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A Study on the Strategic Planning of Waste Lithium-Ion Battery Recycling

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Abstract. In the context of the new energy vehicle industry's rapid growth, the large-scale abandoned of used power batteries has become a pressing issue that requires immediate attention. This paper developed a four-level used power battery reverse logistics network optimization model using bibliometric analysis, mixed research methods and system dynamics simulation. It focuses total cost minimization by integrating mixed-integer linear programming and variable neighborhood-genetic algorithm (VNS-GA). Taking the Northeast region of China as a case, this paper explores the spatiotemporal distribution feature of retired batteries and verifies its model effectiveness in cost control, transport optimization and resource recovery efficiency enhancement. The findings of the research shown that the model could effectively reduce total operation cost, improve capacity layer filling and regeneration processing efficiency, optimize operating routes and node distribution, reduce environmental risk in practice. This paper offered a theoretical foundation and practical guidance for the scientific planning and construction of regional used power battery recycling systems, as well as decision support for promoting the green and sustainable development of new energy vehicle industry in order to achieve national 'dual carbon' strategic goals.

Keywords: Waste recycling, Battery, New Energy Vehicles, Carbon Neutrality

1. Introduction

In recent years, the global new energy vehicle industry has continued to grow exponentially, among which China's new energy vehicle market is firmly at the head: in 2024, China's sales of new energy vehicles will amount to 12.866 million units and be topping the world for nine consecutive years. The development of new energy vehicles is not only conducive to the changing of the structure of energy, but supports us in slowing down climate change and reaching the dual carbon targets. 1. Lithium-ion power battery is a key part of new energy vehicles, lasting generally 3-5 years, It can be seen that China has entered the large-scale elimination stage. It is estimated by China Society of Automotive Engineers that the cumulative volume of end-of-life power batteries in China will exceed 3.5 million tons by 2030. These retired batteries, besides their strategic metals (lithium, cobalt and nickel), also embrace toxic electrolytes; mismanagement of them would cause critical damage such as heavy metal pollution in the soil and eutrophication in bodies of water. Meanwhile, from the perspective of scientific recycling and reutilization, dependence on overseas resources can

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be effectively curbed, self-support ability of strategic metals can be increased; meanwhile costs to some degree will decrease and industrial chain resilience can also have certain improvement. Therefore, the scientific and systematic planning for recycling of used power batteries is of great significance in realizing sustainable development of new energy vehicle industry and national dual carbon strategy.

Through literature review, the problems and different optimization methods of used power batteries reverse logistics have been studied. Gonzales-Calienes et al. [1] proposed a spatial distribution model to optimize the location of the battery disassembling centers, and recycling processing plants, laying the foundation for an efficient network. Fan et al. [2] built a multilevel reverse logistics model for multi-recycling technology with cost and carbon reduction, showing the great importance of choosing recycling technology and network hierarchy in integral optimization. Muduli et al. [3] studied the maturity of blockchain technology in reverse logistics, and emphasized its vital contribution to solve information asymmetry, enhance recycling transparency, and control the circulation of recyclable materials. In the algorithmic side, Fayazi et al. [4] used mixed-integer linear programming for vehicle scheduling problems, and proved that the method outperforms others in logistics optimization; Huang et al. [5] adopted a similar method to realize this and their study can be used as reference for controlling logistics cost and distribution of resources. As for genetic algorithms, Ozcan et al. [6] presented better genetic algorithm for the facility layout of optimization, improving solution quality and computing time adopted adaptive large neighborhood search (ALNS) and genetic algorithm, and applied it to the optimization of cold chain transportation routes, extended the application scope of heuristic algorithms on complex logistics network systems [7]. These works have shown that systemic design in a variety of aspects, including network structure and technology choice, as well as scheduling strategies and algorithm optimization results in the improved recycled efficiency of used battery and lower operating costs.

Nevertheless, there are still some limitations in the previous work. First, the majority of these works were solely directed towards single link optimization (either by selecting technology or by deciding upon node location), without a systematic network planning as in multi-entity cooperation [8-10]. Second, domestic research usually focuses on a single administrative area with no unified cross-region and scalable system design scheme to solve practical problems of unbalanced spatiotemporal distribution of retired batteries and great regional differences in industry [11]. Moreover, a number of classic optimization algorithms (e.g., standard genetic algorithms and single-objective linear programming) have various drawbacks such as low convergence speed and being sensitive to local optimal solutions in large-scale, multi-objective and multi-constraint problems, which are hard to satisfy the practical requirements for complex networks. It is thus required to integrate multi-level network design and state-of-art heuristic optimization algorithms in order to obtain better solutions and more practical results.

This paper takes the construction of a multi-agent coordinated four-level reverse logistics network model as the main research topic, introduces Variable Neighborhood Search-Genetic Algorithm (VNS-GA) to improve solving performance and uses typical industrial clusters in Northeast China for empirical analysis. Based on the evolution rule and condition of CE marked retired power batteries, utilizing multi-factors nonlinear regression method, with an aggregate discharge service value as characteristic index, we made forecasting on spatial-temporal allocation rules of liquidated resource mode for retired power batteries in use phase besides simulating validation in a MATLAB environment: this model can raise recycle rate by 18%～25%, lowering electrolyte leakage risk over 90%, significantly reducing operating cost and environmental hazard. This study not only enriches and systematises the regional networked layout research in China, but

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also provides decision-making support for policy makers, enterprises, which is also of theoretical reference value and practical significance to the green sustainable development of new energy automobile industry in China.

2. Regional case study: northeast China

The case study is situated in China's Northeast (Liaoning, Jilin, and Heilongjiang). As an old industrial base, the new energy vehicle market in northeastern China is expanding: from 2018 to 2023, the sales of new energy vehicles accounted for 5% of the national total, by which time it had reached 474.8 thousand vehicles in 2023. As early vehicles begin to retire, the region is experiencing significant pressure from retired power batteries as their quantity are surging and there will continue to be more in the next few years by putting a higher demand on the regional recycling system. On the other hand, there is a well-developed industry and transportation system in northeast China, which creates conducive conditions for regional recycling management, but there are also various requirements and problems of governance [12-13].

Implementation Phase Based on the policy advocacy, the Northeast is pursuing a recycling system initially and has built up the network: 1/2 tiered utilization centers and waste deal-ing centers in three places including Liaoning (Jilin) and He ilongjiang in 1 each; 2 recycling detection houses and distribution hubs of geological bodies at local levels with more than three powers, other cities have set nodes at scrapyards and 4 S stores. For instance, Shenyang of Liaoning Province and Changchun of Jilin are regional tiered utilization centers that undertake a car battery tiered utilization and regeneration processing project which is provided with professional detection equipment as well as technical personnel to guarantee the safety and reusability of the recycled batteries [14]. The network runs through the core cities and industrial belts, yet there are extremely few recycling facilities in the wide rural and remote areas, resulting in a 'dense in cities, sparse in villages' pattern. Furthermore, there are also cities that have expanded the coverage of recycling point service to remote mountain towns based on the model of \"mobile recycling automobile,\" making the convenience degree and citizen participation ratio in recycling higher.

But northeast China still has three factors that may hinder the recycling of used power batteries. First, the recycling point network is quite uneven, as dense networks are located in urban areas but some rural and remote regions lack availability of these facilities. Information isolation exists among manufacturer, third-party company and government department, which results in poor recycling efficiency [12]. It has led to low resident enthusiasm for recycling because, as in Huludao, Liaoning and Baishan, Jilin only 2-3 recycling points exist and this falls short of the local demand. Some retired batteries may be discarded or flow into informal sector. Second, the technology is not mature and cost is high: current local recycling firms still adopt traditional pyrometallurgy method, with lithium and cobalt respective recovery of only 60% -70%, far lower than that of our national level (85%). The detection costs as a consequence for cascading utilization constitute 30% of the processing cost and large node-to-node transportation cost adds further overhead on the operations. In addition, the processing and recycling methods differ according to types of batteries which leads to further complexity management. Thirdly, the division of labor is not clear and regulation is insufficient: the factory like First Automobile Works do not possess professional recycling team, meanwhile third party including local scrapping yard have irregular behavior. The lack of unified regulatory system gives rise to frequent abnormal recycling behaviors such as 'price competition', increasing environmental risks [15].

Moreover, the policies and incentives are still inefficacious. Although some local governments have implemented recycling subsidies and incentive policies, these remained inadequate in terms of

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provision on the transportation subsidies to remote areas, tax reductions for enterprises and rewards for consumers,so that all aspects were difficult to achieve complete motivation. The recycling concept is not well known in the society, some residents have a limited awareness of the harm of used power batteries and simple recycling technology all this against an overall lack of rational, efficient and substantive packaging transport system. Thus, the Northeast urgently need to optimize recycling network layout, technical upgrade mode of development, clarification of corporate responsibility, regulatory platform construction a healthy and sound system and enhance policy incentives stressed that provides demonstration replicable experience for other regions.

3. Algorithmic performance and cost structure analysis

For the regional network model solving, this paper compared VNS with GA and the Genetic Algorithm (GA) respectively to verify the efficiency of our algorithm in solving four-level reverse logistics network for waste power battery optimal problem. The comparison results indicate that VNS-GA has achieved evident improvement in both iteration convergence number and solution quality: at the same network scale and constraint condition, traditional GA needs 380 iterations to meet the stopping criteria while VNS-GA requires only 150 iterations to reach the e-convergence criterion, resulting in a cost saving of approximately 4.1% (from 18.74 million yuan to 17.97 million yuan). It shows that VNS-GA can effectively escape local optima and enhance the accuracy of solution,and the ability of dealing with complex network multi-objective optimization problems also is stronger for it has adapted and stable performance obtained from adaptive adjustment of parameters and variable neighborhood search.

On the cost side, the model has decomposed all the costs involved in total cost into processing cost, recovery cost, transportation cost, operational cost and carbon emission. Details indicate that the processing cost accounts for 34.71% of the business operation cost, mainly from cascading utilization and recycle; recovery cost accounts for 28.93%, including investment in node layout and recycle facility building; transportation cost accounts for 23.44% with an initial cutting of 12% of the total via optimized nodes connection (such as Benxi to Tieling, Dandong to Tonghua); operational cost accounts for 12.73%; carbon emission is just accounted for less than a half percent (0.19%). Based on the optimized cost structure, we not only clarify the focus of funding investment in various stages, but also give a reference for subsequent policy development and corporate resource allocation and investment decision-making.

In addition, it will also be investigated the robustness of the algorithm in a variant environment. Sensitivity analysis of fluctuations in the quantity of retired batteries, degree of variations in transportation distance, and variation scale of layout arrangement inside collection node is implemented to show that VNS-GA provides a stable performance on solving uneven spatial-temporal distribution, changing condition for nodes adjustments and dynamic fluctuations for transport costs with the total cost swings less than 3%, which outperforms traditional GA above 6%. Moreover, for the region that cascading utilization detection cost ratio and transportation expensing between nodes are high, VNS-GA can effectively reduce burden of the nodes with more cost from them to establish a path in order to optimize routing selection taking into account node connections so as to improve network operating efficiency.

Moreover, this paper also investigate the flexibility of the algorithm under different circumstances. By sensitivity analysis of quantity fluctuation of retired battery, distance variance and node layout adjustment, it is proved that VNS-GA has a good stability to solve the uneven space-time distribution, dynamic change of nodes and transportation costs fluctuation problems with total cost variation range less than 3%, while GA can exceed 6%. Meanwhile, for the cascading

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utilization detection cost and heavy transportation costs between the nodes are more than half of the total detect time in some areas, VNS-GA has significantly reduced load on high-cost nodes and improved overall operational utilization by rout selection optimization as well as node connection.

4. Policy and strategic recommendations for battery recycling

It is necessary for the waste power battery recycling in current problem, from a variety of perspectives to provide a systematic planning strategy. First, improve the policy and legal framework Improving the producer responsibility extension system specify the basic responsibilities of enterprises in automobile and battery production, from designing proportioning for consideration of batteries recyclability, to improving supervision assessment dealers a high degree of punishment morbid meat That does not perform its duty. Simultaneously carry out strict industry access and supervision systems, raise entry barriers for recycling firms, strengthen daily supervision, and order them to make rectifications or take back certifications from those which do not meet the standard; speed up efforts to establish or improve the recycling qualification system that covers battery classification, testing and assessment criteria, dismantling standards, graded usage and recycling so that the reclaiming activities are conducted in accordance with rules of procedure; ensure safety during bouts of recycling.

Second, improving the configuration of recycling network. Depending on the sales service windows, 4S shops and the community concerned with New energy vehicle, popularize recycling sites; co-operate with logistics enterprises to initiate movable recycling sites in remote areas to increase working area coverage and standardize recycling operation. Reasonably arrange regional recycling centers according to the number of new energy vehicles and waste battery production, with advanced devices and professional personnel responsible for centralized storage, testing sorting and preliminary treatment. At the same time, a special transportation system for waste power batteries to be built up, selected qualified transport units and specialized equipment, information technology means to real-time tracking of transport routes and the status of battery monitoring battery; optimize routing service with cost minimization reached. Based on this, a smart management platform can be established to organize recycling information, logistics traces, and environmental monitoring for digital control of the whole process.

Also promotes technological innovation. The government should step up financial support for the R & D of recycling technologies, set up special funds to promote cooperation between research institutions, colleges and universities and enterprises, urge companies to increase investment in R & D and break through key technology bottlenecks, give rewards and policy incentives to companies or teams with great R & D achievements. Conduct key R&D on highly-efficient non-destructive battery dismantling technology, processes for high-valued metals recycling and scientific testing and evaluation methods for graded use. Foster a variety of use products for different needs, and build up new technical demonstration and promotion platforms, which will provide opportunities for the transformation of advanced technology into real application, that are gathered at technical exchange meeting, field pilot expedition etc., popularize the new technology, the process and equipment so as to drive industrial lifting. Meanwhile, explore commercial operational patterns of the recycling materials remanufacturing and tiered utilization products to enhance resources utilization value and build a close-loop industry chain.

It should also contain an economic stimulating mechanism. The subsidisation of the cost can be borne by the government by providing financial support to formal recycling entities, where subsidy guidelines are based on recycled total volume, and resource recovery rate and environmental performance. On the other hand, batteries coming back from consumers should also be rewarded in

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order to motivate both parties. Preferential tax treatment can be given to recycling firms, including value-added tax and income tax relief, as well as expedited depreciation of recycling machinery. A deposit-and-refund system looking into the experience of other countries may be facilitated, where customers can pay deposit for batteries upon purchasing new energy vehicles and get refund when they return their old batteries that acts as funding support for recycling and recycling rates, so as to form a benign cycle. What's more, it could be worthwhile for local governments to team up with businesses to create a recycling reward fund that offers exclusive rewards based on a high-efficiency recycling network and technical innovation project, furthering healthy industry development.

5. Conclusion

Taking the Northeast China as a case, this paper systematically analyzed and optimized the reverse logistics network of used power battery. Many retired batteries have accumulated in recent years due to the rapid growth of new energy vehicle, placing higher requirements on regional recycling industries. Based on existing recycling network, node distribution, level of technology and policy environment within Northeast China, this paper found that there are several evident problems such as uneven distribution of recycling nodes, insufficient level of technology with higher costs to match.reused due to the increasing amount of these devices; unclear producer responsibility and lax supervision. Moreover, the local policy stimulus and public mobilization still need to be improved, which will all influence the efficiency and safety in recycling system.

To solve these problems, this paper built a four-level reverse logistics network model that considering multi-agent collaboration and uses a Variable Neighborhood Search Genetic Algorithm (VNS-GA) to be optimized. The results show that VNS-GA has a remarkable performance of convergence speed and cost savings compared with classic genetic algorithms, and can increase the risk by 4.1% total The transportation cost was optimized by 12%. The single electrolyte leakage risk is more than 90%). Sensitivity analysis indicates that the algorithm is robust against uncertainties in retired battery quantities, transportation distances, and layout of nodes, which provides technical support for the efficient operation of regional recycling networks. Nevertheless, the model in this paper primarily deals with static overall cost optimization and to a large extent neglects dynamic factors such as consumer's recycling willingness, policy changes or market price variation; meanwhile empirical research is only limited to the industrial clusters in Northeast China, so that application of the model into other regions will become more flexible due to localization.

Through model analysis and provincial empirical results, this paper proposed multi-dimensional strategic countermeasures from aspects of policy perfection, network layout optimization, technological innovation and economic incentive mechanism, providing an implementation path for the construction of recycling system for waste power batteries: enhancing the extension system of producer responsibility and supervision systems, optimizing node layout of recycling network as well, promoting technology research on cascade utilization and efficient recovery technologies, setting up a financial subsidies mechanism combined with deposit systems. Generally speaking, the systematic design of the network, the optimization of advanced algorithms and policy supports can effectively make waste power battery recycling efficient, reduce operating costs and environmental risks, and provide a solid guarantee for the new energy vehicle industry to develop in a green manner, as well as achieving national" double carbon "strategic target. Meanwhile, the theoretical framework and methods of this paper can offer reference for waste power battery recycling planning in other regions and even the whole country, and promote entire industry development towards efficiency, safety and sustainability.

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