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A Review of Research on Power Battery Recycling and Cascade Utilization: Technical Paths, Policy Impacts and Sustainable Development Paths

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Abstract **Original Research Article**

This paper systematically reviews the research progress in the field of power battery recycling and cascade utilization, and analyzes it from four dimensions: technical path, economic model, policy impact and environmental benefit. In terms of technical paths, battery sorting technology based on performance characterization, echelon sorting model with multi-state coupling, and adaptability evaluation of echelon utilization scenarios are current research hotspots. The economic model research focuses on the closed-loop supply chain game, the cost sharing and profit distribution mechanism, and the impact of carbon policy on the economic boundary of cascade utilization. The policy impact analysis shows that there are differences between national and local policy frameworks, and the effects of EPR system and subsidy policy are significant, and the coupling effect of policy mix has become a new research focus. In terms of environmental benefit assessment, life cycle carbon footprint analysis, comparison of environmental performance of different processes, and spatiotemporal distribution and environmental risk research are the key contents. However, there are deficiencies in the existing research on multi-objective optimal integration, dynamic scenario adaptation, policy combination effect, interdisciplinary integration, and long-term environmental impact data. Future research directions should include the construction of multi-objective collaborative optimization models, the quantification of policy portfolio effects, the development of interdisciplinary integration of technology-economic models, the full-cycle management based on digital twins, the research of regional collaborative recycling systems, and the environmental and economic assessment of new recycling technologies. The purpose of this paper is to provide a theoretical reference for building a sustainable battery circular economy system, promote the high-quality development of power battery recycling and cascade utilization, and help achieve the "dual carbon" goal..

Keywords: Power Battery Recycling, Cascade Utilization, Closed-Loop Supply Chain, Environmental Benefits.

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1. INTRODUCTION

With the rapid development of the new energy vehicle industry worldwide, the number of retired power batteries has shown an amazing geometric growth trend. According to the forecast data of authoritative institutions, by 2035, the total number of retired power batteries in China will reach an astonishing 11.77 million tons. In the face of such a large number of retired batteries, how to achieve their efficient recycling and cascade utilization has become an important issue to achieve the "double carbon" goal proposed by the state and promote resource recycling.

This paper discusses the latest research results in the field of power battery recycling and cascade utilization, and makes a comprehensive analysis from four key dimensions: technical methods, economic models, policy impacts, and environmental benefits. Through a systematic review of existing research, this paper not only reveals the core findings in this field, but also points out the limitations of existing theoretical research. On this basis, this paper further proposes a potential breakthrough direction for future research, aiming to provide a solid theoretical support and reference for the construction of a sustainable battery circular economy system.

2. RESEARCH ON THE TECHNICAL PATH AND SORTING METHOD OF POWER BATTERY CASCADE UTILIZATION

2.1Battery sorting technology based on performance characterization

The primary problem in the cascade utilization of retired power batteries lies in the accurate evaluation and classification of battery status. Traditional detection methods based on electrical parameters are difficult to capture the local abnormalities of single cells, and ultrasonic body wave detection technology provides a new idea to solve this problem. He Cunfu et al. built an ultrasonic body wave test system, and realized the sub-region detection of the uniformity of the internal material of the prismatic aluminum shell battery by analyzing the acoustic wave propagation law under the conditions of low rate and high rate charge and discharge and stepped temperature change, which can effectively screen out the batteries suitable for cascade utilization and lay a technical foundation for non-destructive classification. The introduction of digital twin technology has further improved the dynamics and accuracy of battery condition assessment. Yan Ning et al. proposed a dynamic functional state (SOF) screening method for retired battery modules based on digital twins, constructed a SOF characteristic characterization model through voltage, current, SOC and SOH parameters, combined with generative adversarial network (GAN) and long short-term memory network (LSTM) to deal with the problem of data loss, and finally used the K-means algorithm to realize module clustering and screening. The simulation results show that this method can significantly improve the dynamic consistency of retired batteries and prolong the cascade service life. Similarly, Liu et al. pointed out that battery state of health (SOH) assessment and remaining life (RUL) prediction have become current research hotspots through CiteSpace visual analysis, and data-driven artificial intelligence methods (such as LSTM and GAN) have shown unique advantages in this field.

2.2 Echelon sorting model with multi-state coupling

It is difficult for a single state parameter to meet the needs of complex cascade utilization scenarios, and multi-state coupling model has become a new research direction. Li Chunsheng et al. proposed a multi-state coupling sorting method considering the state of energy (SOE), state of health (SOH) and power state (SOP), firstly established a three-state coupling characterization model, the first stage of dynamic sorting was completed by improving the K-means algorithm, and then the second stage of screening was carried out based on SOP deviation analysis, which effectively reduced the life loss in cascade utilization. This method provides theoretical support for large-scale energy storage applications and verifies the necessity of multi-dimensional parameter integration. Dynamic Reconfigurable Battery Network (DRBN) technology improves the applicability of retired batteries from the system architecture level. The analysis of the operation data of 80 DRBN units by Cisong et al. showed that 90% of the DRBNs could achieve good consistency management, and the system could accurately identify the modules with poor consistency. By reconstructing the battery connection topology in real time, this technology effectively alleviates the inherent defect of poor consistency of retired batteries, and provides a practical reference for the engineering application of large-scale cascade utilization energy storage system.

2.3 Evaluation of the adaptability of echelon utilization scenarios

There are significant differences in the requirements for battery performance in different application scenarios, and a scientific scenario adaptability evaluation system is crucial. Xie Hua et al. constructed a three-dimensional evaluation index system including technical performance, economic performance and safety performance, and used the improved VIKOR algorithm to quantitatively evaluate the peak-to-valley arbitrage, calming renewable energy fluctuations and frequency modulation auxiliary services. This study provides a scientific decision-making method for the scenario matching of retired batteries, and makes up for the shortcomings of the insufficient scene adaptability analysis in the early research. Xu Qing et al. constructed a multi-scenario joint optimization model from the perspective of economic benefits, and found that when retired batteries participate in energy storage, communication base stations, low-speed power supplies and other scenarios, the annual net income is 3.378 times higher than that of a single wind/solar storage scenario, and the payback period is shortened by 10.774 years. This study confirms that the scenario combination optimization of cascade utilization can significantly improve the economic feasibility and provide a quantitative basis for enterprise investment decision-making.

3. ECONOMIC MODEL AND SUPPLY CHAIN DECISION-MAKING OF POWER BATTERY RECYCLING AND CASCADE UTILIZATION

3.1Closed-loop supply chain game model construction

The economic research on power battery recycling is mostly based on the closed-loop supply chain theory, and the decision-making behavior of each subject is analyzed through the game model. Xu Jie et al. constructed a two-stage game model composed of battery manufacturers and authorized processors, and found that only when the competition intensity of the two types of cascade products is moderate, the two sides can cooperate, and the profit increases with the increase of competition intensity. The study also points out that there is a cost threshold for the introduction of blockchain technology, and manufacturers are motivated to adopt it when the cost falls below the threshold, when both consumer surplus and social welfare are improved. Under the framework of the EPR system, Wang Daoping compared the Stackelberg game model of four recycling entities: manufacturers, vehicle manufacturers, retailers and third-party recyclers, and found that the government subsidy threshold is the key factor in the selection of recycling mode—when the subsidy is higher than the threshold, the manufacturer recovers best, and on the contrary, the vehicle manufacturer recovers better. This conclusion provides theoretical support for the government to formulate differentiated subsidy policies, and reveals the internal relationship between policy parameters and the behavior of market entities.

3.2 Cost-sharing and profit-sharing mechanisms

Recycling cost sharing is an important means to promote closed-loop supply chain coordination. Ding's research shows that recycling cost sharing can always improve the recycling rate of waste products, consumer surplus and manufacturer profits, and when automakers bear more than two-thirds of the recycling costs, the entire supply chain can achieve Pareto improvements. The compensation mechanism designed based on the Nash bargaining model further verifies the effectiveness of cost sharing in improving system efficiency. Considering the heterogeneity of consumers, Li Xiaobing constructed a closed-loop supply chain model of recycling under different alliance models of manufacturers, and found that the alliance between manufacturers and retailers promotes the sales of new batteries, while the alliance with recyclers promotes the recycling of old batteries. Centralized supply chain systems have the highest benefits, while decentralized supply chains have the lowest. The study also points out that the choice of alliance strategy is more significantly affected by cost factors, which provides a decision-making reference for the choice of enterprise partners.

3.3 Carbon policy and cascade use of economic boundaries

Carbon allowance trading and fiscal subsidy policies significantly affect the economic feasibility of cascade utilization. Wang Kangli proposed an optimal control method for energy storage system considering multi-factor capacity attenuation, and found that when the total lease cost is lower than the net thermal power price, the cascade utilization of energy storage system can achieve a win-win situation of life extension and economic improvement. Taking wind power energy storage as an example, Song Mingzhen compared the capacity charging and the two-part charging model, and found that when the capacity retention rate is low or the electricity price is high, the capacity charging strategy is more advantageous, and the government energy storage allocation constraints have a significant impact on the strategy selection. In the context of patent licensing and carbon quota trading, Wang Xuanxuan established a Stackelberg game model of financial subsidies, and found that the increase in patent licensing fees and carbon trading prices has an adverse impact on cascade utilization, while increasing the proportion of low-energy-density batteries can achieve a win-win situation between price and demand. This study reveals the complex interaction effects under multiple policy instruments, and provides new ideas for policy portfolio design.

4. THE INFLUENCE MECHANISM OF THE POLICY SYSTEM ON THE RECYCLING OF POWER BATTERIES

4.1 Analysis of national and local policy frameworks

China has initially built a policy system for power battery recycling, but there are significant differences between national and local policies. Gao Wenfang summarized the current situation of national and local policies, and found that policy development can be divided into different stages, and the number and direction of local policies are obviously different. There is a lack of unified guidance in the ternary lithium and lithium iron phosphate recycling market, and the progress of recycling technology should be used as the basis for policy optimization. Based on this, the "4C" policy principles (cost, synergy, innovation, circulation) provide a systematic framework for policy formulation. The new EU Battery Law (EU 2023/1542) has a profound impact on China's recycling industry. Feng Xiaoyu analyzed from the dual perspectives of technology and market, pointing out that enterprises need to improve the level of environmental protection design and recycling technology to meet the requirements of foreign markets for circular economy. The study emphasizes the importance of international policy coordination and provides a strategic reference for Chinese enterprises to deal with international trade barriers.

4.2 EPR system and subsidy policy effects

The Extended Producer Responsibility (EPR) system is a core policy tool to promote recycling. Based on the life cycle assessment, Deng Xiangyan found that the recycling of retired ternary lithium batteries has positive emission reduction benefits, and the carbon footprint per kWh of batteries under the hydrometallurgical process reaches -51.2kgCO2-eq, and the recycling stage has the largest contribution to emission reduction. This conclusion provides a basis for environmental benefits for the selection of technical pathways under the EPR system. Ding Junfei compared the three scenarios of no cost sharing, battery supplier sharing and car manufacturer sharing under the EPR framework, and found that car manufacturers can share recycling costs to improve economic benefits, environmental benefits and social welfare at the same time, while battery supplier sharing only changes profit distribution. This study provides quantitative support for the division of responsible subjects in the EPR system, and clarifies the differences in the policy effects of different subjects.

4.3 Research on the coupling effect of policy mix

The effect of a single policy is limited, and the synergistic effect of policy mix has become a new research focus. It is found that the technological innovation policy can increase the lithium metal recycling volume by 25.3% in 2035, and the recycling volume of retired batteries in 2035 will be close to 8 million tons under the combined policy. This study breaks through the limitations of single policy analysis and reveals the importance of policy coordination. Zhang Chuan studied the selection of mixed channel recycling mode under carbon allowance trading, proposed four recycling modes and solved the equilibrium results, and found that when the recycling competition coefficient is lower than the threshold and the price sensitivity coefficient is higher than the threshold, the tripartite co-recovery mode is optimal. This study combines carbon policy with the selection of recycling channels, expands the dimension of policy impact research, and provides theoretical support for the construction of a low-carbon recycling system.

5. ENVIRONMENTAL BENEFIT ASSESSMENT OF POWER BATTERY RECYCLING

5.1 Life cycle carbon footprint analysis

Life Cycle Assessment (LCA) is a core method for assessing environmental benefits. Gigi Dou's research on retired lithium iron phosphate batteries shows that the environmental benefits of energy storage scenarios are the greatest, and they are better than direct recycling in terms of climate change and fossil energy consumption. In 2023, the carbon emission reduction of cascade utilization will reach 1.05×10^8kgCO2-eq, and if the cascade utilization rate increases by 10%, the emission reduction will reach 5.98×10^9kgCO2-eq in 2030. This data confirms the key role of cascade utilization in reducing pollution and carbon emissions. Wu Benben compared the different recycling paths of NCM and LFP batteries, and found that the recycling of NCM batteries is more conducive to carbon emission reduction, while the cascade utilization of LFP batteries has obvious advantages. According to the optimal pathway, 4.2 million tons of carbon emission reduction benefits can be achieved in 2026. This study reveals the matching relationship between battery type and recycling path, and provides an environmental basis for the formulation of differentiated recycling strategies.

5.2 Comparison of the environmental performance of different processes

The choice of recycling process has a direct impact on the environmental benefits. Deng Xiangyan compared the wet and pyrometallurgical processes and found that the wet process has more advantages in emission reduction benefits due to its high material recovery rate and low energy consumption, and the carbon footprint per kWh of battery is 21.1kgCO2-eq lower than that of the fire method. This conclusion provides an important reference for the selection of recycling technology routes and promotes the development of the industry in the direction of a more low-carbon process. Lai Zhiying reviewed the research progress of carbon accounting for retired battery recycling, and pointed out that cascade utilization and recycling can reduce carbon emissions, but the environmental impact of different technology paths is significantly different. The study calls for the establishment of a unified carbon accounting standard to regulate the development of the industry and provide accurate data support for policy development.

5.3 Spatiotemporal distribution and environmental risk research

The spatial and temporal distribution characteristics of retired batteries affect environmental risk and recycling efficiency. Hou Siyu used LSTM and Weibull models to predict the decommissioning and critical metal stocks, and found that the eastern provinces such as Guangdong and Zhejiang had the largest decommissioning amount, while the western provinces such as Tibet and Qinghai had the least. By 2035, Jiangsu will become one of the provinces with the largest number of decommissionings, and there is a spatial dislocation in China's recycling capacity, and the recycling capacity of Shanghai, Jiangsu and other places will not be able to meet the demand. This study provides a spatial dimension for decision-making for the optimization of the layout of recycling facilities, and emphasizes the importance of regional synergy. Chen Hongyu pointed out that the traditional detection methods are inefficient and lack effective value evaluation methods, while the data-driven methods perform well in life prediction, but the long-term reliability still needs to be verified. This view reveals the lack of data support in environmental benefit assessment, and calls for strengthening the collection and analysis of long-term operation data.

6. LIMITATIONS OF EXISTING RESEARCH AND FUTURE RESEARCH DIRECTIONS

6.1 Theoretical shortcomings of existing research

6.1.1 Insufficient integration of multi-objective optimization

At present, most of the research mainly focuses on the optimization of a single goal, such as focusing only on cost minimization or maximization of environmental benefits, while ignoring the co-optimization between economic, environmental and social objectives. For example, in supply chain management models, carbon reduction targets are often not closely aligned with economic benefits, which leads to shortcomings in the sustainability of optimization schemes.

6.1.2 Lack of adaptability to dynamic scenes

Most of the existing optimization models are based on static assumptions, which are difficult to adapt to the dynamic changes in the number of retired batteries, technical costs, and policy environment. For example, Hou Siyu pointed out in his research that the spatial and temporal distribution differences of retired batteries have not been fully considered and applied in the existing recycling network optimization models.

6.1.3 The research on the effect of policy mix is weak

Although scholars such as Wei Lang have begun to pay attention to the impact of policy mix, most of the studies are still limited to the analysis of a single policy, and there is a lack of in-depth research and discussion on the interaction mechanism between policies such as carbon trading, fiscal subsidies, and technical standards.

6.1.4 Lack of depth of interdisciplinary integration

There is a clear disconnect between technical research fields (such as battery sorting technology) and economic models (such as supply chain decision models), and there is a lack of two-way coupling between technical parameters and economic variables, which leads to a disconnect between theoretical models and engineering practice.

6.1.5 Data on long-term environmental impacts are scarce

Current LCA studies are mostly based on short-term data, and there is a lack of long-term tracking of environmental impacts throughout the life cycle of cascade use (e.g., more than 10 years), which makes it difficult to accurately assess long-term ecological benefits.

6.2 Breakthrough directions for future research

6.2.1 Multi-objective collaborative optimization model construction

By integrating multiple goals such as economic cost, carbon emission reduction, and social welfare, a multi-objective optimization model is developed that can consider the dynamic changes of time and space. For example, machine learning technology can be used to predict the number of retired batteries, and on this basis, the collaborative optimization of the recycling network can be carried out to achieve a three-dimensional balance of "cost-environment-society" optimization scheme.

6.2.2 Quantitative study of the effects of policy mix

Using system dynamics or game theory and other methods, the interaction effects between policy instruments such as carbon trading, fiscal subsidies, and EPR systems are deeply analyzed, and the corresponding quantitative evaluation models are constructed. This will provide a scientific basis and support for the design of the national policy system.

6.2.3 A techno-economic model of interdisciplinary convergence

The technical parameters of battery sorting (such as SOH and SOF) are deeply coupled with the decision-making variables of the supply chain (such as recycling price and cascade utilization rate) to develop a technology-economic integration model to enhance the guiding value of theory to practice.

6.2.4 Full-cycle management based on digital twins

The digital twin technology is used to build a virtual model of the whole life cycle of retired batteries, track the evolution of battery status and environmental impact in real time, and provide data support for long-term performance evaluation and cycle strategy optimization.

6.2.5 Research on regional collaborative recycling system

According to the spatial and temporal distribution characteristics of the number of retired batteries, the construction of cross-regional recycling network and resource allocation mechanism are studied to solve the problem of spatial dislocation of recycling capacity, so as to improve the overall recycling efficiency and environmental benefits.

6.2.6 Environmental-economic assessment of new recycling technologies

Strengthen the comprehensive environmental and economic assessment of new recycling technologies such as dry recycling and direct remediation, establish a multi-dimensional evaluation system for technology screening, and promote green innovation and sustainable development of recycling technologies.

7. CONCLUSION

At present, the research on power battery recycling and cascade utilization has formed a comprehensive research system that includes multiple dimensions such as technology, economy, policy and environment. In this system, the application of blockchain technology, multi-state coupling sorting technology, the design of EPR system, and the analysis of life cycle carbon footprint have become the core contents. These research areas not only cover all aspects of power battery recycling and cascade utilization, but also provide a solid foundation for in-depth research in related fields.

However, although the existing research has achieved certain results, there are still obvious shortcomings in multi-objective integration, dynamic adaptation, and policy combination effect. Specifically, the existing research needs further in-depth research on how to achieve multi-objective collaborative optimization, how to conduct quantitative analysis of policy mix, and how to construct interdisciplinary techno-economic models.

Future research needs to focus more on multi-objective collaborative optimization, quantitative analysis of policy portfolio, and interdisciplinary techno-economic modeling. Through theoretical innovation, we will promote the high-quality development of the circular economy of power batteries, so as to provide solid academic support for the realization of the "double carbon" goal. Only in this way can we better respond to environmental challenges, promote sustainable development, and make greater contributions to the green economy of the future.

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