Annals of Management
ISSN Print: 3079-5567
ISSN Online: 3079-5575
https://doi.org/10.63313/Management.8015

Research on Reverse Logistics Network of Power Batteries under Government Incentive Policies

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How to cite this paper: Yang, Q. (2026). Research on Reverse Logistics Network of Power Batteries under Government Incentive Policies. Annals of Management, 1(2), 62–73. ISSN Print: 3079-5567, ISSN Online: 3079-5575.
https://doi.org/10.63313/Management.8015
Published: 2026-09-28

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Abstract

In pilot projects carried out by some local governments, promoting the recycling and utilization of power batteries through financial subsidies has achieved preliminary results, which is expected to be popularized nationwide after further optimization and improvement. Focusing on incentive policies for new energy vehicle power battery recycling, this study constructs a closed loop supply chain system including battery manufacturers, original equipment manufacturers (OEMs) and consumers, and considers two recycling approaches for power batteries: echelon utilization and regenerative dismantling. Under two scenarios, namely no government intervention and government reward penalty mechanism implementation, this paper conducts an in depth analysis of the optimal strategy choices for each supply chain participant and the influences of these strategies on the recycling rate of retired power batteries. Comparative analysis demonstrates that the recycling rate of retired power batteries is significantly improved under active government intervention. This research not only provides a new perspective for understanding the role of government policies in power battery recycling, but also supplies empirical evidence and theoretical support for policymakers to design and optimize incentive mechanisms for power battery recycling and utilization. By revealing the positive effect of government subsidies on raising recycling rates, this study highlights the critical role of governments in advancing the sustainable development of the new energy vehicle industry.

Keywords

Power Battery; Reverse Supply Chain; Echelon Utilization; Reward Penalty Policy

1. Introduction

Over the past decade, inevitable changes in consumer consumption patterns and product diversification have greatly shortened the life cycle of electronic products. With the rapid development of the new energy vehicle industry, the market demand for power batteries, one of its core components, has surged. The attendant challenge lies in the disposal and recycling of large quantities of retired power batteries. This issue concerns not only resource recycling, but also environmental protection and sustainable development. In 2018, China issued the Interim Measures for the Administration of Power Battery Recycling and Utilization of New Energy Vehicles,

which clearly stipulates the primary responsibility of automobile manufacturers for power battery recycling. Against this backdrop, how to effectively motivate all participants and increase the recycling rate of power batteries has become an urgent practical problem. At present, the recycling and reuse of power batteries in China is still in its initial stage with an imperfect recycling system. It is urgent for the government to adopt tools such as subsidy policies to guide relevant enterprises and consumers to participate actively in recycling. In practice, some local governments including Guangxi and Shenzhen have attempted to implement interventions via financial subsidies. Central government ministries such as the Ministry of Ecology and Environment are also studying supporting fiscal and tax policies. Nevertheless, to formulate a more scientific subsidy mechanism for power battery recycling, the combined impacts of multiple factors must be taken into full consideration.

Scholars currently identify two major modes for retired power battery disposal: recycling dismantling and echelon utilization. Recycling dismantling refers to crushing degraded batteries to extract high value metals for reuse. Echelon utilization means reorganizing retired batteries with acceptable performance for application in other scenarios such as energy storage systems for communication base stations and low speed electric vehicles. Relevant academic research mainly focuses on reverse supply chains and recycling regulatory policies, exploring the construction of recycling networks, the division of responsibilities among supply chain stakeholders, and the influences of government policies on recycling systems.

However, most existing studies are built on the assumption of power battery remanufacturing and fail to pay sufficient attention to the widely discussed industrial topic of echelon utilization, creating discrepancies with actual enterprise operations. This paper attempts to fill this research gap. By incorporating both echelon utilization and regenerative dismantling, we construct a reverse supply chain model composed of battery manufacturers, OEMs and consumers. We compare supply chain decision making under no government intervention and the government reward penalty mechanism, analyze how different policies affect key performance indicators of power battery recycling, and propose effective government incentive policies to boost the recycling rate of retired batteries while pursuing the objective of fostering a mature market.

·Based on the above practical challenges and research motivations, this paper puts forward the following research questions:

·In the reverse supply chain for power batteries, how can both echelon utilization and regenerative dismantling be considered simultaneously so as to raise the recycling rate of retired power batteries?

·How do OEMs' profits change under the government reward penalty mechanism, and what impacts will such policies exert on battery manufacturers' profits?

How does the sensitivity of retired battery recycling volume to recycling price affect the design of government incentive policies? How should policies be adjusted to

motivate OEMs to strengthen the recycling of retired power batteries?

This paper integrates echelon utilization and regenerative dismantling into the power battery reverse supply chain and establishes a tripartite reverse supply chain model covering battery manufacturers, OEMs and consumers. It analyzes the decision making behaviors of all supply chain members under the scenarios of no government intervention and government reward penalty mechanism. Key performance indicators for power battery recycling in the reverse supply chain are compared between the two scenarios. Combined with the goal of cultivating a mature market, government incentive measures that can effectively improve the recycling rate of retired batteries are proposed. This study helps understand how reward penalty policies affect power battery recycling rates, and provides important theoretical foundations and practical references for designing efficient incentive mechanisms and promoting the sustainable development of the new energy vehicle industry. Through in depth analysis of policy effects, it is expected to offer decision making evidence for policymakers and support the development of the new energy vehicle power battery recycling sector.

2. Literature Review

The rapid growth of the electric-vehicle industry brings huge challenges to the recycling and utilization of power batteries. As the new-energy-vehicle industry booms, the issue of power-battery recycling has attracted increasing academic attention. The recycling of lithium-ion power batteries (LIBs) relates to resource circulation, ecological protection and supply-chain sustainability. This subsection sorts out existing literature from three dimensions: recycling channels, recycling benefits, and government reward-penalty policies.

Recycling pathways for retired power batteries have long been a key research focus. The selection of recycling channels is critical to achieving high-efficiency recycling. Wang et al. (2022) [1-2] and Feng et al. (2023) analyzed the roles of third-party recyclers in recycling systems and explored recycling-channel selection under government regulation empowered by blockchain technology. Zhang et al. (2023) [3] investigated multi-channel recycling choices and emphasized policy impacts on channel selection. Yang Yuxiang (2023) [4] constructed a multi-objective mathematical model for online-offline dual-channel recycling, which covers broader recycling regions and consumer groups to raise the recycling rate of spent power batteries. Hu Wenjie (2024) [5] established a single-channel recycling model and further developed two types of dual-channel recycling models. She conducted an in-depth analysis of supply-chain members' strategic preferences and overall system performance under different modes. Taleizadeh et al. (2018) [6] compared reverse recycling networks with and without retailer participation, and found that supply-chain performance is better when retailers take part in recycling. Peng (2024) [7] built four multi-channel recycling models including battery suppliers,

third-party recyclers and new-energy-vehicle manufacturers to improve the recycling efficiency of retired power batteries.

Research on the benefits of spent-power-battery recycling is summarized below. The economic benefits are mainly reflected in resource recovery and cost saving. Studies show that recycling spent power batteries can effectively cut raw-material procurement costs, especially for key metals such as lithium, cobalt and nickel (Gu et al., 2024) [8]. Recycling spent power batteries also delivers substantial environmental benefits: it mitigates environmental pollution caused by waste batteries and reduces hazardous-substance emissions. Chen et al. (2022) [9] pointed out that recovering heavy metals and harmful chemicals from batteries can effectively reduce soil and water contamination and facilitate the sustainable development of ecological environments. Beyond economic and environmental benefits, spent-power-battery recycling generates prominent social benefits. For one thing, the recycling industry creates jobs and drives local economic growth. Zhao et al. (2022) [10] found that building an industrial chain for spent-power-battery recycling and reuse can provide a large number of jobs and improve residents' living standards.

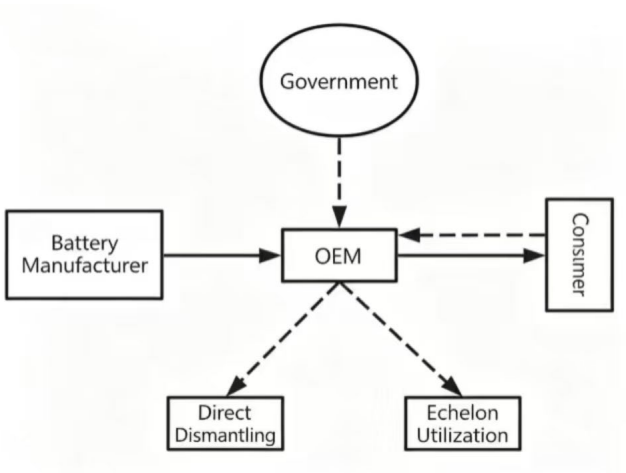
As an important stakeholder in power-battery recycling, governments have adopted various intervention instruments including deposit-refund schemes and reward-penalty mechanisms. As a vital tool for advancing power-battery recycling, government reward-penalty policies have become a research hotspot for academia and industry. Most existing literature focuses on government subsidy policies, while studies on reward-penalty mechanisms are relatively limited. Tang et al. (2018) [11] indicated that reward mechanisms can effectively raise battery recycling rates, particularly under fierce market competition. Using game models, Gao et al. (2023) [12] analyzed recycling strategies of manufacturers and third-party recyclers under different policies. They found that government subsidies can promote cooperation between manufacturers and recyclers and build efficient recycling networks. On the contrary, without effective policy constraints, enterprises tend to select the lowest-cost recycling channels, leading to low recycling efficiency (Li et al., 2023) [13]. Yu et al. (2022) [14] argued that implementing reward mechanisms can significantly improve battery recycling rates, boost resource recycling and support sustainable development. Zhang Chuan (2021) [15] suggested that subsidizing third-party recyclers constitutes the optimal strategy for power-battery echelon utilization compared with subsidizing manufacturers and retailers. Ding (2020) [16] found that subsidies for recycling enterprises exert the strongest effect on recycling rates, whereas subsidies for dismantling enterprises have the greatest influence on social welfare.

3. Model Description and Assumptions

3.1. Model Description

Figure 1 is a schematic diagram of reverse-supply-chain structure, depicting the recycling process for new-energy-vehicle power batteries. The system involves four stakeholders: the government, battery manufacturers, OEMs and consumers. Retired batteries have two primary recycling routes: direct dismantling and echelon utilization.

Figure 1. Schematic diagram of the reverse supply chain structure



Battery manufacturer: Purchases raw materials such as nickel and cobalt from the market to produce brand-new power batteries.

Original equipment manufacturer (OEM): Purchases new power batteries from the battery manufacturer, assembles them with other components to manufacture new energy vehicles and sells the vehicles to consumers. The OEM is also responsible for purchasing retired power batteries from consumers at a certain price, and then sends these batteries for direct dismantling or echelon utilization.

Consumer: It is assumed that consumers purchase brand-new new energy vehicles directly from the OEM. When the power battery of the vehicle approaches retirement, consumers can freely decide whether to sell the retired battery back to the OEM.

Government: Acts as a regulator outside the entire supply chain. It may implement subsidies or reward-penalty mechanisms for the OEM to improve the recycling rate of retired power batteries. Government policies directly affect the OEM's recycling decisions and the efficiency of the whole supply chain. Government intervention aims to raise the recycling rate of retired power batteries and promote resource recycling.

Direct dismantling: A recycling treatment mode, in which the OEM dismantles retired batteries to extract valuable materials such as nickel, cobalt and lithium for reuse.

Echelon utilization: For retired batteries with acceptable residual performance, the

OEM can disassemble them into battery modules. Battery modules with good consistency are regrouped and applied to other scenarios, such as energy storage for communication base stations and low-speed electric vehicles.

This model describes the full life cycle of power batteries from production to recycling, as well as the interactions among the government, enterprises and consumers in this process. This description helps better understand the complexity of power battery recycling and the role of government policies.

3.2. Basic Assumptions

·Let the demand function for new power batteries be $q_1 = a - bp$, where a denotes the market size of new power batteries, b represents consumers'sensitivity coefficient to the retail price p of new power batteries, and.[17][18]

·Products remanufactured from recycled batteries are homogeneous with products manufactured with brand-new components.

·It is assumed that the retired power batteries can only be applied for echelon utilization or dismantling after recycling.

·Assume that the metal raw materials in retired batteries can be recycled at a recovery rate of 100%.，The metal value contained in each set of battery is v_a .When the OEM sells retired batteries to echelon utilization enterprises, the profit per unit battery is v_b , and it is assumed that v_a is less than v_b .

·The government sets a reward (penalty) of k per unit battery. The expression for the reward (penalty) obtained by the OEM from the government is $k = (\varphi - \varphi')Dk$.

3.3. Notation

The symbols and variables adopted in this paper are shown in Table 1.

Symbol	Definition
c_{m1}	Unit processing cost for battery manufacturers to produce power batteries, excluding raw-material cost
c_a	Unit raw-material cost for battery manufacturers to produce power batteries
c_{m2}	Sum of raw-material and processing costs for OEMs to manufacture one electric vehicle
B	Fixed cost for OEMs to establish a recycling department
f	Proportion of collected retired batteries that cannot be used for echelon utilization and have to be dismantled
v_a	Raw-material value of each retired battery after dismantling
v_b	Value of each retired battery available for echelon utilization （$v_a < v_b < \omega$）
k	Unit reward for exceeding the government-set target recycling rate or unit penalty for falling below the target recycling rate under the reward-penalty mechanism

φ	Target recycling rate set by the government under the reward-penalty mechanism
φ'	Actual recycling rate of retired power batteries
D	Market demand for brand-new new-energy vehicles
Q	Quantity of retired batteries collected by the OEM from consumers
π_s	Quantity of retired batteries collected by the OEM from consumers
π_m	Profit of battery manufacturers
ω	Selling price of each brand-new power battery
p	Retail price of brand-new new-energy vehicles
r	Price paid to consumers for collecting one unit of retired power battery

4. Model Construction

Reverse-Supply-Chain Decision-Making Model without Government Reward-Penalty Policies.

This scenario excludes government intervention. Only two decision-makers exist in the supply chain: battery manufacturers and OEMs. Both make independent decisions to maximize their own profits. When selling one unit of battery at price ω, battery manufacturers bear processing costs c_{m1}, raw-material costs c_a, Their decision-making objective is shown in Formula (1).

$$\max_{w} \pi_s = (w - c_{m1} - c_a)(a - bp) \quad (1)$$

In Formula (1): $w - c_{m1} - c_a$ the item represents the net profit gained by battery manufacturers from selling one unit battery; $a - bp$ denotes market demand for new-energy vehicles, which equals battery sales volume.The profit-maximization model for OEMs is presented in Formula (2):

$$\max_{(pr)} \pi_m = (p - w - c_{m2})(a - bp) - B - r(m + nr) + (m + nr) f v_a + (m + nr)(1 - f) v_b \quad (2)$$

In Formula (2): $(p - w - c_{m2})(a - bp)$ the first term refers to OEMs' profit from selling new vehicles,B is the fixed cost for OEMs to build a recycling department, $(m + nr) f v_a$ the second term is profit generated by direct dismantling of retired batteries with proportion f, $(m + nr)(1 - f) v_b$ the third term is profit obtained from selling batteries processed for echelon utilization.

We solve the model via backward induction and derive the optimal values as follows:

$$\omega_1 = \frac{a + b(c_{m1} + c_a - c_{m2})}{2b}, p_1 = \frac{3a + b(c_{m1} + c_a - c_{m2})}{4b}, r_1 = \frac{nG - m}{2n}$$

where $G = f_{v_a} + (1 - f) v_b$, $v_a < v_b$ .Assume $v_a < v_b$,so Gis negatively correlated with f .

$$D_1=\frac{a-b(c_{m1}+c_a+c_{m2})}{4},Q_1=\frac{nG+m}{2},\varphi_1=\frac{2(nG+m)}{a-\mathrm{b}\left(c_{m1}+c_a+c_{m2}\right)},\pi_{s1}=\frac{\left[a-b(c_{m1}+c_a+c_{m2})\right]^2}{8b}$$

$$\pi_{m1}=\frac{\left[a-b(c_{m1}+c_a+c_{m2})\right]^2}{16b}-B+\frac{(nG+m)^2}{4\mathrm{n}}$$

where :

（3）

3.2 Reverse-Supply-Chain Decision-Making Model under Reward-Penalty Policies

The government sets a target recycling rate. OEMs will be penalized if their actual recycling rate fails to reach this target and rewarded if they exceed it. $\varphi-\varphi'$ represents the gap between the actual battery recycling rate and the government-set target recycling rate, $\mathrm{k}(\varphi\text{-}\varphi')(\mathrm{a\text{-}bp})$ the reward or penalty amount received by the OEM from the government. The OEM's objective function under this scenario is Formula：

$$\max_{(pr)}\pi_m=(p-w-c_{m2})(a-bp)-B-r(m+nr)+(m+nr)v_a$$
$$+(m+nr)(1-f)v_b+k(\varphi-\varphi')(a-bp)$$

（4）

Battery manufacturers' decision-making objective is unaffected by the government reward-penalty mechanism and remains consistent with Formula (1).

The optimal selling price for new batteries is: $w=\frac{a+b(c_{m1}+c_a-c_{m2}-k\varphi')}{2b}$

The optimal retail price for vehicles is: $p=\frac{3a+b(c_{m1}+c_a+c_{m2}+k\varphi')}{4b}$

The recycling price for retired batteries $r=\frac{nG+nk-m}{2n}$ is negatively correlated with f.

Compared with the scenario without government reward-penalty policies, decisions in the forward supply chain change, while all decision variables in the reverse supply chain increase. $w_1>w_2,p_1<p_2,D_1>D_2,\ r_1<r_2,Q_1<Q_2$ 。

We calculate differences between optimal solutions under the reward-penalty scenario and those under no-intervention scenario and obtain:

$$w_1-w_2=\frac{k\varphi'}{2}>0,p_1-p_2=-\frac{k\varphi'}{4}<0,$$

$$D_1-D_2=\frac{k\varphi'}{4},\pi_{s1}-\pi_{s1}>0,r_2-r_1=\frac{k}{2}>0,$$

$$Q_2-Q_1=\frac{nk}{2}>0,\varphi_2-\varphi_1>\frac{2nk}{a-b(c_{m1}+c_a+c_{m2})}>0,$$

$$\pi_{m2}-\pi_{m1}=\frac{k\varphi'\left[2b(c_{m1}+c_a+c_{m2})+bk\varphi'-2a\right]}{16}$$

$$+\frac{k(2nG+2m+nk)}{4}$$

$$\varphi_2=\frac{2(nG+nk+m)}{a-b(c_{m1}+c_a+c_{m2}+k\varphi')}$$

Recycling rate of retired power batteries:

$$G=fv_a+(1-f)v_b$$

Compared with no government intervention, the reward-penalty mechanism

influences forward-supply-chain decisions and reduces market demand for vehicles. More significant impacts occur in the reverse supply chain: both the recycling price and total collected quantity of retired batteries rise, which effectively stimulates absolute power-battery recycling volume. Larger government intervention intensity k brings stronger incentives for recycling. Exposed to penalty risks under reward-penalty rules, OEMs are forced to raise spent-battery recycling rates. This mechanism increases collected-battery quantity yet suppresses new-vehicle sales volume, which may hinder the popularization of new-energy vehicles to a certain extent.

For intuitive comparison of decision variables, a summary of model optimal solutions is presented in Table 2.

Table 2. Summary of Model Optimal Solutions

	No government intervention	Government reward-penalty mechanism	Ranking
w	$\frac{a+b(c_{m1}+c_a-c_{m2})}{2b}$	$\frac{a+b(c_{m1}+c_a-c_{m2}-k\varphi')}{2b}$	$w_1 > w_2$
p	$\frac{3a+b(c_{m1}+c_a-c_{m2})}{4b}$	$\frac{3a+b(c_{m1}+c_a+c_{m2}+k\varphi')}{4b}$	$p_1 < p_2$
r	$\frac{nG-m}{2n}$	$\frac{nG+nk-m}{2n}$	$r_1 < r_2$
φ	$\frac{2(nG+m)}{a-\mathrm{b}\ （c_{m1}+c_a+c_{m2})}$	$\frac{2(nG+nk+m)}{a-b(c_{m1}+c_a+c_{m2}+k\varphi')}$	$\varphi_1 < \varphi_2$

5. Acknowledgements

Considering the overall production capacity of current new-energy-vehicle manufacturers, the maximum market size of new-energy vehicles is set as a=250 units. The unit reward-penalty value under the mechanism is k=1000，The base quantity of retired batteries voluntarily returned by consumers is m=100000 sets.，Values of other parameters are listed in Table 3.

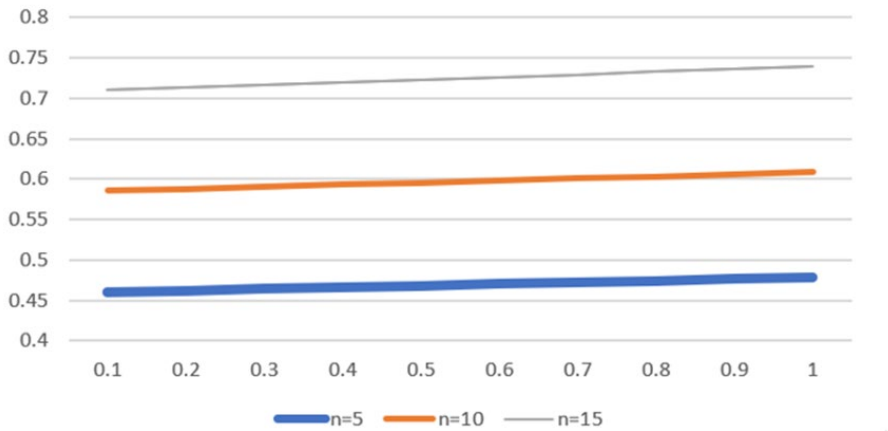
Table 3. Parameter Values

c_a / yuan	c_{m1} / yuan	c_{m2} / yuan	B	v_a / yuan	v_b / yuan	b	f / %
6000	50000	20000	500000	6000	7000	25	50

Under the reward-penalty mechanism, the government presets a target recycling rate. This subsection analyzes how this preset target affects the final actual recycling rate of retired batteries, as illustrated in Figure 2. Horizontally, a higher recycling-price sensitivity coefficient n yields a higher final battery recycling rate. A larger n means that each unit increase in the recycling price brings more than one additional unit of collected batteries. Accordingly, OEMs are motivated to raise recycling prices so as to expand collection scale and gain more profits. Vertically, as

the government-preset recycling rate rises gradually from 0 to 1, the actual recycling rate shifts from exceeding the preset value to falling below it, and OEMs switch from receiving rewards to suffering penalties. Besides, a larger n corresponds to a higher critical value of φ' for this transition point.

Figure 2. Impacts of government-preset recycling rate on final battery recycling rate



Therefore, for government authorities: in the early promotion stage of new-energy vehicles, consumers have limited disposable income and are price-sensitive. At this stage, the preset recycling rate should not be set excessively high, so that OEMs can obtain rewards and maintain enthusiasm for recycling. When the new-energy-vehicle market matures, public acceptance of power batteries improves and residents' income grows, consumers become less sensitive to recycling prices, and governments can appropriately raise the preset recycling rate. It should be noted that 100 % recycling of retired batteries is unrealistic; hence governments should not set the target recycling rate equal to 1.

6. Conclusions

This paper investigates recycling modes for spent power batteries of new-energy vehicles. Innovatively, both echelon utilization and regenerative dismantling are integrated into the power-battery reverse-supply-chain model. This model conforms to industrial realities and supplies more practical references for power-battery recycling decision-making. Research results demonstrate that compared with no government intervention, the government-implemented reward-penalty mechanism can improve battery recycling rates more effectively. This finding verifies the important value of policy instruments in environmental protection and resource recycling. In particular, diverting more retired batteries to echelon-utilization channels improves resource-use efficiency and raises profits for both OEMs and battery manufacturers, achieving a win-win outcome for economic and environmental benefits.

Numerical examples further confirm that the recycling-price sensitivity coefficient exerts influences on retired-battery recycling rates. When the recycling-price sensitivity coefficient is high, consumers respond strongly to price changes. A relatively low preset recycling rate can fully mobilize OEMs' enthusiasm and promote industrial development. As market acceptance of new-energy vehicles and their batteries increases and consumers become less price-sensitive, governments may moderately raise the preset recycling rate to match market maturity.

Nevertheless, while increasing retired-battery recycling rates, the reward-penalty mechanism may bring about certain side effects. For instance, to meet government recycling targets, OEMs may raise selling prices of new-energy vehicles, which suppresses new-vehicle sales and hinders further market expansion. Although higher retired-battery recycling rates are achieved under the reward-penalty mechanism, this results partly from enterprises' global optimal decision-making and partly from institutional deterrence pushing OEMs to attach importance to recycling businesses. The long-term effects and potential negative impacts of this mechanism require further research.

Although this study offers references for power-battery recycling, it still has limitations. This paper assumes linear relationships between new-energy-vehicle demand and price, as well as between spent-battery collection volume and recycling price. Such assumptions cannot fully replicate complex real-world markets. Future research may introduce non-linear models and incorporate more variables such as consumer preferences, technological progress and market competition to enrich research conclusions. Moreover, follow-up work can explore recycling modes in different regions and market contexts, and investigate how policy innovation improves recycling efficiency and reduces costs, so as to support efficient and sustainable development of the power-battery recycling industry.

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