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REVIEW

Overview of Battery recycling Technology for New Energy Vehicles in China

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Abstract: With the increasing number of new energy vehicles, the development of new energy vehicle battery recycling technology is becoming urgent. This article provides a comprehensive analysis and summary of the strategies for new energy vehicle battery recycling. The article outlines existing battery recycling technologies and provides detailed descriptions of recycling methods and techniques for lithium-ion and nickel-metal-hydride batteries. In addition, the article thoroughly investigates recycling networks and explores how to establish efficient networks to achieve comprehensive and sustainable battery recycling. In terms of optimizing recycling economics, the article proposes some optimization strategies to ensure that battery recycling is economically feasible and effective. Finally, the article looks forward to future technological developments and discusses new battery recycling technologies and methods.

Keywords: Lithium-ion batteries, Nickel-metal hydride batteries, Recycling, Circular economy

1. Introduction

With the continuous growth of global carbon dioxide emissions and the intensification of climate change, the development of new energy vehicles has gradually become a common concern of the international community. As one of the key components of new energy vehicles, battery recycling and reuse have gradually become the focus of people’s attention. Battery recycling and reuse are of great significance for reducing the dependence on limited resources, reducing carbon dioxide emissions, and protecting the environment.

According to the “New Energy Vehicle Industry Development Plan (2021-2035)” issued by the National Development and Reform Commission and other relevant departments in China, the market share of new energy vehicles in 2025,2030 and 2035 should reach 20%, 50% and 80%, respectively, which means that in the next few years, the penetration rate of new energy vehicles will be significantly increased. At the same time, with the increase of new energy vehicle battery production, recycling and reuse will also become a major problem to be solved.

Global research results show that the number of used batteries will increase from 10,000 tons to 78,000 tons from 2012 to 2018, and then reach 15 to 33 million tons in 2040. About 50% of the waste is estimated to be metal material, providing a great opportunity for material recycling for

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battery recycling. From an economic perspective, battery recycling for energy storage is expected to generate more economic benefits than pure material recycling ($147.8 billion versus $7.69 billion). However, in the foreseeable future, the supply of waste batteries is difficult to meet the demand for renewable energy storage, and there is a spatial mismatch between the supply and demand of energy storage capacity in eastern and western China [1].

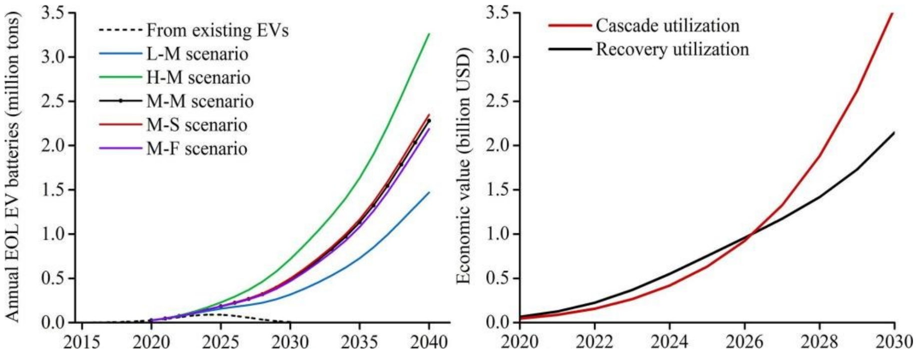

Figure 1. Development process of new energy power batteries [1].

Therefore, the research on the battery recycling strategy of new energy vehicles is crucial. This paper mainly reviews the relevant literature research on the battery recycling strategies of new energy vehicles, including the recovery technology, environmental impact, economic value and development trend. Through this review, this paper provides a valuable reference for the practice of battery recycling strategies for new energy vehicles.

2. Overview of Recycling Technology

New energy vehicle battery recycling technology is a complex task involving chemistry, material science, engineering technology and environmental science, aiming to realize the efficient recycling and reuse of waste batteries. This section will introduce several major types of new energy vehicle batteries and the recycling technologies for these batteries [2].

Lithium-ion battery is the most widely used battery type in new energy vehicles. Its main components include lithium ion anode (such as graphite), lithium ion salt solution, and cathode materials (such as lithium cobalt oxide, lithium iron phosphate, etc). Recycling lithium-ion batteries involves processes like decomposition of batteries, recycling lithium metal, recycling valuable cathode materials and recycling the electrolyte. In the current study, the recovery technology adopted mainly includes wet dissolution and high-temperature melting. The wet dissolution recovers the cathode material and lithium metal, while recovering the electrolyte, and the high temperature melting solves the battery and recovers the valuable materials.

Secondly, nickel metal hydride battery is another common type of new energy vehicle battery. The main components of nickel metal hydride battery are nickel hydroxide negative electrode, cobalt hydroxide positive electrode and hydrogen storage alloy. At present, the main technologies for recycling NiMH batteries include wet leaching, electrochemical reduction and high-temperature melting. Wet leaching solves the cathode material by solvent and recovers valuable substances such as nickel hydroxide and cobalt hydroxide; electrochemistry also reduces the cathode material to nickel metal and nickel hydroxide by electrolysis reduction process; high temperature melting decomposes the battery and recovers various valuable materials through high temperature treatment.

In addition, solid-state battery, as a new energy vehicle battery technology, has the advantages of high energy density, high safety and good cycle life. However, due to its complex material structure and engineering process, the solid-state battery recycling technology is currently in the initial research stage. The recovery of solid-state batteries involves the recovery of battery decomposition, cathode materials and solid electrolyte recovery. Current research focus on how to efficiently decompose solid-state batteries and recycling valuable materials.

New energy vehicle battery recycling involves a variety of battery types and complex technological processes. Different types of batteries require different recycling technologies to achieve efficient recycling and reuse. With the continuous development and innovation of recycling technology, we can look forward to achieving more efficient, economical and environmentally friendly technological breakthroughs in the field of new energy vehicle battery recycling, and making greater contributions to the construction of a sustainable new energy vehicle industry chain.

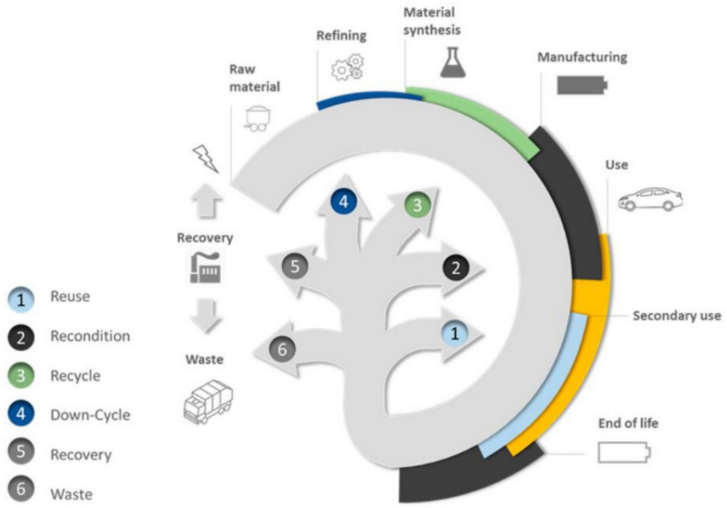

Figure 2. Cyclic flowchart of manufacturing, usage, and end of life (EOL) lithium-ion batteries (LIBs) [2].

3. Current Research Status

3.1 Lithium-ion Battery Recycling Technology

For discarded lithium-ion batteries, finding harmless disposal and resource utilization options has important economic, environmental and social benefits. Although China's new energy vehicles lithium recovery potential scale is small, but its growth rate is fast [3]. Lithium-ion batteries contain a lot of valuable metal elements (such as lithium, nickel, cobalt, manganese, copper and aluminum) and toxic chemicals (such as lithium hexafluorophosphate and polyvinylidene difluoride) [4]. There is no denying the fact that electric cars are good for climate protection. However, the challenge is deciding whether to reuse the lithium-ion battery or recycle after first use.

Research in the field of recycling and reuse shows that there are a variety of battery recycling processes for commercial applications, and some processes are still under study to recover as many materials and quantities as possible [5]. The concept of battery reuse has great potential for development, because after the first round of use, lithium-ion batteries can be used in multiple applications, such as storing energy generated from renewable energy sources to support the government grid. However, the cost and life cycle analysis suggest that multiple aspects are involved in battery reuse applications. Thus, a general method fails to provide an optimal solution for all cases. For each battery reuse application, a detailed study is very important. Until then, it's safe to say that reuse battery is a good option because it will give recycling companies some time to develop cost and energy-efficient methods.

For the recycling of lithium ion batteries, the cascade utilization method is born. In the Chinese market, the application prospect of using waste power batteries in new energy vehicles through the cascade utilization method is very promising [6]. However, there are some obstacles, such as the lack of product standards, inadequate cascade utilization technologies, and imperfect recycling network systems, which require the immediate strengthening of policy measures. The study uses content analysis to classify policies, and studies China's central and local policies, involving the cascade utilization of discarded power batteries. The research focuses on the basic policy tools and the industrial chain processes.

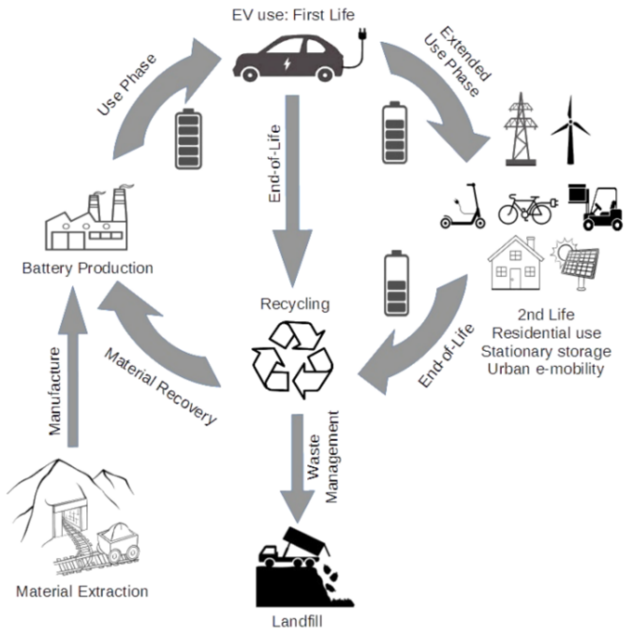

Figure 3. Battery life in a circular economy perspective [5].

The study found that central policy mainly emphasizes structural mandatory tools, while local policy tends to emphasize contract incentives, indicating a preference for diversification. Interaction impact tools are least used in central and local policies. As for the recycling industry chain, the central and local policy tools mainly focus on the cascade utilization, testing and evaluation stages, while paying less attention to the collection and transportation stages.

Based on the results, the following suggestions are proposed: (1) strengthen the research and development of cascade utilization technology and reduce the technical threshold; (2) formulate perfect product standards and regulations to promote the healthy development of the industry; (3) strengthen the recycling network system to improve the recovery efficiency and quality; (4) strengthen the coordination and integration of policy, establish a unified policy system to promote the cascade utilization of waste power batteries; (5) strengthen publicity and education to improve the public awareness of environmental protection and promote sustainable development.

There are many limitations that can affect battery recycling. Due to the influence of battery type, model, material, status and vehicle information, the scrapped new energy vehicle batteries cannot achieve efficient and convenient recycling. Considering the requirements of some recently issued government documents and the characteristics of electric vehicle batteries, an integrated vehicle identification number (VIN) code is proposed. Based on the analysis of the current national standard GB 167352019 road vehicle-VIN identification code and GB/T 34,0142017 motor vehicle power battery coding rules, the standard of combining battery code and tracking code is proposed [7]. Finally, the possible coordination codes were applied in a case study. The results of this study have already been applied to the national standards in China.

3.2 Nickel Recovery Technology

Nickel recycling has an important environmental and economic significance. Nickel is one of the most important components of electric vehicle batteries, providing a high energy density and a long range. However, large amounts of nickel ore mining and nickel battery production can have a non-negligible impact on the environment, including soil, water and air pollution. From 2012 to 2020, the production and sales volume of new energy vehicles in China continues to reach new highs, and the mineral resources such as lithium, cobalt and nickel related to power batteries are extremely scarce [8].

In addition, nickel recovery is of economic significance. With the rapid growth of the electric vehicle market, the battery recycling industry will also embrace new business opportunities. Through the efficient recycling of nickel, the production costs can be reduced, and the profit space of the recycling enterprises can be increased. At the same time, nickel recycling can also create jobs, promote a circular economy and sustainable development.

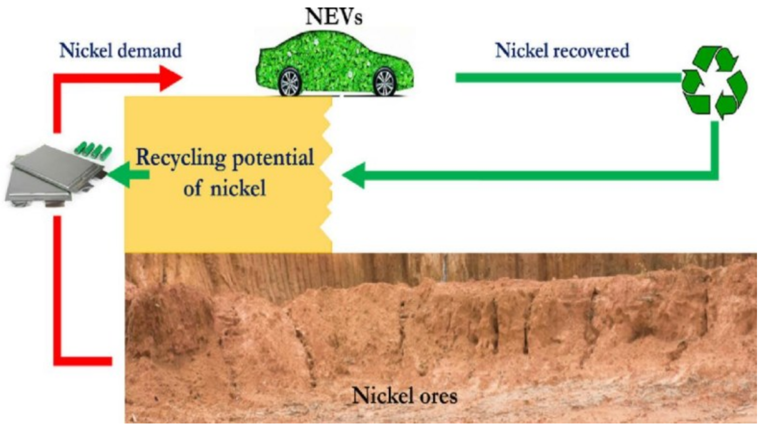

Figure 4. Power battery recycling process diagram [9].

The study predicted the recovery potential of nickel in the new energy vehicles (NEVs) abandoned in China under three sales growth scenarios, adopted linear regression and Weibull distribution methods, and quantitatively studied the role of the recovered nickel in the closed nickel cycle [9]. The forecast results show that by 2030, under the high growth rate scenario, China's new energy vehicles will reach about 3.8 million, and the number of abandoned new energy vehicles will reach 2.3 million. If used nickel batteries can be fully recycled, 44.5 million tons of nickel will be recovered, which will account for nearly a third of the total demand for manufacturing nickel batteries. The research results show that the nickel recovered from the waste nickel batteries plays a vital role in the nickel cycle of the new energy vehicle industry.

3.3 Recycling Network

The market for electric vehicles has been booming globally in recent years, and it has grown sharply amid the global response to climate change. As lithium-ion batteries are widely used to drive electric vehicles, and a large number of batteries are nearing the end of their life, how to recycle these batteries to reduce environmental pollution and promote the sustainable development of the electric vehicle market has become an urgent challenge for the moment. It is a valuable recycling strategy for the reuse of waste electric vehicle batteries. However, there is a lack of research to explore the design of the electric vehicle battery recycling network at the enterprise level, which hinders the sustainable development of electric vehicles [10].

Based on this, the research proposes a new scheme, that is, to establish a cooperative alliance between different brands of new energy vehicle recycling outlets, in order to reduce the distance and time cost of the owners to recover batteries, so as to improve the owners' recycling willingness and recovery rate [11]. Under this scheme, a collaborative recovery mechanism based on the third-party information platform is designed. Secondly, by optimizing the path scheme of car owners to the recovery network, a car recovery time cost model is established. At the same time, based on the Shapley method, the time cost saving of the alliance members is reasonably calculated. In addition, the current recovery needs of car owners are used to describe the relationship between recovery rate and time cost.

Finally, under this scheme, the cost of the owner's time can be saved by 40% -70%. Combined with the results of the questionnaire, the recovery rate after the collaboration can be increased by 8.23% -10.71%. If this program is implemented nationwide, the recovery volume is expected to increase by 947-123,200 tons, which verifies the practical effectiveness of the multi-party collaborative recovery model. With the promotion of big data technology, the waste power battery recycling platform for new energy vehicles can be built [12].

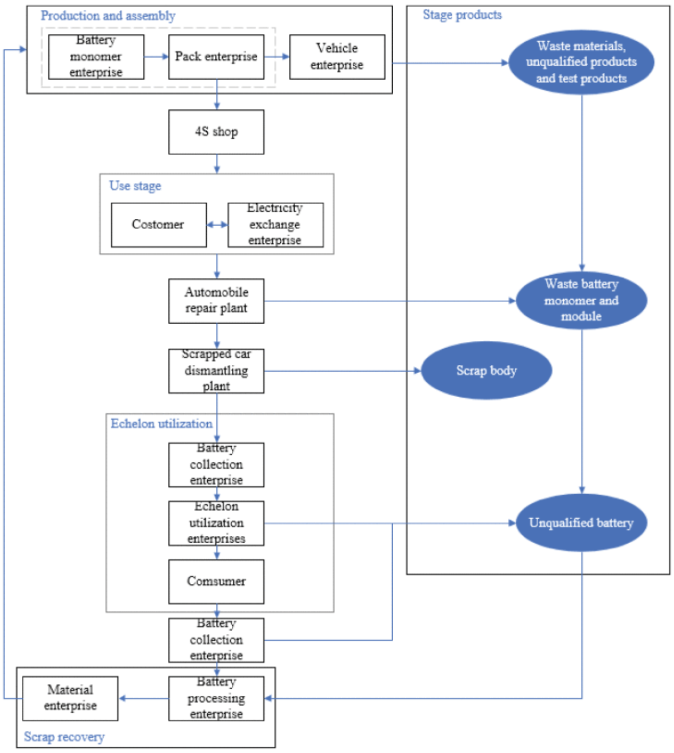

Figure 5. Power battery life cycle recovery pipeline process [12].

By integrating the characteristics of big data information, the operation mechanism of the power battery recycling platform based on big data is analyzed. The functional modules on the platform were designed and studied based on user functional requirements and shared information based on big data. Through the analysis of traffic big data, Baidu map application program interface has established a traction battery dangerous goods transportation optimization system (API). The improved ant colony algorithm is adopted to obtain the shortest path model, reduce the transportation cost and risk, and maximize the value of information resources, and promote the transformation and upgrading of the power battery recycling industry.

3.4 Economic Optimization of Recovery

Considering the huge potential of China's energy storage market, the design of future vehicle power batteries should fully consider the performance requirements of energy storage batteries [13]. From the perspective of closed-loop supply chain, the research aims to improve the recovery rate of power batteries for new energy vehicles. To this end, a dual-channel battery recovery game model between new energy vehicle manufacturers and retailers is constructed, including the cost sharing contract and the liability sharing contract. By comparing the single-channel recovery mode, the impact of different recovery contracts on the retail price of new energy vehicles, market demand, battery recovery rate and the profits of supply chain members are studied [14].

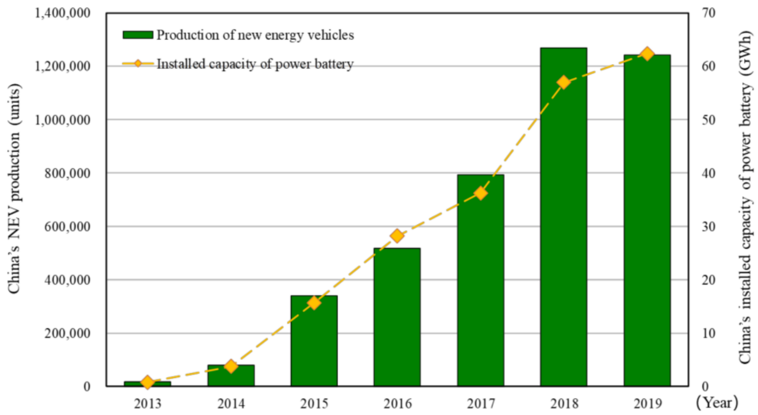

Figure 6. Production of new NEVs (new energy vehicles) and installed capacity of power batteries in China (2013–2019) [13].

From the perspective of production, relevant papers study in the competitive environment, considering the impact of battery recycling subsidy policy and double integral policy on the production decision of new energy vehicles and fuel vehicles, the market demand is determined by the utility of heterogeneous consumers. Due to the rapid expansion of the new energy vehicle market, waste batteries are in a period of renewal and replacement, but the efficiency of these two policies in implementation in the presence of battery recycling is unclear. Considering the markets of the three major players, namely new energy vehicle manufacturers, fuel vehicle manufacturers and the government, a non-cooperative game model was established, taking into account battery recovery rates and consumer environmental awareness. The optimal policy decisions of the government and the manufacturers are analyzed under the subsidy policy, single point policy and double point policy, respectively. The results show that under the two policies, the battery recovery rate is the most critical factor affecting the competitive position of the new energy vehicle manufacturers. At the same time, no matter how consumers' environmental awareness, recovery rates and the value of consumer subsidies change, new energy vehicle manufacturers are still in a weak position unless the government provides new financial subsidies, to the new energy vehicle manufacturers, rather than consumers. In addition, only in the case of double integral policy and two points, improving the battery recovery rate can produce a maximum demand spillover effect of 20.59%, further proving that the efficiency of double integral policy is better than the subsidy policy [15].

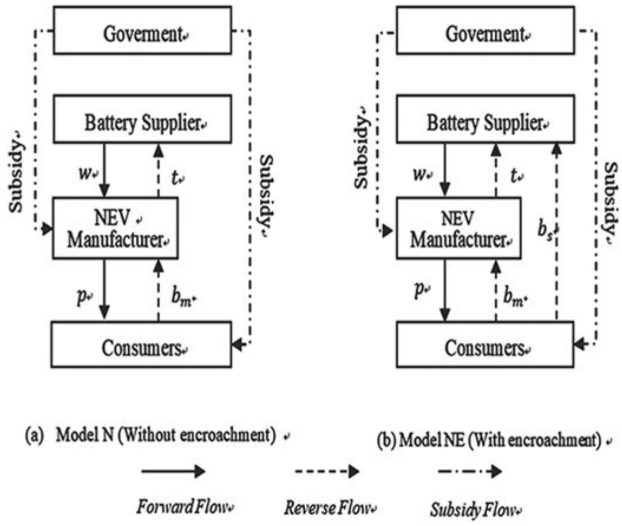

Figure 7. Channel structures under government subsidy (with and without the battery supplier's encroachment) [17].

Nevertheless, the double-integral policy still has its shortcomings. Until the beginning of 2023, the relevant research has established a closed-loop supply chain model composed of the government, power battery suppliers and new energy vehicle manufacturers. Using the game theory method, we study the government subsidy policy on the optimal decision of supply chain members and its influence on corporate profit and social welfare. This coincides with the research of East China Normal University: three recycling decision models [16]. The research results show that, compared with the no-subsidy policy, the subsidy policy for new energy vehicle manufacturers is more conducive to the improvement of corporate profit and social welfare; within the cost range of the recovery channel, the influence of battery suppliers on their own interests is different. Finally, the influence of key parameters on corporate profit and social welfare is studied through numerical experiments, and it is found that consumers' environmental awareness has a significant impact on social welfare [17]. Through numerical analysis, it is found that the social welfare is higher than the no-subsidy strategy after introducing the two subsidy strategies [18].

4. Technical Outlook

New energy vehicle battery recycling technology is a field of continuous development, and the emergence of new technologies and new ideas will bring new opportunities and challenges to the field of battery recycling.

First, the comprehensive application of multiple existing technologies will become a trend. With the increasing types of new energy vehicle batteries, the recycling technology also needs to be continuously innovated and improved. Therefore, the integration and optimization of multiple recovery technologies to improve the recovery efficiency and resource utilization will be a major development direction in the future. For example, high-temperature melting, wet leaching, and electrochemical reduction techniques can be combined to better recover a variety of valuable materials.

Secondly, the new energy vehicle waste battery dismantling automation will become the trend of future development. The traditional waste battery disassembly needs to rely on manual or semiautomatic machines, and the work efficiency and recovery effect are relatively limited. With the development of robot technology, artificial intelligence and other technologies, the automation degree of waste battery disassembly will be gradually improved, improve the recovery efficiency and resource utilization, while reducing the safety risks of manual operation and environmental pollution of people.

Third, the resource recovery and energy utilization in the new energy vehicle battery recycling will be an important development direction. At present, the production of new energy vehicles and electric power generation is still heavily dependent on fossil fuels, leading to major environmental problems. At the current stage, new energy vehicles may not be as environmentally friendly and sustainable as expected [19]. Recycling of valuable materials and metal resources in waste batteries can not only reduce the consumption of resources, but also reduce the production cost. At the same time, the recycling of chemical energy and heat energy inside the battery will also be a future research hotspot. The recovery of these energy will likely become a new energy source, and can also bring more business opportunities for the new energy vehicle battery recycling industry.

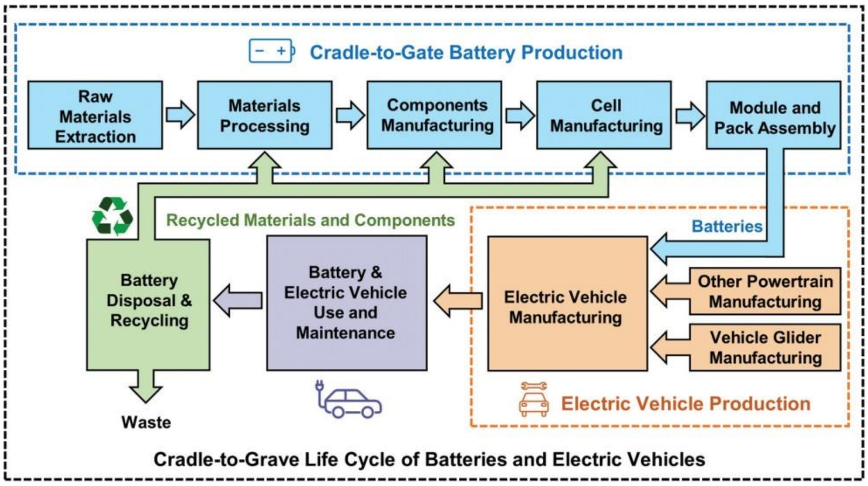

Figure 8. Major-cradle-to-grade life cycle stages for batteries and EVs [20].

Finally, the new energy vehicle battery recovery technology also needs to make continuous breakthroughs in the theoretical research. At present, the research of battery recycling technology mainly focuses on the practical application, but the in-depth analysis of theoretical research and the research of simulation and prediction are not enough. An analysis of multiple guidelines based on Eurostat data and 10 scholars shows that Sweden's purchase rate performed well between 2015 and 2019, with only a few countries above the European average. Furthermore, a quantitative analysis based on these experts identified the key success factors for purchasing EVs. The most important thing is the purchase cost, followed by the battery range [20]. Therefore, the investment and attention in the theoretical research of materials science, chemistry and other disciplines behind battery recycling will gradually increase, which will provide a more important foundation for the innovation and development of battery recycling technology.

The development prospect of new energy vehicle battery recycling technology is broad, which requires continuous innovation and development to meet the needs of future development. Researchers need to focus on finding better recovery technology, more accurate recovery materials and lower costs. At the same time, theoretical research should be more in-depth and sufficient to provide a solid theoretical and practical foundation for the future development of the new energy vehicle battery recycling industry.

5. Environmental Impact and Policy Recommendations

With the rapid development of the new energy vehicle industry, the research and application of battery recycling technology have become crucial issues for environmental protection and sustainable resource utilization. The environmental impacts that may arise during the battery recycling process include heavy metal pollution, leakage of toxic chemicals, and energy consumption and carbon emissions. Addressing these issues requires the joint efforts of policymakers, enterprises, and the public [21].

5.1 In-depth Analysis of Environmental Impacts

Heavy Metal Pollution: Lithium, nickel, cobalt, and other heavy metals contained in batteries may enter the environment through wastewater and emissions if not properly managed during the recycling process, posing long-term effects on ecosystems. These heavy metals can accumulate through the food chain, ultimately affecting human health.

Toxic Chemical Leakage: Electrolytes, solvents, and other chemicals in batteries may contaminate soil and groundwater if leaked, affecting human health and ecological safety. The long-term accumulation of these chemicals can lead to severe environmental problems.

Energy Consumption and Carbon Emissions: The energy consumption and carbon emissions associated with battery recycling processes are also significant. High energy consumption is particularly evident in processes such as high-temperature smelting and wet dissolution, which contradicts the initial intention of reducing carbon emissions from new energy vehicles.

To mitigate these environmental impacts, a series of measures need to be taken, such as improving recycling technologies, strengthening regulation, and raising public awareness.

5.2 Comprehensive Policy Recommendations

Governments and relevant departments should consider the following aspects in policy formulation for the battery recycling industry:

Establish Strict Environmental Standards: Governments should establish strict environmental standards for battery recycling to ensure that waste is properly managed and the impact on the environment is minimized. These standards should cover the entire lifecycle of the battery, including production, use, and recycling [22].

Provide Policy Support and Incentives: Governments can encourage enterprises to adopt environmentally friendly recycling technologies and methods through tax reductions, subsidies, and other means, promoting clean production. Additionally, governments can establish special funds to support the research and development and innovation of battery recycling technologies.

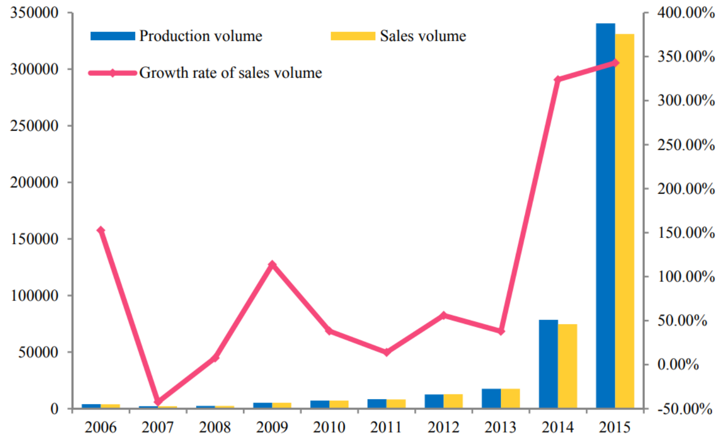

Figure 9. NEV production and sales volume in China from 2006 to 2015 [23].

Strengthen Industry Regulation: A comprehensive battery recycling regulatory system should be established to ensure that all recycling activities comply with environmental requirements, with strict penalties for non-compliant enterprises. The regulatory system should include regular environmental impact assessments and audits to ensure compliance with relevant regulations.

Public Education and Outreach: Raise public awareness of the importance of battery recycling and encourage consumers to participate in recycling activities, fostering a positive recycling culture. Governments and enterprises can use various channels, such as media and community activities, for public education and outreach [23].

Furthermore, policy formulation should also consider the following aspects:

Promote Technological Innovation: Policies should encourage enterprises to innovate technologically and develop more efficient and environmentally friendly battery recycling technologies. Governments can support enterprises in technological innovation in the field of battery recycling through R&D subsidies, tax incentives, and other measures.

Establish a Recycling System: Governments should promote the establishment of a national battery recycling system, including the setting up of recycling points, optimization of recycling processes, and construction of recycling networks. This helps to improve the efficiency and coverage of battery recycling.

International Cooperation and Exchange: Battery recycling is a global issue that requires the joint efforts of the international community. Governments should actively participate in international cooperation, share best practices, and promote the development of global battery recycling technologies.

6. Technological Innovation and Development Trends

Technological innovation is the core driving force behind the development of the new energy vehicle (NEV) battery recycling industry. As the NEV sector continues to grow, the need for efficient and environmentally friendly recycling solutions becomes increasingly critical. The current trends in technological innovation in battery recycling are focused on developing more efficient recycling technologies, automating and intelligent the recycling process, and creating closed-loop recycling systems. Future development will place a greater emphasis on interdisciplinary integration, global cooperation, and green sustainability [26].

Table 1. Research on the Technology Innovation Efficiency of China’s Listed New Energy Vehicle Enterprises [26].

Enterprises	2012	2013	2014	2014	2016	2017	2018	Mean value
BYD	0.7736	0.7230	0.5126	0.5681	0.5820	0.4509	0.5484	0.5941
Dongfeng	0.6059	0.6075	0.5407	0.5530	0.6563	0.8024	0.5608	0.6181
Foton	0.9475	1.0000	0.9969	0.7265	0.8247	0.7642	0.5188	0.8255
GAC	0.2635	0.5336	0.5046	0.7449	0.9651	1.0000	1.0000	0.7160
Haima	0.5585	0.7461	0.7351	0.6561	1.0000	0.9937	1.0000	0.8128
Lifan	0.4340	0.4773	0.4314	0.3890	0.3868	0.3518	0.3950	0.4093
JAC	1.0000	1.0191	0.8143	0.7805	0.7498	0.8680	0.8915	0.8748

6.1 Multifaceted Discussion on Technological Innovation

Development of Efficient Recycling Technologies: Current research is exploring new recycling technologies such as bioleaching and microbiologically assisted recovery, which aim to increase the recovery rate of resources and reduce environmental impacts. These technologies are being developed to complement existing physical and chemical methods, forming comprehensive recycling solutions [24].

Automation and Intelligence in Recycling: The application of robotics, artificial intelligence (AI), and other advanced technologies is transforming the recycling process. Automation can improve the efficiency and safety of recycling operations, while AI can optimize the process by predicting and adjusting to various conditions.

Closed-Loop Recycling Systems: The concept of a closed-loop system, where materials are recycled back into the production process, is gaining traction. This approach not only conserves resources but also minimizes waste and pollution, aligning with the principles of circular economy.

6.2 In-Depth Prediction of Development Trends

Industry Standardization: As the industry matures, more standards and regulations are expected to emerge, guiding the healthy development of the sector. These standards will cover various aspects, including technology, environmental protection, safety, and economics.

Technology-Driven Innovation: Technological innovation will continue to be the primary driver of industry growth. The application of new technologies will continuously improve the efficiency of recycling processes and reduce costs, contributing to the sustainable development of the industry [25].

Strengthened International Cooperation: Addressing global resource and environmental challenges will require increased international collaboration. By sharing technologies, experiences, and resources, the global community can work together to advance battery recycling technologies and applications.

Green and Sustainable Development: Future battery recycling technologies will place a greater emphasis on environmental protection and sustainability. Research will focus on reducing energy consumption and carbon emissions associated with recycling processes, aiming to minimize environmental impacts and maximize resource utilization.

In addition to these trends, the development of the battery recycling industry will also be influenced by the following factors:

Integration of Interdisciplinary Knowledge: The complexity of battery recycling requires knowledge from various disciplines, including material science, chemistry, environmental science, and engineering. Integrating this knowledge will lead to more effective and innovative recycling solutions.

Advancements in Materials Science: The development of new battery materials with improved recyclability will impact the recycling industry. Research into materials that are easier to recover and reuse will be crucial for the future of battery recycling.

Evolving Consumer Demands: As consumers become more environmentally conscious, there will be a growing demand for products that utilize recycled materials. This trend will drive the market for recycled batteries and promote the development of the recycling industry.

Regulatory Frameworks and Incentives: Governments around the world are implementing regulatory frameworks and incentives to encourage the adoption of sustainable practices, including battery recycling. These policies will play a significant role in shaping the future of the industry.

7. Conclusion and Perspectives

This article provides an overview of battery recycling technology for new energy vehicles, and delves into the technical strategies, research status, environmental impact, policy recommendations, and future development trends in this field. In the context of the rapid development of new energy vehicles, the research and application of battery recycling technology are particularly important. This section will summarize the entire content and propose future research directions and industry development trends.

7.1 Technical Strategy and Research Status

The research on battery recycling technology for new energy vehicles involves multiple levels, including but not limited to the development of recycling technology, the construction of recycling networks, and the optimization of recycling economy. Lithium ion batteries and nickel hydrogen batteries, as common types of batteries in new energy vehicles, have made certain progress in their recycling methods and technologies. Technologies such as wet dissolution, high-temperature melting, and electrochemical reduction have been applied in both laboratory and industrial settings. Meanwhile, as an emerging technology, the recycling technology of solid-state batteries is still in its early research stage and requires further technological innovation and breakthroughs.

The current research status at home and abroad indicates that battery recycling technology is gradually shifting from a single physical method to chemical and biological methods, and from low efficiency and high consumption to high efficiency and low consumption. In addition, the construction and optimization of recycling networks are also key to improving battery recycling efficiency. By establishing an efficient recycling network, the comprehensiveness and sustainability of battery recycling can be achieved, while also helping to reduce recycling costs and improve resource reuse rates.

7.2 Environmental Impact and Policy Suggestions

The environmental impact that may occur during battery recycling cannot be ignored. Heavy metal pollution, toxic chemical leakage, energy consumption and carbon emissions all need to be addressed through technological innovation and policy guidance. The government and relevant departments should establish strict environmental standards, provide policy support and incentives, strengthen industry supervision, and conduct public education and publicity to promote the sustainable development of the battery recycling industry.

7.3 Technological Innovation and Development Trends

Technological innovation is the core driving force behind the development of the new energy vehicle battery recycling industry. Currently, the innovation trend of battery recycling technology is manifested in the research and development of efficient recycling technology, the application of automation and intelligence, and the construction of closed-loop circulation systems. The future technological development will place greater emphasis on interdisciplinary integration, global cooperation, and the concept of green sustainability. Through continuous technological innovation, the battery recycling industry will be able to better adapt to the development needs of the new energy vehicle industry, achieve efficient resource utilization, and effectively protect the environment.

7.4 Future Research Directions

Future research should focus on the following aspects:

Research and development of efficient recycling technology: Explore new recycling technologies, such as bioleaching and microbial assisted recycling, to improve resource recovery rates and reduce environmental impacts.

Optimization and Intelligence of Recycling Networks: Research how to utilize technologies such as big data and the Internet of Things to optimize recycling networks, improve recycling efficiency, and reduce costs.

Battery full lifecycle management: Manage the entire lifecycle of battery production, use, and recycling to achieve maximum resource utilization and minimize environmental impact.

Improvement of policies and regulations: Study how to formulate more effective policies and regulations to promote the healthy development of the battery recycling industry.

7.5 Industry Development Trends

The development trend of the new energy vehicle battery recycling industry will be reflected in the following aspects:

Industry standardization: With the maturity of the industry, more standards and regulations will be introduced to guide the healthy development of the industry.

Technological innovation driven: Technological innovation will become the main driving force for industry development, and the application of new technologies will continuously improve recycling efficiency and reduce costs.

Strengthening international cooperation: Faced with global resource and environmental issues, international cooperation will become closer, jointly promoting the development and application of battery recycling technology.

Green and sustainable development: Future battery recycling technology will pay more attention to environmental protection and sustainability, striving to achieve minimal impact on the environment and maximum utilization of resources.

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Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Jiang S, Zhang L, Hua H, et al. Assessment of end-of-life electric vehicle batteries in China: Future scenarios and economic benefits. Waste Management, 2021, 135: 70-78.

[2] Beaudet A, Larouche F, Amouzegar K, et al. Key challenges and opportunities for recycling electric vehicle battery materials. Sustainability, 2020, 12(14): 5837.

[3] Sonoc A, Jeswiet J, Soo V K. Opportunities to improve recycling of automotive lithium ion batteries. Procedia cIRP, 2015, 29: 752-757.

[4] Zhao Q, Hu L, Li W, et al. Recovery and regeneration of spent lithium-ion batteries from new energy vehicles. Frontiers in Chemistry, 2020, 8: 807.

[5] Kotak Y, Marchante Fernández C, Canals Casals L, et al. End of electric vehicle batteries: Reuse vs. recycle. Energies, 2021, 14(8): 2217.

[6] Zhang H, Huang J, Hu R, et al. Echelon utilization of waste power batteries in new energy vehicles: Review of Chinese policies. Energy, 2020, 206: 118178.

[7] Yu H, Dai H, Tian G, et al. Key technology and application analysis of quick coding for recovery of retired energy vehicle battery. Renewable and Sustainable Energy Reviews, 2021, 135: 110129.

[8] Wang E, Nie J, Wang Y. Government subsidy strategies for the new energy vehicle power battery recycling industry. Sustainability, 2023, 15(3): 2090.

[9] Yao P, Zhang X, Wang Z, et al. The role of nickel recycling from nickel-bearing batteries on alleviating demand-supply gap in China's industry of new energy vehicles. Resources, Conservation and Recycling, 2021, 170: 105612.

[10] Wang L, Wang X, Yang W. Optimal design of electric vehicle battery recycling network–From the perspective of electric vehicle manufacturers. Applied Energy, 2020, 275: 115328.

[11] Wang Y, Zhang Z, Li X, et al. Collaborative decision-making based on effort level: power battery recycling alliance. Procedia Computer Science, 2023, 221: 1155-1161.

[12] Yu H, Dai H, Tian G, et al. Big-data-based power battery recycling for new energy vehicles: information sharing platform and intelligent transportation optimization. IEEE Access, 2020, 8: 99605-99623.

[13] Liu Z, Liu X, Hao H, et al. Research on the critical issues for power battery reusing of new energy vehicles in China. Energies, 2020, 13(8): 1932.

[14] Zhu X, Li W. The pricing strategy of dual recycling channels for power batteries of new energy vehicles under government subsidies. Complexity, 2020, 2020: 1-16.

[15] Li J, Ku Y, Liu C, et al. Dual credit policy: promoting new energy vehicles with battery recycling in a competitive environment? Journal of Cleaner Production, 2020, 243: 118456.

[16] Guo R, He Y, Tian X, et al. New energy vehicle battery recycling strategy considering carbon emotion from a closed-loop supply chain perspective. Scientific Reports, 2024, 14(1): 688.

[17] Liu K, Wang C. The impacts of subsidy policies and channel encroachment on the power battery recycling of new energy vehicles. International Journal of Low-Carbon Technologies, 2021, 16(3): 770-789.

[18] Zhao X, Peng B, Zheng C, et al. Closed-loop supply chain pricing strategy for electric vehicle batteries recycling in China. Environment, Development and Sustainability, 2022, 24(6): 7725-7752.

[19] D'Adamo I, Gastaldi M, Ozturk I. The sustainable development of mobility in the green transition: Renewable energy, local industrial chain, and battery recycling. Sustainable Development, 2023, 31(2): 840-852.

[20] Yang Z, Huang H, Lin F. Sustainable electric vehicle batteries for a sustainable world: Perspectives on battery cathodes, environment, supply chain, manufacturing, life cycle, and policy. Advanced Energy Materials, 2022, 12(26): 2200383.

[21] Dong F, Liu Y. Policy evolution and effect evaluation of new-energy vehicle industry in China. Resources Policy, 2020, 67: 101655.

[22] Zhang L, Qin Q. China's new energy vehicle policies: Evolution, comparison and recommendation. Transportation Research Part A: Policy and Practice, 2018, 110: 57-72.

[23] Zhang X, Bai X. Incentive policies from 2006 to 2016 and new energy vehicle adoption in 2010–2020 in China. Renewable and Sustainable Energy Reviews, 2017, 70: 24-43.

[24] Hu H, Zhang Y, Rao X, et al. Impact of technology innovation on air quality—An empirical study on new energy vehicles in China. International Journal of Environmental Research and Public Health, 2021, 18(8): 4025.

[25] Zhang T, Ma C, Yong C. Development status and trends of new energy vehicles in China//AIP Conference Proceedings. AIP Publishing, 2019, 2066(1).

[26] Chen S, Feng Y, Lin C, et al. Research on the technology innovation efficiency of China's listed new energy vehicle enterprises. Mathematical Problems in Engineering, 2021, 2021: 1-9.