Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 13, No. 3, 2024

Progress and Suggestions on the Recyclability Design of Automotive Power Batteries

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Abstract: The rapid development of new energy vehicles (NEVs) and the significant increase in their stock have drawn attention to the recycling and utilization of power batteries. This paper reviews the current status of the development of the NEV industry, starting with the concept and content of recyclability design, and analyzes the main technological routes for the recycling and utilization of used power batteries. It discusses the policy and standard requirements for recyclability design (Design For Recovery and Recycling), current research progress, and the main challenges faced. Based on these issues, the paper proposes suggestions for future work from the perspectives of policy and standard systems, advanced technology research and development, and platform tool support.

Keywords: New Energy Vehicles, Power Batteries, Recyclability Design, Recycling and Utilization.

1. Introduction

The development of new energy vehicles is an important measure in China to improve the energy consumption structure, reduce air pollution, and promote the transformation and upgrading of the automotive and transportation industries. It is also a major direction for the global automotive industry. Under the national dual-carbon strategy, the development of the NEV industry has made positive progress and become a crucial force in the global automotive industry's electrification transition. According to data from the Ministry of Public Security, as of June 2024, the national stock of NEVs reached 24.72 million, of which 18.13 million were pure electric vehicles. In the first half of the year, 4.397 million new NEVs were registered, a 39.41% year-on-year increase, setting a new historical record. [1] In terms of power battery installation volume, the domestic installation volume of power batteries for NEVs was approximately 48 GWh before 2016, while the installation volume reached 203 GWh in the first half of 2024. As the number of NEVs increases and their service life grows, some power batteries begin to retire in batches due to faults or reaching the end of their lifespan, entering the recycling and utilization phase. According to data from the Ministry of Industry and Information Technology, the total utilization of waste power batteries from NEVs in 2023 was 225,000 tons. [2] According to estimates from the China Automotive Battery Recycling and Collaborative Development Alliance (CABRCA), the amount of retired power batteries will reach 63.8 GWh (530,000 tons) during the 2023–2025 period, with the annual amount of retired power batteries expected to exceed 1 million tons by 2030.

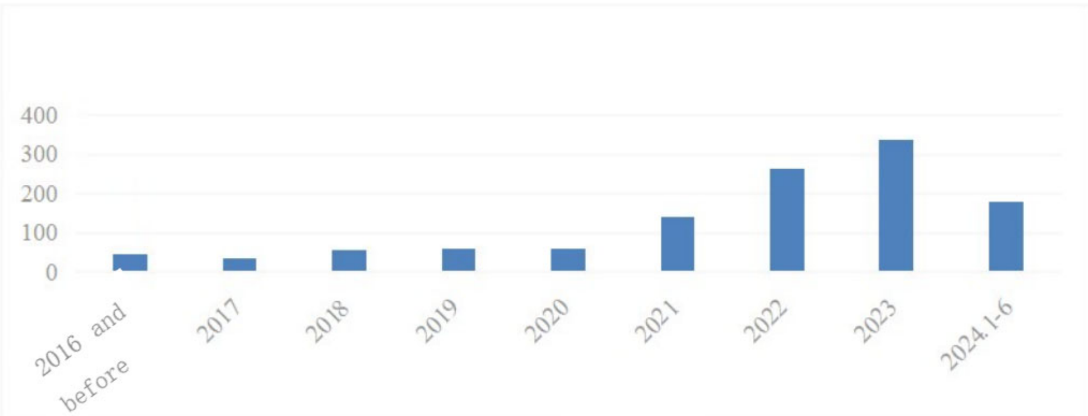

Figure 1. Annual assembly of domestic new energy power batteries (Gwh)

The recycling and utilization of used power batteries involve safety, environmental protection, and resource factors, spanning multiple stages of the product lifecycle, including design and production, usage and maintenance, decommissioning, recycling, and resource utilization. This process plays an important role in ensuring the security, resilience, and high-quality development of the NEV industry chain and supply chain. Although the design of power batteries is at the front end of the industry, it directly impacts the safety, convenience, and cost-effectiveness of recycling and utilization after decommissioning, which is crucial for achieving a sustainable recycling model. Therefore, this paper discusses the progress and challenges of recyclability design for automotive power batteries (Design For Recovery and Recycling).

2. Concept and Content of Recyclability Design

Recyclability design for products is a key component of green product design. It involves fully considering the potential for recycling parts and materials, the value of recycling, the methods of recycling and processing, and the recyclability of the design structure to achieve maximum utilization of resources and energy with minimal environmental impact. Recyclability design primarily includes the following four aspects:

1) Recyclable Materials and Their Identification: When designing a product, it is essential to consider material selection, aiming to use green materials that have low energy consumption, low noise, non-toxicity, and are harmless to the environment. These materials are generally existing materials or those developed for green design. Additionally, material identification should be clearly marked on components, which will facilitate disassembly, sorting, and processing of recyclable components during product recycling.

2) Recycling Processes and Methods: The design must consider the technical aspects of component material recycling, including the relevant symbols and methods for processing, to ensure proper marking during production and reasonable handling by users after the product is decommissioned. The recycling process requires collaboration and sharing of research efforts across many technical departments. Designers should understand and master the principles and methods of different recycling technologies.

3) Economic Viability of Recycling:

In the design process, it is important to understand the economic feasibility of recycling and support market conditions for recyclable materials. The goal is to use limited resources in the most economical way and maximize environmental compatibility. Economic feasibility can be analyzed using a mathematical model that incorporates product type, production methods, material types, and other related data, along with current cost estimation methods.

4) Structural Design of Recyclable Parts:

The prerequisite for recyclability is that parts can be easily and economically removed from the product without damage. Therefore, the structural design of recyclable parts must ensure easy disassembly. The Restar software system developed by Carnegie-Mellon University's Integrated Manufacturing Decision Research Center can analyze the entire disassembly process and display the time, cost, and effectiveness of each disassembly step, the value of recyclable parts and materials, and the associated energy costs and carbon dioxide emissions. It can also provide technicians with suggestions for improving disassembly and reuse efficiency. [3]

3. Progress in Recyclability Design of Power Batteries

3.1. Recycling and Utilization Technical Routes for Retired Power Batteries

Currently, there are two main directions for recycling **and utilizatio**n of retired power batteries in China: secondary utilization and regeneration utilization. Before carrying out secondary or regeneration utilization, retired batteries must undergo pre-treatment. Retired power batteries suitable for secondary utilization are disassembled and processed into modules or individual cells, then tested, sorted, and reassembled into final secondary-use products. Batteries not suitable for secondary use are subjected to pre-treatment processes such as disassembly, discharging, and component separation to create powder materials, which are then processed by dry or wet metallurgy methods to recover raw materials. The specific technical processes are shown in the table below:

Table 1. Technical Routes for Recycling Retired Power Batteries

Link	Main process	Content
Cascade utilization technology and process	Residual energy detection	The industry mainly uses actual testing to characterize battery residual energy, and is also promoting the application of technologies such as residual value assessment based on historical data and non-destructive testing.
	Disassemble and reassemble	"manual + semi-automatic" dismantling of batteries;
	Coded identification	Reorganization is the capacity and consistency screening matching of the same type of battery, and reorganization into a cascade utilization product that can be applied in other fields in a cascade.
	Operation monitoring	Code and identify the echelon utilization products in accordance with the Code for Automotive Power Battery (GB/T 34014-2017).
Recycling technology and process	Group separation process	Product operation monitoring through echelon utilization of the product's BMS.
	Fire recovery process	Use the solution immersion method or conductor (semiconductor) discharge method to release the remaining power battery;
	Wet recovery process	Separation of the components by exploiting differences in their physical characteristics (e.g., particle size, magnetic properties, density, and electrical conductivity).
	Material repair process	According to the difference in temperature, the fire recovery process can be divided into low temperature pyrolysis process and high temperature roasting process;

3.2. Relevant Regulations, Policies, and Standards

1) Legal Level:

China has early on adopted principles for recyclability design in its legislation, learning from the experience of developed countries. For example, Article 19 of the Circular Economy Promotion Law of the People's Republic of China requires that products, packaging materials, and designs must prioritize the use of recyclable, disassemblable, degradable, non-toxic, or low-toxic materials, as well as comply with relevant national standards. [4] The Solid Waste Pollution Prevention and Control Law of the People's Republic of China, Articles 66 and 67, encourages manufacturers to implement eco-design and promote resource recycling. [5]

2) Policy Level: In 2016, the General Office of the State Council issued the "Extended Producer Responsibility System Implementation Plan," which clearly stated that producers are responsible for conducting ecological design. Manufacturing enterprises are required to comprehensively consider the resource and environmental impacts of raw and auxiliary material selection, production, packaging, sales, use, recycling, and disposal, and to carry out in-depth product ecological design. Specific measures include lightweighting, unification, modularization, non-toxic (low-toxicity) designs, easy maintenance, as well as extending product life, green packaging, energy conservation, emission reduction, and recycling. [6] In 2018, the Ministry of Industry and Information Technology and other departments issued the "Interim Measures for the Recycling and Utilization of Power Batteries for New Energy Vehicles," which stipulates in Article 7 that power battery manufacturers should adopt standardized, universal, and easily disassemblable product structures, open up interfaces and communication protocols for the power battery control system that are conducive to recycling, and design detachable and easily recyclable fixed components. The harmful substances in materials should meet the national standards, and the use of recycled materials should be maximized. The design and development of new energy vehicles should follow the principle of ease of disassembly to facilitate the safe and environmentally-friendly disassembly of power batteries. [7]

3) Standards Level: The "Product Specifications and Dimensions for Power Batteries of Electric Vehicles" (GB/T 34013-2017), which was implemented in 2018, specifies the size and specifications of battery cells, modules, and standard battery packs. It guides enterprises to conduct standardized design, reducing the variety of power batteries, and making their recycling, disassembly, and storage after decommissioning easier. The national recommended standard "Recycling and Utilization of Vehicle Power Batteries - Tiered Utilization - Part 5: Design Guidelines for Tiered Utilization Products," which is currently under research and development, stipulates the design requirements for tiered utilization of power battery packs, modules, and cells. This standard aims to guide power battery manufacturers to enhance the tiered utilization performance of new batteries, reduce future tiered utilization costs, effectively reduce the technical and financial investment by national, industry, and enterprise parties in subsequent processes, and alleviate technical difficulties in using retired vehicle batteries in low-speed electric vehicles and energy storage scenarios. It also aims to minimize damage and loss to the batteries during tiered utilization and reduce resource waste in the process.

3.3. Domestic and International Research Progress

In China, Long Qin and others have conducted research on green design methods for power batteries, proposing a comprehensive evaluation approach that mainly includes methods such as the Analytic Hierarchy Process (AHP), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), as well as Life Cycle Assessment (LCA) methods to guide and improve the design of power batteries. [8] Some enterprises have also started to consider recyclability design in their practical processes. Certain automobile manufacturers are collaborating with comprehensive utilization enterprises to adopt a dual Battery Management System (BMS) design in power batteries, which facilitates the tiered use of retired batteries in fields like energy storage or low-speed transportation. Additionally, some companies are optimizing battery designs to reduce the use of potting processes in battery packs, improving ease of disassembly.

Internationally, the U.S. Federal Consortium for Advanced Batteries (FCAB) has developed the "U.S. Lithium Battery National Roadmap 2021-2030," which promotes battery pack design for easier second-use and recycling. [9] The European Union has released an updated version of the "Battery Strategic Research and Innovation Agenda," focusing on two key areas of innovation research related to battery design: 1) Safe and sustainable battery design. This includes four research topics: defining universal principles, tools, and methods for evaluating circular design, transforming safety and sustainability frameworks into practical guidelines for the battery industry; evaluating battery designs and materials from the perspectives of reuse, recyclability, and repairability; reducing the use of critical raw materials through alternative materials or designs; and increasing the use of digital tools such as virtual reality, machine learning, and artificial intelligence. 2) Design of functional battery cells and packs. This focuses on three research topics: scaling up the production of self-healing materials and battery cells containing these materials, and researching effective recycling methods for embedded smart function batteries; using digital models to optimize sensor placement and efficient sensor communication technologies; and conducting production demonstrations of embedded functional batteries during small-scale production stages. [10]

3.4. Major Issues Currently Faced

Regarding the recyclable design of power batteries, all industry stakeholders acknowledge that it is a key factor affecting the efficiency of waste power battery recycling and utilization. However, there are still some issues and challenges in the specific implementation process, mainly in the following four areas:

1) Weak Policy and Standard Support: Overall, current regulations, policies, and standards do require recyclable design for power batteries, but they are mostly recommendatory or encouraging in nature, with a guiding role for the industry. The existing recyclable designs for power batteries are mainly based on the exploration of power battery manufacturers, guided by their own needs and experience. Most of these efforts involve optimizing and improving existing designs, but there is a lack of unified, systematic research, methodology, and evaluation system support.

Moreover, recyclable design requires collaboration between upstream and downstream parts of the industry chain and relevant stakeholders to form a closed-loop system for recyclable design. However, the industry has not yet formed a relatively mature and systematic cooperation model.

2) Insufficient Focus on Technological Development: The new energy vehicle industry experiences rapid technological development and iteration, with most companies focusing on improving the performance of power batteries and reducing costs. There is an emphasis on highly integrated battery systems, such as Cell to Body (integrating the vehicle's bottom plate with the battery pack cover, making the battery system and the car body one) and Cell to Chassis (integrating the battery unit directly into the vehicle chassis, reducing the number of components, saving space, improving structural efficiency, and increasing battery range). While these technologies help improve overall vehicle performance and reduce costs, the increased integration makes the dismantling and recycling of scrapped batteries more difficult.

3) Significant Impact from Market Volatility: Between 2021 and 2022, the price of lithium carbonate surged significantly (rising from 40,000-50,000 yuan/ton to a peak of 590,000 yuan/ton), making the recycling of waste power batteries highly profitable and generating strong market enthusiasm. However, since 2023, lithium carbonate prices have fallen sharply, and by October 2024, the price had dropped to around 70,000 yuan/ton, only 50% of the price in the same period last year. As a result, the enthusiasm in the recycling market has significantly diminished. In addition, the introduction of new materials like sodium-ion batteries has further reduced the value of battery materials. A key issue to address is how to improve the economic feasibility of waste power battery recycling and establish a positive development model through recyclable design.

4) Lack of Support Tools: Recyclable design is a systematic project that requires gradual improvements to power battery design while ensuring battery performance and safety. In the design process, on one hand, there needs to be a complete system of methodologies and workflows as support; on the other hand, professional platform tools are needed to assist companies in standardizing and regulating the development of recyclable designs. Currently, there are no standardized information tools to support the design and research stages of enterprises, and there is a lack of standardized information exchange channels with the recycling stage. This hinders the implementation of recyclable design.

4. Suggestion

The recyclable design of power batteries is a key step in advancing the sustainable development of the new energy vehicle and power battery industries. Based on relevant policies issued by the European Union and other countries and regions, recyclable design is considered an important factor. Therefore, this article offers the following suggestions. It is recommended to expedite the research and formulation of a unified industry standard for the recyclable design of power batteries, along with the development of methods and evaluation systems. This would encourage upstream and downstream enterprises, research institutions, and other stakeholders within the industry chain to form regular cooperation mechanisms centered around recyclable design, creating a closed-loop system for this process. It is recommended to treat recyclable design as a key factor in implementing the Extended Producer Responsibility (EPR) system. Enterprises should be encouraged to balance attention between improving power battery performance and reducing costs, while also focusing on the ease and economy of dismantling and recycling power batteries after the disposal of new energy vehicles. This would foster technological innovation in recyclable design and help establish a well-functioning market for the recycling and utilization of waste power batteries. It is recommended that research institutions collaborate with relevant enterprises to develop specialized tools that support recyclable design based on the design requirements. These tools should help enterprises standardize and regulate their design processes and assess the recyclability of their designs. It is recommended that industry associations, research institutions, and other organizations regularly collect and showcase exemplary cases of recyclable design for power batteries. These cases should be compiled into a casebook and promoted within the industry to encourage the adoption of advanced design concepts.

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