

Status and Progress of the Retired Power Batteries Recycling in the Context of “Double Carbon”

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Abstract. In recent years, to promote goal of "carbon peaking and carbon neutrality", replacing the traditional vehicles by electric vehicles becomes the essential solution to reduce the environmental pollution. The power battery, as the power source of electric vehicles, is also one of the core components of new energy electric vehicles. As an important part of the future development of pure electric vehicles, the decommissioning process of power battery recycling is summarized and analyzed from the current situation of decommissioned power batteries, the relevant standards and policies of power batteries in recent years, and the development and utilization of two kinds of decommissioned power batteries: dismantling and recycling and secondary utilization, respectively, and for the secondary utilization process, the focus is on the residual energy detection process and the screening and reorganization application scenarios. Finally, relevant suggestions are given to provide ideas for the green development of retired power batteries under the dual carbon target of "carbon peaking and carbon neutral".

Keywords: Double Carbon, Power Battery Recycling, residual energy detection, screening and reorganization scenarios.

1. Introduction

In recent years, to promote China's goal of "carbon peaking and carbon neutrality", reduce the dependence of traditional vehicles on fuels and reduce the environmental pollution caused by vehicle exhaust, the country has introduced a series of incentive policies such as "Tax Exemption" for electric vehicles to actively promote the development of new energy vehicles [1]. To develop pure electric vehicles well, we must grasp the key technologies such as battery technology and energy management technology. The battery package system, as one of the three core systems of pure electric vehicles, includes battery package management system (BMS), which is the energy source of electric vehicles. The power battery, as the power source of electric vehicles, is also one of the core parts of new energy electric vehicles [2]. The ageing of power batteries for vehicles is a long-term gradual process. SOC (state of charge) is a key technology of the battery management system and is a quantitative indicator of the remaining power of the electric vehicle, while SOH (state of health) can be used to describe the state of health of the battery, which can also be expressed as the ageing state of the battery. Combined with the current average service life of automotive power batteries of about 5-8 years, the retirement of automotive power batteries will become an inevitable outcome, and a wave of retirements will sweep in.

After 10 years of cultivation and development, China's new energy vehicle technology level has been continuously improved, product performance has been significantly enhanced, and industrial development has been accelerated. The rapid development of the new energy vehicle industry has led to rapid growth in the installed capacity of power batteries. The installed capacity of power batteries in China increased from 15.7 GWh in 2015 to 154.5 GWh in 2021, with a compound annual growth rate of 46.4%. With the rapid growth of new energy vehicle sales in recent years, expect that power batteries will be retired on a large scale in the next 2-3 years, and the demand for recycling of retired power batteries is becoming urgent. If it is assumed that the retirement period of power batteries in China is 5 years, the level of retired power batteries in 2021 is expected to be 252,000 tons, and by 2030, the level of retired power batteries in China is expected to reach 2,373,000 tons [3]. As shown in Figure 1.

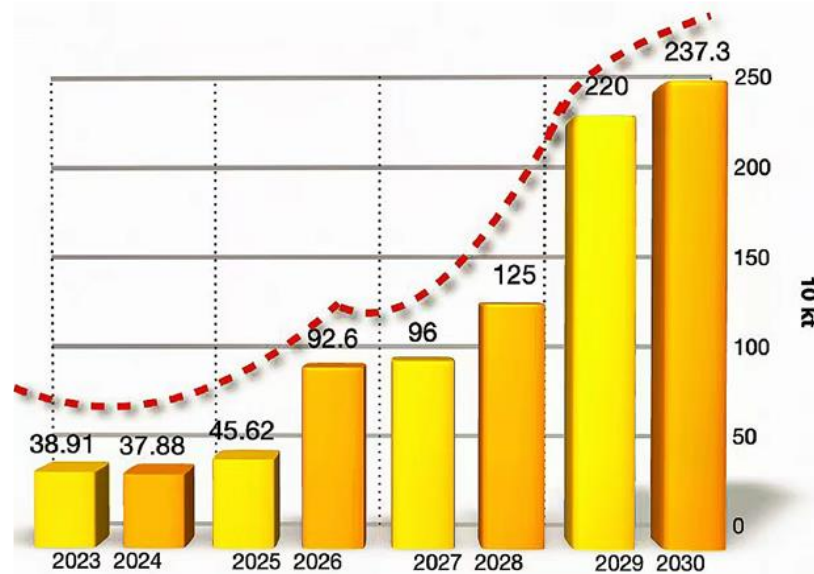


Figure 1. In 2023-2030 power battery retirement forecast

Power batteries need to enter the decommissioning process when their capacity has decayed to 80% of their rated value. At present, there are two main ways to recycle retired power batteries: dismantling and laddering use. This paper summarises and analyses the power battery-related standards and policies in recent years from the current situation of retired power batteries, and analyses and elaborates on the development of two types of retired power batteries: dismantling and laddering use. Based on the current relevant standards and policies, the potential of retired power batteries is fully explored to help the development of pure electric vehicles and effectively promote the goal of China's "double carbon."

2. Relevant standards and policies

Government departments attach great importance to the recycling of used power batteries and gradually build a policy system for the whole life cycle management of power battery recycling. The policy system involves the division of labour among all parties involved in power battery recycling, industry regulations, power battery traceability management, and requirements for graded products. The Interim Measures for the Management of Power Battery Recycling and Utilisation of New Energy Vehicles, as the top-level system for power battery recycling management, provides requirements for the scope of power battery recycling and utilisation management, responsibilities and requirements of relevant parties, and supervision measures. In addition, to explore the operational mechanism of power battery recycling, pilot projects on power battery recycling have been carried out in 17 provinces and cities across China to promote the construction of recycling systems [4]. Under the background of "double carbon", the standards for power batteries will pay more attention to the enhancement of environmental, energy and resource efficiency, and a standard framework for green and low-carbon recycling development should be built.

2.1. Standards for recycling and laddering

When the performance of power batteries can no longer meet the needs of electric vehicles, they should be replaced with new batteries, i.e., the old batteries should be retired. IEC 62660-1, published by the International Electrotechnical Commission (IEC) in 2010, stipulates that power batteries should be retired when their actual capacity is less than 80% of their initial capacity [1]. Under the background of "double carbon", power battery standards will pay more attention to the improvement of environmental, energy and resource efficiency, and should build a standard framework for green and low-carbon recycling development. Industry standards should be improved so that enterprises and regulatory authorities have something to rely on to support the green and low-carbon

development of the industry. At the same time, power battery recycling needs to be regulated and developed, and it is also worthwhile to plough deeper. It is necessary to build a perfect recycling system to help the healthy development of the new energy vehicle industry. The literature [5] focuses on six aspects of power battery safety, life and residual value assessment, comprehensive all-climate performance, green and low-carbon recycling requirements, compatibility and interchangeability requirements, and the applicability of the existing standard system to new technologies, etc. It discusses the main missing items of the existing standard system and new demands for standardization, and puts forward suggestions for standard formulation and revision on this basis, to optimize and improve China's standard system for power batteries in China will be optimized and improved.

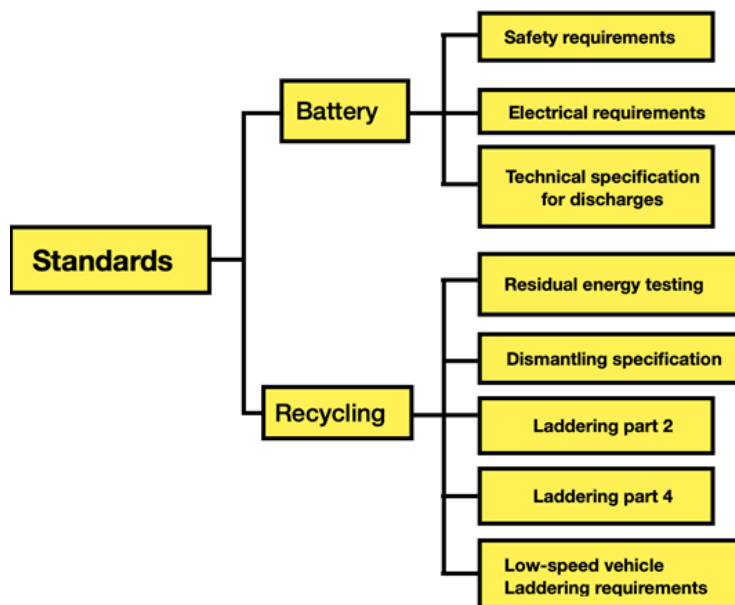


Figure 2. China’s Recycling and Ladder Utilisation Standards

2.2. Power battery recycling policies

In 2021, "accelerating the construction of a power battery recycling system" was written into the government work report for the first time, and the Development and Reform Commission and other departments issued a notice on the "14th Five-Year Plan" for the development of circular economy, with power battery recycling being one of the 11 key projects. With the national level attaching great importance to the power battery recycling industry, the construction of the power battery recycling system will press the "accelerator button". "From the new battery design dimension, we should build a standard system of renewable biomaterials, recycled materials and renewable use to increase the use rate of green and low-carbon products. From the waste battery recycling dimension, a standard system for laddering, recycling and related management should be constructed. The literature [6] raises the issue of the government's decision on the target and the number of subsidies for the closed-loop supply chain of EV power battery recycling. A two-cycle power battery recycling closed-loop supply chain model including fuel vehicles as well as electric vehicle manufacturers, battery manufacturers and vehicle consumers is constructed. It is also mentioned that the target of government subsidies is related to the quality of the recycled batteries, and if the quality of the used batteries is small, then the consumers of power battery recycling should be subsidised; to maximise the benefits of the supply chain, all parties should try to increase the remanufacturing rate of used batteries and reduce the cost of consumers in participating in battery recycling. The main power battery recycling policies are summarized in Table 1.

Table 1. Main power battery recycling policies.

Time	Policy Documents
Stage 1	<ul style="list-style-type: none"> • Normative Conditions for the Automotive Power Battery Industry • Technical Policy on Electric Vehicle Power Battery Utilization (2015 Edition)
Stage 2	<ul style="list-style-type: none"> • Extended Producer Responsibility System Implementation Programme • Interim Measures for the Management of New Energy Vehicle Power Battery Recycling
Stage 3	<ul style="list-style-type: none"> • The 14th Five-Year Plan for Circular Economy Development; • Carbon Peaking Action Programme by 2030 • Implementation Plan to Accelerate the Promotion of Comprehensive Utilisation of Industrial Resources

In general, the development of China's power battery recycling policy can be roughly divided into three stages. In the first stage, power battery recycling appeared as part of the provisions in the policy document for promoting the application of new energy vehicles, which was part of the stage of the overall new energy vehicle policy. This stage further guided enterprises to strengthen the recycling and utilization of retired power batteries. In the second stage, the National Development and Reform Commission, the Ministry of Industry and Information Technology and the Ministry of Environmental Protection and other relevant departments began to issue relevant policies specifically for power battery recycling one after another. It is a thematic policy stage. The Extended Producer Responsibility System Implementation Programme implemented the extended producer responsibility system and clarified the relevant responsible subjects. It is proposed that the comprehensive recovery rate of wet smelting of nickel, cobalt and manganese should be no less than 98%; the comprehensive recovery rate of pyrometallurgical smelting of nickel and rare earth should be no less than 97%. In the third phase, the relevant national authorities have successively introduced a pilot scheme for the recycling of new energy vehicle power batteries, which belongs to the pilot implementation phase. In January 2022, the Ministry of Industry and Information Technology and other eight ministries and commissions jointly proposed the implementation plan for accelerating the comprehensive utilization of industrial resources, and made guiding opinions on improving the recycling system of retired power batteries, strengthening the whole life cycle traceability management of new energy vehicle power batteries, promoting upstream and downstream cooperation in the industry chain to build recycling channels, and building cross-regional recycling and reuse system.

From a policy perspective, to strengthen the recycling management of retired power batteries and regulate the development of the recycling industry, the state has introduced several policies related to retired power batteries since 2012. After years of development, the power battery recycling system is gradually being standardised and improved. Especially in recent years, with the rapid development of new energy vehicles, the state has intensively introduced policies related to power battery recycling, established a full traceability management platform, guided the construction of recycling outlets and introduced a series of guiding policies. From the technical point of view, the technical standards followed by power batteries and energy storage batteries are different, the high-temperature performance requirements of batteries in the field of energy storage, while some retired power batteries may not meet the requirements for the use of energy storage batteries, and the establishment of battery life prediction models based on the analysis of the capacity decay mechanism is not yet perfect, resulting in difficulties in the evaluation and testing of retired power batteries for gradient utilization.

3. Dismantling and recycling

From the perspective of power battery types, ternary lithium batteries and lithium iron phosphate batteries occupy the majority of China's electric vehicle market, while other types of batteries, such as lithium manganese acid batteries, account for very little, and each type of power battery contains many valuable resources. We divide power batteries into three stock units: ternary lithium batteries,

lithium iron phosphate batteries and lithium iron manganate batteries, with each type of power battery focusing on nickel, cobalt, manganese, and lithium, to analyse the material flow characteristics of the reuse resource stock in power batteries [7]. Dismantling and recycling are one of how retired power batteries are recycled. The retired power batteries are discharged, dismantled, crushed, and refined, which in turn yields precious metal compounds (mainly nickel, cobalt, manganese, and lithium compounds), which are then sold for a profit. Power batteries contain a large amount of recoverable high-value metals such as lithium, cobalt, and nickel. Figure 3 shows the percentage of the metal content of the two different types of power batteries, from which we can see that in NiMH batteries, the nickel content is as high as 35%, while in ternary batteries, the percentages of nickel, cobalt and manganese are 12%, 5% and 7% respectively.

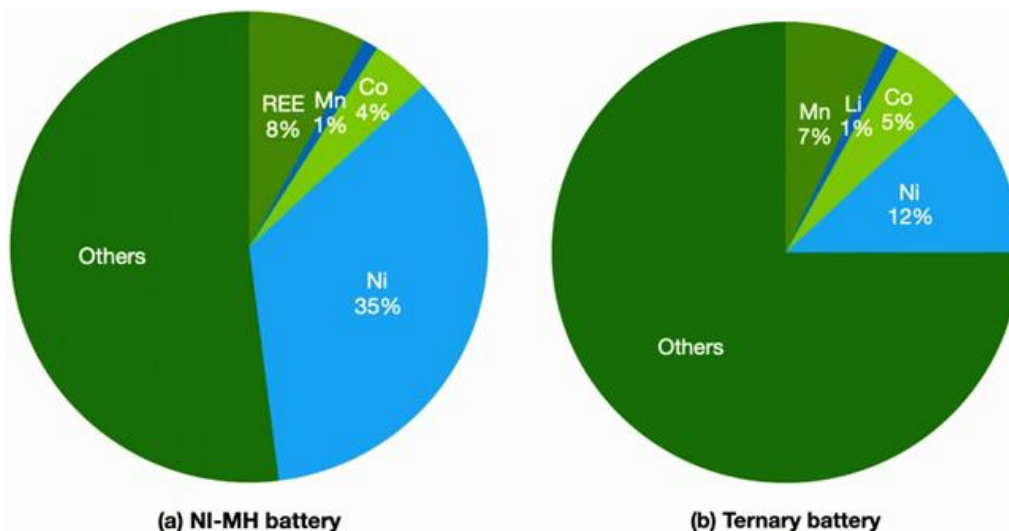


Figure 3. Percentage of the metal content of different types of power cells

(a) NI-MH battery; (b) Ternary battery

The current recycling value of used power batteries mainly lies in the recovery of precious metals in the positive electrode material of power batteries. Ternary materials can recover valuable metals such as nickel, cobalt and manganese at the same time, and the recycling of used power batteries will achieve the reuse of the above metal materials and create a higher recovery. The literature [8] mentions that the dismantling and recycling of ternary material batteries are highly economical and that the dismantling and recycling of lithium iron phosphate batteries are not economical and are recommended for stepwise use. Relatively speaking, the recycling value of ternary batteries is higher than that of lithium iron phosphate batteries. Whether the retired power battery can be used for secondary use and its application area mainly depends on the remaining capacity of the battery, when the remaining capacity of the battery is 30% to 80%, it can be used for secondary use; when it is less than 30%, it does not meet the criteria for secondary use and should be dismantled and recycled [9].

At present, the recycling process of retired power batteries at home and abroad mainly contains pre-treatment, single unit disassembly and material recovery processes, each process contains a variety of treatment methods. Figure 2 is a flow chart of power battery dismantling and recycling, combining various methods to recover metal materials from retired power batteries, with a metal recovery rate of over 90% and a purity of over 95%. A major bottleneck in the development of the new energy vehicle industry is that the growth rate of resource supply is much lower than the growth rate of demand, and the recycling technology has not kept up, which will cause serious environmental pollution and waste of resources after the power battery is scrapped [10]. At present, most domestic enterprises adopt the wet metallurgy process. Some data show that with the wet metallurgy process, the recovery rate of the whole group of ternary lithium batteries is less than 44%, and the recovery rate of the whole group of lithium-ion batteries is less than 28%. In contrast, standardised enterprises are using other processes, and the recovery rate of the whole group of the two batteries can reach

more than 90%. Therefore, improving power battery recycling technology is an effective way to solve the contradiction of resource supply.

3.1. Material recovery

Ternary materials are important materials with a high market share and high added value in lithium-ion. Because the decommissioned power battery cathode material contains Nickel, cobalt and other key prevention and control heavy metals, without professional recycling treatment, will cause heavy metal pollution. Therefore, recycling is a strategic resource and of great significance in terms of environmental protection. Typically, positive electrodes are mainly recycled for aluminium foil and positive materials, while negative electrodes are recycled for graphite and copper foil [11]. Currently, the main recycling methods include direct repair and reclamation, pyrometallurgy and hydrometallurgy and summarized in Table 2.

Table 2. Comparison between different recycle process

Recycling process	Advantages	Disadvantages
Direct repair regeneration	Reduce recycling costs	In preliminary stage
Pyrometallurgy	High maturity	High energy consumption and pollution-prone gases
Wet metallurgy	High recovery rate and purity	High secondary pollution

The literature [12] proposed low eutectic solvents (DESs) as a green solvent that shows great potential in the recovery of valuable metal elements from used lithium-ion batteries. The literature [13] proposed the development of a combined microwave-assisted fire-wet process in the roasting reduction process, leaching process and extraction process. The participation of microwaves saves the carbon thermal reduction time, improves the leaching rate of metal ions, and accelerates the mass transfer rate of the extraction process, ultimately achieving an increase in the yield and quality of the target metal. In the literature [14], an electrochemical recovery process route based on solid phase electrolysis technology was proposed to reduce the risk of secondary contamination and achieve high yield and low-cost recovery of waste LiFePO_4 . The process used electrolysis and stepwise precipitation of the phosphate system to prepare dehydrated iron phosphate and lithium phosphate. The results show that by precipitating iron phosphate dihydrate and lithium phosphate in steps through ammonia-controlled solution pH, the recovery of iron phosphate dihydrate can reach 98.8% and the recovery of lithium ions can reach 99.4%. Here is power battery dismantling and recycling flow chart.

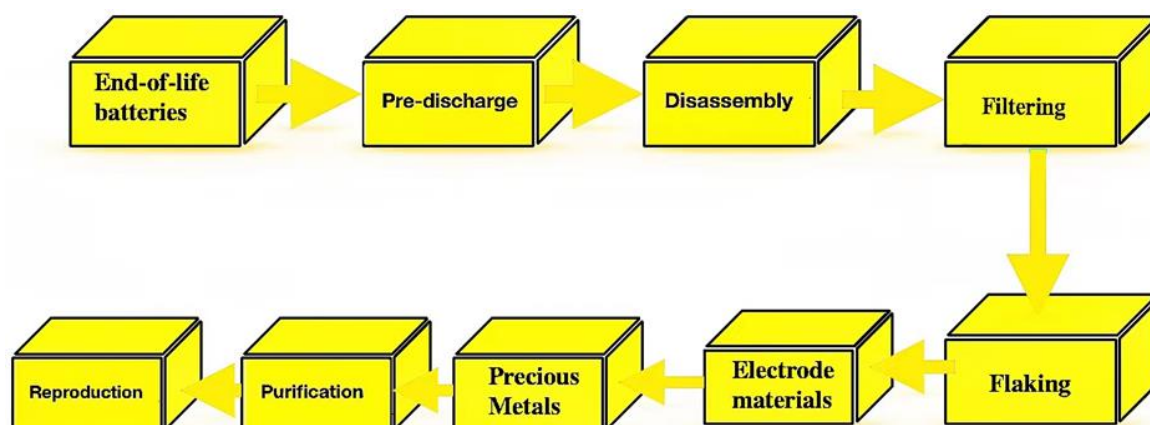


Figure 4. Power battery dismantling and recycling flow chart

3.1.1. Direct repair regeneration

Direct repair regeneration is a non-destructive repair technique that involves repairing the crystal structure of the material and restoring its electrochemical activity without leaching treatment. Compared with material extraction and recycling techniques, the main advantage of the direct repair regeneration process is that it can reduce recycling costs, maximise the value of the recycled material and achieve a closed loop for lithium battery electrode materials, and is therefore expected to be the best way to recycle used power batteries. Failure of the cathode material is usually associated with a breakdown of the solid electrolyte interface (SEI) film, the collapse of the electrode material structure or a decrease in lithium content. The complex chemistry in the NCM cathode can affect the crystal structure and local phase changes after cycling, making the direct repair regeneration process more difficult. In addition to Li^+ loss due to the thickening of the solid electrolyte interface (SEI), crystal structure and microphase changes on the particle surface (or subsurface layer) are also the main causes of the capacity drop in layered oxide cathodes. For ternary cathode materials where failure is mainly triggered by the loss of active lithium elements and cation, mixing is not severe, they can be directly regenerated into commercially viable recycled ternary materials after a simple heat treatment and lithium replenishment calcination [15].

The literature [16] addresses the green recycling of the commonly used waste lithium-ion battery cathode material NCM523 in an extremely innovative and simple process for the direct regenerative repair of NCM523 from waste ternary cathode materials. The lithium salt was regenerated by using a low eutectic mixture of $\text{LiNO}_3\text{-LiOH}$ in an air atmosphere, thus restoring the failed NCM523 to its initial specific capacity. The short calcination process can restore the components and crystal structure of the failed cathode material to its original state. This study helps to promote the industrialization of the recycling of used ternary cathode materials, and also provides a unique idea for the green recycling of other lithium battery cathode materials, such as lithium manganate and lithium iron phosphate, etc. This method has good prospects for application in the field of lithium battery recycling. In the paper [17], the failure process mechanism of lithium nickel cobalt manganate (NCM) ternary materials was systematically investigated and based on this, the direct regeneration and short-range comprehensive utilization of ternary cathode waste were achieved through mechanical force chemical activation and structural repair. In addition, the direct regeneration mechanism of NCM cathode scrap was analyzed and proposed by using in situ high-temperature XRD to monitor the changes in the crystal structure of the regenerated material in real time.

3.1.2. Pyrometallurgy

Pyrometallurgy is the recovery of valuable metals by high-temperature treatment and their purification by physical and chemical transformation. Pyrometallurgy is a simple and efficient process and is therefore widely used worldwide for the industrial recovery of lithium-ion batteries. In the pyrometallurgical process, the battery monomer can be pretreated and then pyrometallurgical recovered for further active cathode material, or fed directly into the furnace during the smelting process, or used in combination with pretreatment and wet metallurgy. The pyrometallurgical recovery process has the advantages of high chemical reaction rates, large processing capacity, relatively flexible raw materials, simple operation, and low environmental impact of the waste residue. However, the recovery of metals such as lithium and aluminium in pyrometallurgy is low, subsequent separation is difficult, energy consumption is high, and toxic emissions are present; incomplete recovery of lithium results in a significant waste of resources, resulting in low returns from pyrometallurgy. The economics of pyrometallurgy depend on the price of metals, especially cobalt. As the current trend in the study of ternary materials is towards high nickel and low cobalt, the recovery of ternary materials by pyrometallurgy is bound to be limited to a certain extent.

3.1.3. Wet metallurgy

Wet metallurgy is a method of dissolving the separated cathode material, leaching out the metal ions and separating or regenerating them using extraction, precipitation as well as electrochemistry. Wet metallurgy usually consists of four steps: leaching, removal of impurities, recovery of transition

metals and recovery of lithium. Compared to pyrometallurgy, hydrometallurgical processes are an ideal method for the recovery of used batteries because of their higher recovery rates, the ability to obtain higher purity products, the recovery of most of the battery components and the lower operating temperatures, and are therefore currently the most used method. The literature [7] suggests that acid leaching processes can dissolve almost all transition metal oxides into solution, usually using strong inorganic acids as leaching agents. Inorganic acid leaching is a traditional approach to the recovery of used lithium batteries with high leaching efficiency. The most used leaching agents are HCl, H₂SO₄ and H₃PO₄ and the leaching process usually requires the use of additional reducing or oxidising agents based on leaching kinetic factors. Unlike the leaching process for NCM materials that require reducing agents, the pretreatment process for LFP requires Fe²⁺ to Fe³⁺, usually by heating at 600°C under an air atmosphere, or by using chemical oxidants such as H₂O₂ or Na₂S₂O₈ before leaching and separation, as Fe³⁺ is more prone to forming precipitates such as phosphates and hydroxides.

Wet recycling is currently the mainstream process technology in the power battery recycling industry. Wet recycling technology is relatively mature and the purity of the metal salts, oxides and other products obtained can meet the quality requirements to produce power battery materials. At present most of the leading domestic recycling enterprises such as Green America and Bump Recycling, as well as international leading enterprises such as AEA and IME, have adopted wet recycling technology as the technology for lithium, cobalt, and nickel recycling.

4. Secondary use

To rationalize the use of resources while obtaining greater economic benefits, the secondary use of retired power batteries appears to be necessary. Power batteries have a limited-service life, and when the capacity of an electric vehicle's power battery decays to less than 80% of its rated capacity, it will not be able to meet the requirements of electric vehicle use. Therefore, these retired batteries can be tested for residual energy after charging and discharging cycles, and suitable applications can be selected according to the residual capacity. Among them, retired batteries with higher capacity after residual energy testing can be used for battery replacement and energy storage applications; batteries with lower capacity can be used for milder low-magnification discharge application scenarios such as lighting, uninterruptible power supply, backup batteries, mobile charging piles, low-speed electric vehicles, home energy storage power, base station power supply scenery street light energy storage.

4.1. Residual energy testing

The secondary use of retired power batteries generally includes steps such as residual energy testing, screening, system integration, etc. Among them, residual energy testing is the more critical part of the secondary use process, which is also a relatively technical part. The power battery can be regarded as a non-linear system, and the performance change of the battery in the process of use is a long-term process affected by many factors. Therefore, the prediction of performance at retirement is a key technology for the secondary utilisation of power batteries. The state of charge (SOC) and state of health (SOH) are the most critical factors in judging the current performance of a battery [1]. The state of health measures how well the battery is ageing, while the remaining capacity describes the battery's endurance, i.e., how long it has been in operation can be judged by its remaining capacity. Both can show the performance index of retired batteries more clearly, characterise the degree of ageing of retired batteries and provide a parameter basis for subsequent screening and restructuring of batteries. The literature [18] introduced how to screen batteries based on their electrical performance, emphasising the importance of maintaining a consistent battery charge state; the analysis of the application of ladder batteries to different energy storage scenarios, such as charging stations, communication base stations, photovoltaic power stations and user-side energy storage, proved that ladder batteries have good economic benefits. The collected retired power batteries were tested for residual energy and tested by charging and discharging cycles to obtain the residual capacity

of the batteries and select their laddering application scenarios for the subsequent screening and restructuring process.

4.1.1. SOC estimation

SOC is an important indicator for assessing the condition of a battery. Accurate estimation of the battery's SOC value can effectively determine the current state of the battery, thus improving the efficiency and extending the life of the battery. The SOC of a battery reflects the remaining charge of the battery and is the ratio of the remaining charge Q_r to the rated charge Q_n of the battery under the same operating conditions and specific discharge conditions (constant temperature, constant current). The literature [1] suggests that most of the common model-driven methods for estimating SOC are based on the equivalent circuit model, using the battery equivalent circuit to construct the spatial equation of state, and using methods such as Kalman filtering to observe SOC, where the extended Kalman filtering algorithm is one of the more classical algorithms that can reduce errors and suppress noise from the perspective of minimum error variance and is suitable for non-linear systems, but the main drawback of this method is that the system is non-linear and the observation noise is only applicable to Gaussian distribution. Based on this problem, many studies have proposed improved Kalman filtering methods, including double Kalman filtering, traceless Kalman filtering and adaptive Kalman filtering. The data-driven approach does not require an in-depth study of the electrochemical reactions within the battery and relies on historical data analysis and model training to obtain highly accurate SOC values, with the BP neural network model being one of the simpler and most used estimation models. The advantage of this method is that it does not require complex mathematical models, and only requires data such as internal resistance, voltage and current to complete the evaluation; its disadvantage is that it requires a large amount of data support and repeated training, which makes it difficult to perform SOC evaluation in this way for power batteries in the absence of perfect historical data. Based on the above problems, the fusion model combining multiple methods has become a research hotspot: fuzzy neural networks can be combined with the extended Kalman filter method to effectively solve the problem that the traditional Kalman filter method relies too much on the battery model while reducing errors and having better convergence and robustness; or a neural network model can be used instead of the polynomial model in the traceless Kalman filter method to effectively improve the estimation degree, while the master-slave adaptive traceless Kalman filter MS-AUKF algorithm is designed to effectively control the noise variance, which has higher accuracy and convergence speed than the traditional Kalman filter method [1].

4.1.2. SOH estimation

SOH reflects the life state of the battery and generally refers to the degree of ageing of the battery. Battery ageing causes changes in a variety of parameters, the main ones being increased internal resistance and capacity decline. Indicators such as battery internal resistance, self-discharge and battery capacity are the main indicators used to assess the health status of retired batteries. Both redundancies between features and insufficient generalization of the estimation model will affect the accurate estimation of battery SOH. To reduce the redundancy between data-driven features, increase the generalization of the model and improve the SOH estimation accuracy, a SOH estimation method based on principal component analysis and the whale optimization algorithm (WOA)-Elman was proposed in the literature [19]. Firstly, the features that are highly correlated with the ageing of Li-ion batteries are extracted from the charging process curve and selected, and the principal component analysis method is used to reduce the redundancy between the features. For validation, the commonly used long and short-term memory neural networks, support vector regression and extreme learning machines, as well as the unoptimized Elman model were compared, and the results showed that the root-mean-square error of the WOA-Elman estimation model was 1.2113%. Finally, the SOH of the remaining two batteries was estimated and validated using three sets of battery experimental test data alternatively as the training set, and, the maximum root means square deviation of the estimation results was only 0.1771%. Therefore, the method in this paper can estimate the battery SOH more accurately and has better generalization performance. In the paper [20], a 3-layer back-propagation

neural network was constructed using a neural network algorithm with DC internal resistance, discharge multiplier and surface temperature as inputs. The neural network has better convergence and can more accurately assess the health status of the ladder-use battery. The literature [21] is based on a model-driven approach, using a second-order Thevenin equivalent battery model, proposing a double adaptive traceless Kalman filter algorithm, performing multiple iterations to estimate the internal resistance of the battery, and estimating the SOH value from the internal resistance of the battery, which maintains an estimation accuracy within 2%, which is a more accurate method. The literature [22] proposed a method for accelerated evaluation of battery decay in a ternary lithium battery energy storage system by experimentally analyzing the characteristic curves of retired power batteries, which can evaluate the performance of ternary lithium batteries quickly and non-destructively. The test method is simple and efficient, with less equipment and more accurate judgment results, but is limited by the working conditions and battery types.

The literature [23] proposed a method for SOH estimation of Li-ion batteries based on attention-improving bi-directional gated cycle units (BiGRU). Firstly, the voltage, current and impedance parameters of the battery charge/discharge curve are extracted and dimensioned down by auto encoder (AE) to extract the feature quantity and reduce the redundancy among the data. Secondly, an attention mechanism (AM) is introduced to assign weights to the input variables to highlight the features that play a key role in SOH estimation. Finally, BiGRU is used to learn the mapping relationship between input variables and capacity to capture long-term dependence under capacity decay. The results on a dataset of batteries with different charging multipliers show that the method can achieve high accuracy estimation of SOH for all types of batteries with a root mean square error of less than 1.1%. The literature [24] specifies the maximum available capacity of the battery pack, i.e. the capacity of the lowest SOH cell, and adjusts the SOC of each cell so that the lowest SOH cell can be fully charged and discharged to maximise the capacity of the reconstituted battery pack; the peak charging power of the battery is inversely correlated with the open circuit voltage OCV and the internal resistance of the charge, the lower the open circuit voltage and the lower the internal resistance of the charge, the higher the peak charging power. The lower the open circuit voltage and the lower the internal resistance, the higher the peak charging power. By lowering the SOC of each cell to make the voltage at each SOC point as low as possible, the charging power capacity of the reconstituted battery pack can be increased. Similarly, the peak discharge power is the opposite of the peak charge power, and the peak discharge power can be increased by increasing the SOC of every single cell of the reorganized battery pack performance optimization control strategy, raising the battery pack voltage at each SOC point, and reducing the internal resistance of the discharge: the adjustment strategy is calculated to satisfy the premise of maximizing the capacity of the reorganized battery pack so that the SOC of every single cell works in the middle region to slow down the performance degradation of the reorganized battery pack.

4.1.3. Screening and reconfiguration

Screening is the consistent screening of components of retired batteries that meet the requirements of each scenario based on the results of condition diagnosis and assessment. The screening and classification of retired power batteries is a key part of secondary use. To ensure the safety and efficiency of the secondary use, the most important issue for the screening process is to improve the speed accuracy and rationality of the process. At present, domestic, and foreign research on big data for battery screening, no need to conduct a series of experimental measurements such as charging and discharging, reduce time costs, more scientific and economic. However, the current lack of historical data on retired batteries hinders the use of big data to carry out the work. If a perfect battery traceability system is established in the future big data screening will be unimpeded and the screening process for retired batteries will be safer and faster. In the literature [24], a fast sorting and reorganization method based on the combination of short-time pulse discharge and electrochemical impedance spectroscopy (EIS) was proposed to address the problems of low screening efficiency, high energy consumption and low group formation rate of retired power batteries at the present stage. By testing and analyzing 200 retired LiFePO₄ power batteries of the same type and different batches,

the pulse voltage difference, DC internal resistance, EIS curve shape characteristics and EIS equivalent circuit model parameters were used as screening indicators and mathematical models were established to achieve rapid and effective sorting and reorganization of retired power batteries. The results of the validation experiments show that the method can effectively reduce energy consumption, and the average testing time of a single cell is less than 20 min. In the paper [25], a sorting method for retired power batteries is proposed through the design of the retired power battery step-use grouping process, data processing of retired power battery parameters and battery series grouping based on K-means clustering. The new sorting method is compared with the traditional sorting method, and the voltage and capacity utilization of the reconstituted batteries are effectively improved and the sorting scheme is more reasonable. Three sorting methods have been proposed in the literature [25]: a sorting method based on maximizing available capacity, a sorting method based on capacity interval partitioning and a clustering method based on the Mahalanobis distance of the battery pack feature vector. Similar clusters are used together. All three classification methods are based on the 18 battery packs in this project and can be extended to classify a larger number of packs for better results. On balance, there are advantages and disadvantages to each of the three methods. For a fast classification, the best choice is a classification based on capacity interval partitioning; for a cost-effective classification, the best choice is a classification based on maximising the available capacity and a classification based on capacity interval partitioning; for a comprehensive and accurate classification, the best choice is a clustering based on the Mahalanobis distance of the cell feature vector. In literature [26]. The rapid cycle charge/discharge method is an efficient testing method based on "GB/34015-2017 Residual energy testing for automotive power battery recycling", which can greatly improve the production efficiency of recycling enterprises and meet the demand for supporting the parameters of power batteries for secondary use, including the remaining battery power and charge/discharge performance. It provides a new single-power battery testing and sieving test method for power battery recycling enterprises to achieve industrial scale. According to the recycling process of gradient utilization, after screening, retired power batteries are reorganized and integrated based on the principle of consistent screening and reorganization, after which they are put into secondary utilization. The current battery reorganization technology mainly includes two aspects of retired battery monomer and module level, and the inconsistency of retired batteries is weakened through the experimental research of different reorganization technologies to improve the safety performance of the gradient utilization system.

4.2. Application scenarios

In recent years, there have been some successful cases of retired power battery secondary use in China, which can be seen in a wide range of scenarios of retired power battery secondary use. It is of great significance in grid energy storage, communication base stations, peak shaving and valley filling, and weakening the abandoned light rate, which can achieve the purpose of optimizing resource allocation, solving power consumption conflicts, ensuring reliable power supply, stabilizing the power system and improving grid security.

Those with higher battery capacity after residual energy testing are classified as Step-Use I for battery replacement and grid energy storage applications. For example, Beijing Artisan Core Batteries has developed a gradual use optical storage system. Retired power batteries are used for battery replacement and can be used as replacement parts for electric vehicles when they fail. Decommissioned power battery laddering applications for grid energy storage can be more adaptable to the environment, have a short construction cycle and can be dispersed for small-scale configurations. The energy storage system proposed can be divided into power generation side, power supply side and electricity consumption side energy storage devices depending on where the energy storage equipment is installed and what role it plays. The vast majority of energy storage stations are small in scale and utilise power batteries or old power battery ladders to achieve auxiliary regulation of the active power grid. Decommissioned batteries used in grid energy storage can also achieve the large-scale use of renewable energy generation. And for improving the quality of electricity,

improving grid stability and availability, and being able to meet the demand for electricity supply and consumption in different application scenarios.

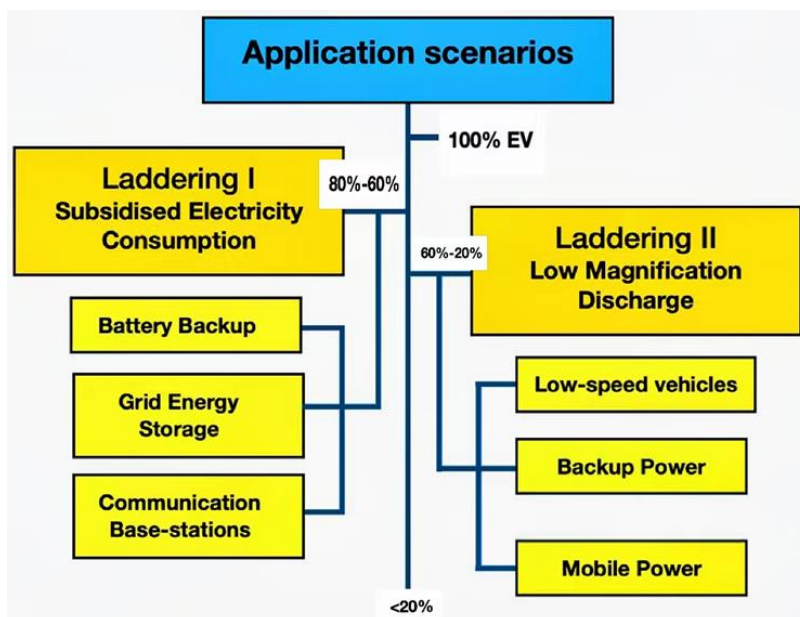


Figure 5. Application scenarios after residual energy detection

The battery with low capacity after residual energy testing is classified as Class II for low-rate discharge scenarios, such as low-power electric vehicles, UPS backup batteries, mobile charging piles and other mild low-rate discharge applications. For example, Shenzhen BYD and other enterprises produce batteries for secondary use in the field of power backup, etc. The application of retired power batteries in urban household life, such as low-speed electric vehicles, household energy storage areas, mobile power sources, mobile charging piles, etc., is an effective way to improve the utilisation of infrastructure. When used as mobile charging equipment, powering an electric vehicle can generate additional electricity revenue; when used as a low-speed vehicle, it can be used as a means of transport to serve people and thus reduce transport costs.

The secondary use of retired batteries is an effective way to maximise the performance of power batteries, which can not only maximise their value in different application scenarios but also create certain economic benefits. The secondary use of retired automotive batteries not only ensures the utilization rate of the resources within the battery but also avoids the environmental hazards brought about by the waste battery, which is in line with the current concept of environmental protection and green and is a major trend in the future. China is in the primary stage of battery secondary use technology development, most battery secondary use methods are still in the demonstration stage, and the secondary use industry is still in the cultivation period.

5. Conclusion

This paper has systematically summarized two ways of developing retired power batteries: dismantling and recycling and gradient utilization. A series of standards and policies issued by the state have been sorted out, the application scenarios of retired power batteries have been addressed from two different dimensions, and the following suggestions have been made to analyse the current technology of secondary use. In terms of dismantling and recycling, at present, power battery recycling enterprises mainly refer to "GT/B34015-2017 Residual Energy Testing for Vehicle Power Battery Recycling", "GT/B31486-2015 Cycle Life Requirements and Test Methods for Power Batteries for Electric Vehicles ", "GT/B34015.2-2020 Requirements for the Recycling of Power Batteries for Vehicles for Gradual Use" and other standards. The recycling process is relatively mature, but the automation level of most enterprises still needs to be strengthened. In terms of laddering, consider the intelligence of the whole life cycle management of power batteries and

promote the clarity, timely tracking and information interaction of the whole life cycle use of power batteries, to guarantee the clear tracking of the whole carbon assets and carbon footprint accounting. In terms of innovative power battery recycling systems and systems, in addition to the need for a sound legal and regulatory system, a perfect recycling system is also key to power battery recycling, while the links and services between automotive enterprises and power battery manufacturers can be strengthened. Research, development, and promotion of complete sets of technology and equipment for recycling and secondary use of waste power batteries. Certain subsidies or incentives can be given for the construction of pilot stations. Only by continuously improving the recycling system and management system, strengthening the whole life cycle traceability management of new energy vehicle power batteries, and strengthening the links and services between automotive enterprises and power battery manufacturers. Only in this way can we continue to promote the development of retired power batteries in the context of double carbon and achieve the double carbon goal.

References

- [1] Cui S H, ZHOU H, HUANG Z X, WANG K 2022 A review of key technologies and applications of power battery recycling Guangdong Electric Power. sin.1 - 14.
- [2] Liu R T, Li J L, Lv Z, Ma S L 2021 Analysis of the application potential of retired power batteries Electrical Technology.1 - 9.
- [3] Liu Y Q, Li J L, Zhang J H, Ma S L 2021 Safety analysis of retired batteries for secondary use Distributed Energy. 6 (01): 7 - 13.
- [4] Yang Y K, Zhang B, Liang Y L, Lu Q 2021 Analysis of the current situation of waste power battery recycling policy and technology Automotive and Accessories. sin.50 - 51.
- [5] Hu J, Lin C J, Hao W J, Zheng T L 2022 Current status and suggestions for the construction of power battery standard system Energy Storage Science and Technology. 11 (01): 313 - 320.
- [6] Automotive and Accessories 2022 Automotive and Accessories. (09): 44 - 47.
- [7] Zhou W, Fu D J, Liu W F, Chen J J, HU Z, ZENG X R 2022 Energy Storage Science and Technology. sin.1854 - 1864.
- [8] Li J L, Li Y X, Guo L J 2021 Distributed Energy.6 (03): 32 - 37.
- [9] Wang G F 2021 Urban and Rural Construction. (19): 48 - 49.
- [10] Li M M 2022 Intelligent Networked Vehicles. (01): 59 - 61.
- [11] Cheng M Q, Ru J J, Hua Y X, Wang D, Cheng X X, Zhang W W, Huang H M, Wang D X 2022 Chemical Progress.3293 - 3305.
- [12] Wang Z X, Li J C, Li J D, Yi J, Shi L, Wu X 2022 Energy Storage Science and Technology.11 (01): 45 - 52.
- [13] Yang S W, Du G C, Wang L X, Liu L P, Hou X C, YING X F 2021 World Nonferrous Metals. (19) :136 - 137.
- [14] Lou P, Xu G H, Yye L P, Li S D, Cheng Q, Cao Y C, Deng H M 2020 Energy Storage Science and Technology.848 - 855.
- [15] Meng X Q 2020 PhD. Study on the failure process and direct regeneration of ternary cathode materials for lithium-ion batteries (Tianjin: Tianjin University).
- [16] Wang S 2021 PhD. Consistent sorting and restructuring of retired power battery modules (Beijing: North China Electric Power University).
- [17] Li X D, Zhang X W 2022 Energy Storage Science and Technology.1 - 15.
- [18] Li Y Q, Lei Q K, Wang H, Hua S C 2021 Huadian Technology. 42 - 46.
- [19] Kang D X, Li L W, Yang Y X, Wang K 2020 Guangdong Electric Power.9 - 16.
- [20] Dong R F, Wang F F, Hu Y X, Zhao G J 2021 Chinese Journal of Power Sources. 45 (7): 890 - 892.
- [21] Wang Fan, Shi Y S, Liu B J, Zo Y J, Fu Z, ALI Jamsher 2021 Energy Storage Science and Technology. 10 (06): 2326 - 2333.
- [22] Jin W T, Liao M S, Huang J, Wei Z D. 2022 Energy Storage Science and Technology.11 (01) :350 - 358.

- [23] Wang H M, Liu J L 2021 Electronic Technology and Software Engineering. (07) :225 - 226.
- [24] Xie P, Zhu H S, Wang, Li X W 2021 Internal Combustion Engines and Accessories. (06): 201 - 203.
- [25] Yang H H, Hong Y, Shi B W, Xie M Y, Zhu Z Y, Yu W 2021 Electric porcelain lightning arrester. (06): 76 - 80.
- [26] Luo F, Huang H H, Wang H X 2022 Journal of Instrumentation. 43 (01): 229 - 238.