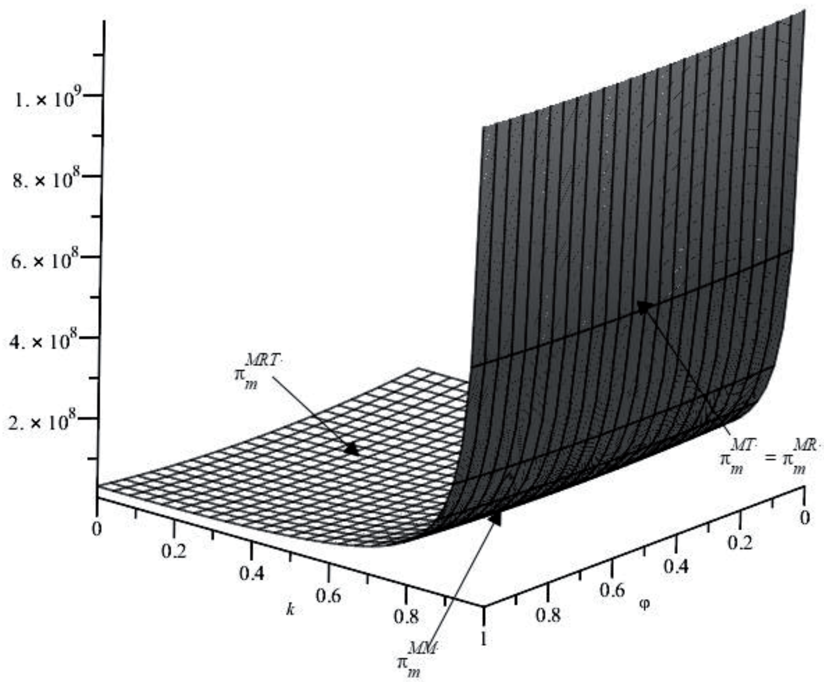

Fig. 4. Impact of remanufactured market share *φ* and substitution effect *k* on manufacturer profits.

Impact of Remanufactured Market Share and Substitution Effect on Firm Profits

Combining Fig. 3 and Fig. 4, it can be seen that: (i) When the substitution utility k of the two products is small, as the substitution utility k and the remanufactured market share φ increase, the profits of the NEV power battery retailer and manufacturer show a decreasing trend under the above four modes. On the contrary, when the substitution utility k of the two products is large, as the substitution utility k and the remanufactured market share φ increase, NEV power battery manufacturers and retailers in all four modes show an upward trend in profits. (ii) When the substitution utility k of the two products is large, as the substitution utility k and the remanufactured market share φ increase, the NEV power battery manufacturer's and retailer's profits show an upward trend under the above four modes. (iii) $\pi_r^{MM*} = \pi_r^{MT*} > \pi_r^{MR*} > \pi_r^{MRT*}$, $\pi_m^{MRT*} > \pi_m^{MM*} > \pi_m^{MR*} = \pi_m^{MT*}$. This result is consistent with the results verified in Table 5, and combined with the above analysis, Corollary 7 is jointly verified.

This shows that when the substitution utility of the two products is low, NEV power battery manufacturers and retailers will pay more attention to their own economic interests. At this time, as the market share of remanufactured products increases, manufacturers and retailers will increase the price of remanufactured products to gain more profits. Due to the fact that the market demand is affected by the substitution effect, the market share of remanufactured products and the product's price, demand will be significantly reduced in this scenario. Profits for NEV battery makers and retailers should fall as well. When the substitution utility of the two products is high, the NEV with new material equipment has the same effect as the NEV with remanufactured batteries. To promote the sales of NEV power batteries, the retail prices of the two products will be reduced, so the profits of the manufacturer and retailer will increase accordingly.

Conclusions

This study presents a closed-loop supply chain system for recycling and remanufacturing waste NEV power batteries. The system encompasses a NEV power battery manufacturer, a retailer, and a third-party recycler, functioning under the restrictions of the EPR system. Our research contrasts three recycling channels: independent recycling, commissioned recycling, and joint recycling, with the objective of analyzing the optimal decision-making strategy for recycling and remanufacturing waste batteries. The goal is to pinpoint the most effective remanufacturing model and recycling channel combination. Furthermore, our study delves into the impact of the market share of remanufactured products and substitution effects on the optimal solution through numerical simulation. The primary findings are as follows:

(i) Looking at the total supply chain profits, NEV power battery manufacturers report the highest profits when adopting the independent recycling model. On the contrary, the joint recycling model leads to the lowest total supply chain profits. When embracing commissioned recycling, manufacturers see a better profit outcome when they commission third-party recyclers rather than retailers. From a corporate profitability perspective, both manufacturers and third-party recyclers stand to gain by participating in waste battery recycling. Conversely, retailers involved in this process may see a decrease in their profits. Therefore, the joint recycling model emerges as the most beneficial option for NEV power battery manufacturers.

(ii) Regarding recycling rates, NEV power battery manufacturers experience identical rates regardless of whether they collaborate with retailers or third-party recyclers. However, the independent recycling model yields notably higher rates compared to commissioned recycling. Thus, for manufacturers seeking to increase their recycling rates, a joint recycling approach is recommended.

(iii) The study uncovers the significant influence of substitution effects and the market share of remanufactured products on the recycling and remanufacturing of NEV power batteries. In terms of pricing, positive correlations exist between substitution effects and the prices of both types of products. Remanufactured products' market share exhibits a negative correlation with the price of new products, but a positive correlation with the price of remanufactured products. Regarding corporate profits, when the substitutability of both products is low, the market share of remanufactured products and substitution effects have a negative correlation with the profits of retailers and manufacturers. However, when the substitutability is high, these correlations become positive.

This study proposes actionable management insights and practical contributions to advance waste power battery recycling, starting with manufacturer-led collaborative recycling to drive supply chain synergy. Joint recycling initiatives are proven to effectively boost recycling rates while increasing manufacturers' profits, yet retailers and third-party recyclers often gain no additional benefits from this model. As core nodes of the supply chain, manufacturers must take proactive steps to incentivize their participation, drawing on successful cooperative governance cases (e.g., the Institute of Public and Environmental Affairs (IPE) leveraging Apple, Huawei, and Dell's influence to push SMEs toward better environmental disclosure and pollution control). Specifically, manufacturers should collaboratively establish and share standardized recycling platforms, collection points, and processing facilities with partners, and use their supply chain leverage to reduce participation costs (e.g., subsidizing transportation, providing technical training, or offering preferential procurement terms) to stimulate active engagement in recycling. A second key insight centers on government subsidies as a complementary driver for sustainable recycling systems. Given that retailers and third-party recyclers still derive no direct economic gains from joint recycling, targeted government subsidies are critical to bridging the profit gap. To maximize policy effectiveness, subsidies should be directed at retailers (for setting up in-store collection bins) and third-party recyclers (for investing in processing equipment) to offset operational costs. Additionally, subsidies should be aligned with recycling performance (e.g., based on the quantity and quality of batteries collected or processed) to incentivize efficiency and accountability, and paired with manufacturers' supply chain influence to form a "dual-driver" model that scales up recycling efforts. The third insight focuses on capitalizing on consumer environmental awareness to promote remanufactured batteries. The growing substitution effect between new and remanufactured products reflects a key shift: consumers now prioritize environmental responsibility alongside product performance when purchasing new energy vehicles (NEVs). NEV manufacturers and retailers should translate this trend into actionable market strategies, such as strengthening marketing campaigns to highlight the environmental benefits (e.g., reduced carbon emissions, resource conservation) and cost advantages of remanufactured batteries, enhancing transparency by disclosing remanufacturing standards, quality certifications, and environmental impact data to build consumer trust, and collaborating with NEV dealers to offer bundled sales (e.g., remanufactured batteries with vehicle purchases or after-sales services) or trade-in programs (e.g., exchanging old batteries for discounts on remanufactured ones), all of which drive market demand for remanufactured products and close the recycling-remanufacturing loop.

Appendix

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Conflict of Interest

The authors declare no conflict of interest.

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