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A Review of Reverse Logistics Network Planning for Retired Power Batteries

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ABSTRACT

The rapid expansion of China's new-energy vehicle industry has driven an unprecedented surge in power-battery installations, making the large-scale management of retired batteries an increasingly urgent challenge. These batteries retain substantial residual capacity and, if subjected to scientifically grounded cascade utilization and recycling, could alleviate mounting pressures on critical resources such as lithium, nickel and cobalt, reduce China's external dependence on these materials, and maximize the value recovered from end-of-life batteries. Yet the absence of adequate treatment pathways poses a countervailing risk: improperly managed retired batteries can generate severe secondary environmental pollution with unpredictable ecological consequences. China's battery-recycling system remains at an early stage of development, underscoring the urgent need for a robust and efficient reverse logistics network. This study therefore focuses on reverse logistics network planning for retired power batteries from new-energy vehicles and offers a comprehensive review of existing research. It systematically examines relevant policies and the state of the art in reverse logistics network planning, revealing notable gaps: policy-oriented studies tend to concentrate on strategic interactions among subsidy recipients within game-theoretic frameworks while neglecting network planning after government subsidies, whereas network-planning studies rarely incorporate the effects of government subsidies. The study further identifies future research directions and likely development trends, aiming to provide theoretical and practical guidance for building a sound power-battery recycling system, promoting the sustainable development of the new-energy vehicle industry, and achieving the dual objectives of economic growth and environmental protection.

KEYWORDS

Power Battery; Reverse Logistics; Government Subsidy; Network Planning.

1. INTRODUCTION

The new-energy sector has expanded rapidly in recent years, with sustained growth in both output and sales and a corresponding surge in power-battery installations. Data released by the China Association of Automobile Manufacturers show that China's electric-vehicle sales reached 12.866 million units in 2024, a year-on-year increase of 35.5%, while annual power-battery installations amounted to 548.4 GWh, up 41.5% year on year. This rapid expansion, however, masks a formidable resource constraint: the lithium, cobalt and nickel required for power batteries remain subject to exceptionally high levels of external dependence[1]. Although China possesses relatively abundant lithium reserves, utilization rates are low and external dependence stands at approximately 58%. Cobalt reserves are scarce, with dependence reaching 98%. China accounts for more than 50% of global nickel consumption, yet more than 86% is imported. Such heavy reliance exposes battery manufacturers to substantial supply risk. At the same time, the coming decade will witness a peak in power-battery retirements. Under prevailing trends, the total volume of retired batteries will reach

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350 GWh by 2030. If handled improperly, the hazardous substances they contain will severely damage the environment; if recycled efficiently, however, they can yield lithium, cobalt, nickel and other metals sufficient to meet one-third of the manufacturing demand of the domestic new-energy vehicle industry, substantially reducing import dependence[2]. Establishing an efficient and well-regulated power-battery recycling network has therefore become a critical step in addressing resource constraints and environmental pollution. Such a network can enable the large-scale collection and treatment of retired batteries, provide stable support for resource circulation, and drive the green transformation and sustainable development of the industrial chain. This paper accordingly offers a comprehensive review of existing research, aiming to clarify the current state and progress of reverse logistics for power batteries, identify shortcomings in present studies, and propose future research directions and likely development trends.

2. RESEARCH SIGNIFICANCE

China's electric-vehicle market is dominated by lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) batteries, which together account for nearly 100% of the market. In addition, the "Industry Standard Conditions for Comprehensive Utilization of Waste Power Batteries from New-Energy Vehicles (2024 Edition)," issued by the Ministry of Industry and Information Technology on 16 December 2024, newly requires recycling enterprises to handle spent lithium-ion batteries (SLIBs) from electric bicycles. This study therefore examines not only LFP and NMC batteries, which are commonly studied, but also spent lithium-ion batteries from electric bicycles. Against this background, the theoretical and practical significance of research on reverse logistics network planning for retired power batteries from new-energy vehicles is as follows.

2.1. Theoretical Significance

Amid the rapid development of the new-energy vehicle industry and the growing scale of retired power batteries, research on reverse logistics network planning can substantially enrich theories of logistics network planning. Traditional logistics network planning has focused predominantly on forward logistics, whereas reverse logistics for retired power batteries exhibits distinctive processes and characteristics, encompassing multi-channel collection, complex testing and classification, and diversified reuse. This study can fill a theoretical gap in reverse logistics network planning within this specific domain and provide a robust basis for constructing realistic, precise and effective reverse logistics network planning models. It also helps refine the portion of circular economy theory concerned with resource reuse at the end of the product life cycle, deepens theoretical understanding of resource-circulation chains, and further extends the application of supply chain collaboration theory to reverse operations, rendering the overall theoretical system more comprehensive and practically instructive.

2.2. Practical Significance

The recycling of retired power batteries is important not only economically, environmentally and in terms of safety, but also constitutes a strategic choice for China in addressing resource constraints, advancing green development, and achieving deep decarbonization across the entire industrial chain. On the one hand, as the world's largest consumer market for new-energy vehicles, China faces the urgent task of properly handling large quantities of retired power batteries. In-depth research on reverse logistics network planning can establish a sound and efficient recycling system, maximize cascade utilization and recycling of retired power batteries, alleviate the scarcity of and external dependence on critical resources such as lithium, nickel and cobalt, and improve overall resource utilization efficiency. On the other hand, it can prevent severe secondary environmental pollution caused by the improper disposal of large volumes of retired power batteries, safeguard ecological security, and help standardize and improve the downstream chain of the new-energy vehicle industry.

This promotes sustainable and healthy industrial development and plays a positive and critical role in jointly enhancing economic and environmental benefits.

3. STATE OF THE ART

3.1. Research on Power-Battery Recycling Policies

The new-energy sector has expanded rapidly in recent years, with sustained growth in output and sales and a corresponding surge in power-battery installations. China has become the world's largest country in both new-energy vehicle application and battery installations. As the stock of new-energy vehicles continues to rise, a peak in power-battery retirements is approaching. Spent power batteries contain large quantities of metals such as lithium and cobalt as well as toxic electrolytes, giving them high recycling value and significant hazardous potential. The recycling of power batteries therefore carries important economic, resource and environmental implications.

The recycling and reuse of retired power batteries has attracted widespread attention from the state and scholars. To advance the recycling of spent power batteries, on 6 March 2018 the Ministry of Industry and Information Technology, the Ministry of Environmental Protection, the Ministry of Science and Technology, the Ministry of Commerce, the Ministry of Transport, the General Administration of Quality Supervision, Inspection and Quarantine, and the National Energy Administration jointly issued the "Pilot Implementation Plan for the Recycling and Utilization of Power Batteries from New-Energy Vehicles." The plan explicitly proposed that pilot regions and cities should establish and improve policy-incentive mechanisms, study policy measures supporting the recycling and utilization of power batteries, explore relevant policy-incentive mechanisms, fully mobilize the enthusiasm of all parties, and promote the recycling and utilization of power batteries. Pilot regions subsequently introduced their own recycling subsidy policies and schemes.

Many scholars have also discussed subsidy policies for power-battery recycling. Tang et al. (2018) proposed reward-penalty mechanisms and policies and used a Stackelberg game-theoretic model to examine their effects on power-battery recycling. Ding et al. (2020) established the first analytical model studying subsidies for two types of power batteries and explored optimal collection strategies and subsidy preferences. Their results showed that recycling strategy depends on fixed recycling costs, and that dismantling efficiency is the key factor determining firms' subsidy preferences. Zhang and Chen (2021) investigated optimal decisions and coordination in a retailer-led closed-loop power-battery supply chain considering government subsidies and scale effects. Their analysis showed that government subsidies can reduce retail prices, increase recycling rates, and raise the profits of all members. Wang (2021) analysed the characteristics of each stage of the power-battery life cycle from a life-cycle perspective and examined policies across the full life cycle. The study found that recycling policies are relatively concentrated at the midstream processing stage, while upstream and downstream policies are relatively lacking; top-level legal construction is absent; the recycling network is incomplete; and incentive and guidance policies for cascade-utilization enterprises require revision. Liu and Ma (2021) established a closed-loop power-battery supply chain model considering the cascade-utilization market, focusing on the effects of reverse subsidies and recyclers' scale effects. Their results showed that subsidizing recyclers and subsidizing manufacturers have the same effect on profit distribution in the closed-loop supply chain but differ in buyback and wholesale prices; both can increase the profits of manufacturers and recyclers, while subsidizing cascade-utilization firms can increase the profits of recyclers and themselves. Yang (2022) employed system dynamics theory and methods, combined with three existing major recycling modes—manufacturer recycling, third-party enterprise recycling, and industrial alliance recycling—to examine the effects of subsidizing different targets on the government's implementation of rapid-growth, phased-growth and fixed recycling subsidy policies. Zhang et al. (2022) constructed three models under a government responsibility extension system based on the extended producer responsibility system, finding that

when the government implements RPM only for vehicle manufacturers, the recycling rate and total closed-loop supply chain profit are highest. Wang et al. (2023) compared the effects of government policies on subsidizing recycling enterprises, subsidizing consumers, and subsidizing both recycling enterprises and consumers, concluding that without government subsidies the market cannot guarantee high returns for both parties, and that recyclers and consumers find it difficult to cooperate proactively in the recycling of spent power batteries. Wu and Zhang (2024) established a closed-loop power-battery supply chain model under subsidy policies and designed coordination strategies to optimize supply chain operation. A review of these studies shows that most adopt game-theoretic methods, while literature on reverse logistics network optimization for power batteries under government subsidies is almost absent. Some scholars focus primarily on strategic interaction among multiple subsidy participants, and few consider logistics network planning after government subsidies.

3.2. Research on Reverse Logistics Network Planning for Power Batteries

Research on reverse logistics network planning in China is relatively mature, whereas research on reverse logistics network planning for retired power batteries started later. Zhu and Chen (2019) took spent power batteries generated by electric vehicles sold by SAIC Motor as the research object, established an evaluation index system, and applied fuzzy comprehensive evaluation to study reverse logistics mode selection for retired power batteries. Wang et al. (2020) developed a carbon-emission-based model from the perspective of electric-vehicle manufacturers, considering three possible battery treatment strategies—recycling, remanufacturing and disposal—and examined the impact of carbon taxes on power-battery recycling networks with cost minimization as the objective, designing a genetic algorithm to solve the model. Chen (2021) used Jiangsu Province as a case study, applied a grey GM(1,1) prediction model to forecast electric-vehicle sales in Jiangsu, and solved the model through Python programming to obtain site selection and flow allocation results for the reverse logistics network, verifying the feasibility of the retired-battery model for electric vehicles under uncertainty. Liu (2021) built a power-battery recycling logistics network model based on a multi-party joint operation recycling mode, with profit maximization as the objective and considering uncertainties in demand, recycling quantity and recycling quality. Using L City as a case study, the model was solved and analysed with LINGO software.

Yan et al. (2022) addressed problems such as inconsistent initial characteristic parameters of retired power batteries and reduced safety and stability during cascade utilization, proposing a progressive sorting method for retired power batteries based on risk defence. An improved K-means algorithm was first used to extract initial clustering data from retired power-battery parameters, followed by secondary sorting based on SOF characteristics, thereby improving risk-defence capability during cascade utilization. Lin et al. (2023) designed a reverse logistics network using a mixed-integer linear programming (MILP) model with cost minimization as the objective, based on existing spent power-battery collection points in Chengdu. Li et al. (2023) established a stylized configuration model for incumbent and entrant firms under two schemes—cross-network cooperation and different cross-network cooperation—using mixed-integer nonlinear programming (MINLP), while considering carbon emissions and government penalties, and finally applied a Lagrangian heuristic algorithm to derive optimal solutions. Wang et al. (2023) considered the costs of transportation, construction, operation, recycling, packaging and emissions, as well as benefits from sales revenue and subsidies, collected and predicted future quantities of retired batteries, and developed a fuzzy-based model to solve the optimal path and distribution problem in the battery recycling network. Yang et al. (2023) studied a dual-channel reverse logistics network for power-battery recycling considering cascade utilization, established a multi-objective linear programming model incorporating the three dimensions of sustainability—economic, environmental and social—under uncertainty, and designed an improved hybrid cooperative co-evolutionary genetic algorithm to solve the model. Saha et al. (2024) proposed a reverse logistics network for LIB recycling under uncertain raw-material quantities and sales prices, developed a two-stage stochastic model to facilitate strategic decisions, and applied

a simple average approximation method to solve the model, quantifying the impact of uncertainty on recycling operations and government policies.

In summary, existing research on reverse logistics network planning for power batteries has achieved important results and progress, but none has approached the problem from the perspective of government subsidies. Research considering reverse logistics network planning for power batteries under government subsidies is therefore highly necessary. This study aims to provide a theoretical basis for reverse logistics network planning under policy subsidies.

4. CRITICAL REVIEW

This study examines in depth the reverse logistics network planning problem for retired power batteries from new-energy vehicles and reveals its far-reaching theoretical significance. In the field of logistics network planning, traditional research has concentrated largely on forward logistics, whereas the characteristics of reverse logistics for retired power batteries—such as dispersed collection, complex classification and diversified reuse—offer new research perspectives. This study helps fill a theoretical gap in a specific domain, supports the construction of more realistic, precise and effective reverse logistics network planning models, and advances the comprehensive development of theory.

The recycling and reuse of retired power batteries is a key component of resource circulation. This study helps refine the portion of circular economy theory concerned with resource reuse at the end of the product life cycle, making the resource-circulation chain more complete and continuous, deepening theoretical understanding of resource recycling, and enhancing the practical guidance value of circular economy theory. At the same time, reverse logistics networks for retired power batteries involve numerous stakeholders, and research on their planning helps re-examine collaborative modes among supply chain segments, promotes deeper application of supply chain collaboration theory in reverse logistics, and facilitates efficient operation of supply chain systems. As the world's largest consumer market for new-energy vehicles, China faces the challenge of handling large quantities of retired power batteries. In-depth research on reverse logistics network planning is essential for building a sound and efficient recycling system. Optimizing reverse logistics networks can enable cascade utilization and recycling of retired power batteries, recover critical resources such as lithium, nickel and cobalt, alleviate resource scarcity, reduce external dependence, improve resource utilization efficiency, and provide resource security for the sustainable development of the new-energy vehicle industry.

The proper handling of retired power batteries is also critical for environmental protection. If retired batteries are not disposed of properly, the heavy metals and hazardous substances they contain will cause severe environmental pollution and threaten ecological balance and human health. This study helps prevent secondary environmental pollution by establishing scientifically sound reverse logistics networks that ensure the safe and environmentally responsible recycling and treatment of retired batteries, safeguard ecological security, and maintain the stability and sustainability of ecosystems. Research on reverse logistics network planning for retired power batteries also positively promotes the sustainable development of the new-energy vehicle industry. A well-developed reverse logistics network can standardize and optimize the downstream chain of the industry, promote the healthy development of the battery-recycling sector, and foster a sound industrial ecosystem. This helps attract more enterprises to participate in battery recycling and utilization, expand and upgrade industrial scale, create employment opportunities, enhance economic benefits, and achieve coordinated improvement of economic and environmental benefits, thereby driving the industry toward green and sustainable development.

However, although existing research on power-battery recycling policy has extensively discussed subsidy policies, research on reverse logistics network optimization for power batteries under

government subsidies remains relatively insufficient. Some studies focus on strategic interaction among multiple subsidy participants and fail to fully consider network planning after government subsidies. Future research should therefore focus on reverse logistics network optimization for power batteries under government subsidies, comprehensively consider multiple factors, and construct scientific, reasonable and practically operable reverse logistics network planning models. At the same time, interdisciplinary research should be strengthened, integrating knowledge from logistics, economics, environmental science, engineering and other disciplines, so as to provide comprehensive, multi-perspective solutions to the problem of reverse logistics network planning for retired power batteries and offer strong support for the sustainable development of China's new-energy vehicle industry.

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