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Green Recycling Path and Industrial Prospect of Spent LFP and Ternary Lithium Batteries Under Dual Carbon Target

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Abstract. Nowadays, more and more new energy vehicles are on the road, and the number of lithium batteries used in the obsolete vehicles is also increasing year by year. Discarded used batteries at will pollute the natural soil and groundwater, and rare metals such as lithium, cobalt and nickel will also be wasted in vain. This article takes the most common lithium iron phosphate batteries and ternary lithium batteries in the market as the research objects, and respectively expounds the working processes, advantages and disadvantages, and applicable situations of three recycling methods: secondary utilization, hydrometallurgy and pyrometallurgy. Research has found that secondary utilization is low-cost and causes less pollution, but this approach cannot completely recover the metals inside the battery; hydrometallurgy has the highest recovery rate for precious metals, but it generates a large amount of difficult-to-treat wastewater; pyrometallurgy can safely handle damaged and dangerous batteries, but it consumes a large amount of energy and causes serious lithium loss. The combined use of multiple technologies is the mainstream direction of the future recycling industry. This article can help everyone gain a simple understanding of various related knowledge about battery recycling and also provide a reference for the green and low cost disposal of used batteries.

Keywords: lithium-ion battery, power battery, battery recycling, secondary utilization, metallurgical recycling

1. Introduction

After China set the "dual carbon" green development goals for the mainland, electric vehicles have become an important tool for energy conservation, emission reduction and low-carbon transformation in the transportation industry. At present, China is the country with the highest sales of electric vehicles globally. It is expected that by the end of 2025, the total number of new energy vehicles in the country will exceed 40 million [1].

Lithium batteries are the most crucial energy storage components in electric vehicles. The interior of a battery not only contains rare and precious metals such as lithium, cobalt and nickel, but also some toxic electrolytes and organic solvents. The service life of ordinary vehicle power batteries is generally only 5 to 8 years. This means that from 2026 to 2035, China will witness a large scale phase of battery scrapping for electric vehicles [2].

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If used batteries are casually discarded or handed over to unqualified small workshops for simple processing, the heavy metals and toxic waste liquids inside the batteries will seep into the soil and groundwater, seriously damaging the ecological environment. At the same time, a large amount of rare metals being wasted will also hinder the longterm development of the new energy industry. Therefore, establishing a standardized, environmentally friendly and efficient waste battery recycling system is particularly important for environmental protection, resource recycling and the development of green industries.

In recent years, many scholars at home and abroad have been studying the recycling technology of waste batteries and the industry management methods. Most domestic researchers are balancing the efficiency of recycling and the cost of treating pollution. Lu Junhao compared the pyrometallurgical and hydrometallurgical processes and found that the hydrometallurgical process could recover over 90% of the metal, but the cost of wastewater treatment was very high. The pyrometallurgical pre-treatment is simple, but it consumes a lot of electricity and lithium is difficult to be completely recovered [3]. Foreign research is more inclined to calculate the carbon emissions of batteries throughout their entire life cycle, as well as the allocation of recycled resources in different regions. Relevant models have calculated that the number of scrapped batteries in various regions of the country does not match the recycling capacity of regular factories, and there is a significant gap between regional supply and demand [4]. There are also studies that use new low-pollution solvents to treat the cathodes of used batteries, providing a more environmentally friendly new idea for wet recycling [5]; Life cycle assessment experiments also prove that the recycling of batteries by regular factories causes much less harm to the environment than the direct mining of new minerals [6].

A review of the existing research materials reveals that most articles only introduce a single recycling technology, rarely comprehensively comparing the treatment effects, costs, and carbon emissions of the three mainstream recycling methods together, nor systematically sorting out what scenarios each technology is suitable for and what its advantages and disadvantages are.

Therefore, this article first distinguishes the common automotive power batteries on the market, then makes a complete comparison of the working principles, advantages and disadvantages of secondary utilization, hydrometallurgy and pyrometallurgy, summarizes the future innovation directions and development trends of the battery recycling industry, and provides theoretical references for the green and efficient recycling of used power batteries.

2. Classification of automotive power batteries

With the rapid popularization of new energy vehicles, there are more and more types of power batteries on the market. The internal materials, service life and recycling difficulty of different batteries vary greatly. According to the classification of cathode materials, the two types that are currently most widely used and have the largest recycling volume after scrapping are lithium iron phosphate batteries and ternary lithium batteries.

2.1. Lithium iron phosphate batteries

Lithium iron phosphate batteries, abbreviated as LFP batteries, have lithium iron phosphate as their cathode material and do not contain expensive rare metals such as cobalt and nickel. Its greatest advantage is its stable chemical properties. It is not prone to fire or explosion during charging and discharging, and has a very high level of safety. The raw material price is low, the cycle service life

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is longer, and the capacity attenuation rate is very slow during daily use. It is widely used in household electric vehicles, city buses, and logistics trucks.

From the perspective of recycling, there are almost no precious metals in lithium iron phosphate. Only lithium has recycling value. Iron and phosphorus are everywhere, and there is not much money to be made from recycling. Many illegal small workshops are reluctant to recycle such batteries, and a large amount of scrapped lithium iron phosphate will flow into unregulated channels. However, the electrolyte and separator in batteries still pose a threat to human health and pollute the environment. Random discarding can pollute water and soil, making them the key targets for the control of used batteries.

2.2. Ternary lithium battery

The positive electrode of ternary lithium batteries contains high-value rare metals such as nickel, cobalt and lithium. The high-nickel version of the battery has a strong power storage capacity and is mostly installed in long-range household new energy vehicles. The profit from recycling ternary batteries is very high and they are the main raw materials processed by large-scale and formal metallurgical recycling plants.

However, ternary batteries have poor chemical stability. After long-term use, they are prone to bulging, leakage, and even internal short circuits. Damaged ternary batteries cannot be reused and can only be treated through metallurgical processes. Random stacking and discarding can cause toxic electrolyte leakage and lead to heavy metal pollution.

3. Recycling methods for used power batteries

At present, there are mainly three technologies for domestic regular factories to handle scrapped batteries: secondary utilization, hydrometallurgy and pyrometallurgy. The three methods have different working processes, and the types of batteries they are suitable for, the processing costs, and the pollution they generate are also different. They respectively correspond to used batteries with different degrees of damage and materials.

3.1. Secondary utilization

3.1.1. Definition and working principle

Secondary utilization, simply put, means "downgrading and reusing batteries". When the battery capacity of an electric vehicle drops to 80% of its original level, it still fails to meet the power supply standards for automobiles. However, the battery itself is not completely damaged and still has the basic power storage capacity. The staff disassemble the used batteries, test and screen them. The batteries that pass the capacity and safety conditions are reassembled and used in equipment with lower requirements for battery life and discharge performance to extend the overall service life of the batteries [7].

The entire process is divided into four steps: The first step is to disassemble the complete battery pack, separating the casing, wires, and heat dissipation components, and then remove individual cells. The second step is to use professional instruments to test the remaining capacity and internal resistance of each battery and check for any damage or leakage. The third step is to discard the bulging, damaged or leaking bad batteries and keep the intact and usable cells. The fourth step is to

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pair qualified batteries with protection circuits and assemble them into brand-new energy storage battery packs for use in new scenarios.

3.1.2. Advantages and disadvantages

Advantages: First, the resource utilization rate is higher. Postponing the battery's entry into the metal dismantling process reduces the wastewater and waste gas generated during metal refining, making it low-carbon and environmentally friendly, and in line with the national dual carbon goals. Second, the recovery cost is low. There is no need for high-temperature equipment or a large amount of chemical agents. The investment in factory equipment is small, and the profit is higher. Thirdly, the operation threshold is low. Without a complete set of high standard environmental protection equipment, small and medium-sized recycling workshops can also carry out operations.

The drawbacks are also quite obvious: Firstly, the screening and testing process is cumbersome. Each battery needs to be tested separately, which consumes a lot of manpower and time. Secondly, the service life of the reorganized energy storage batteries is only 3 to 5 years. After expiration, they need to be recycled again, which can only temporarily reduce pollution but cannot achieve complete metal recycling [8]. Finally, severely swollen, leaking and aged batteries cannot be reused in a second cycle and can only be sent for metallurgical treatment, with limited application scope.

3.1.3. Actual usage scenarios

The secondary utilization of lithium iron phosphate batteries with slight attenuation and intact casings is most suitable. There are mainly three types of applications: The first is large-scale energy storage power stations, where electricity generated by wind and solar energy is stored to stably supply power to the grid; The second category includes low-speed transportation tools such as electric tricycles, sightseeing vehicles in scenic spots, and shared electric bikes in residential areas. The third category includes small backup power supplies, such as household emergency energy storage, backup power supplies for communication base stations, and energy storage power supplies for street lamps. Severely damaged ternary batteries are hardly ever used in a secondary capacity.

3.2. Hydrometallurgy

3.2.1. Definition and working principle

Hydrometallurgy relies on soaking and dissolving the cathode materials of batteries in chemical solutions to separate and extract lithium, cobalt and nickel. It is currently the most popular technology for recycling ternary batteries.

The complete process: First, completely discharge the used battery, crush it, remove impurities such as plastic separators and copper and aluminum casings, and obtain the positive electrode powder. Then put the powder into the acidic leaching solution to allow lithium, nickel and cobalt to dissolve into the liquid. Different metals are gradually separated through chemical reactions such as extraction, precipitation and filtration; Finally, the metal compounds are purified to make brand-new raw materials for battery cathodes, achieving the recycling and reuse of metals [9]. In recent years, many studies have replaced strong acids with low-pollution and low-eutectic solvents to reduce the harm of chemical waste liquids, which is a new development direction for wet recovery.

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3.2.2. Advantages and disadvantages

The greatest advantage is the extremely high metal recovery rate. Data shows that the total recovery ratio of lithium, cobalt and nickel can exceed 90%, and almost all rare metals can be recycled. The purity of the refined metals is high and can be directly sent to battery factories to produce new batteries, forming a complete resource recycling chain. The entire process does not require high-temperature heating, and the carbon dioxide emissions are much lower than those of pyrometallurgy, resulting in a lower carbon footprint.

The main shortcomings are: The production process consumes a large amount of strong acids and organic extraction agents, generates a large amount of industrial wastewater containing salt and heavy metals, the sewage treatment process is complex, and the cost of the supporting water purification equipment is expensive. The entire production line occupies a large area and requires various chemical treatment machines. Small recycling plants do not have the funds to build it [10].

3.2.3. Actual usage scenarios

Hydrometallurgy is specifically designed to handle damaged ternary lithium batteries that cannot be reused, especially suitable for high-nickel ternary batteries. It is mostly used in large and regular enterprises equipped with complete sewage treatment systems, suitable for large-scale centralized treatment of scrapped ternary power batteries, but not suitable for scattered small-scale recycling sites.

3.3. Pyrometallurgy

3.3.1. Definition and working principle

Pyrometallurgy extracts metals by melting batteries in high-temperature furnaces and is the earliest traditional recycling technology with a simple operation process. Used batteries are simply crushed and sent into a high-temperature furnace. The temperature of over a thousand degrees Celsius will burn off the separator, electrolyte, plastic and other organic substances. Metals melt in layers at high temperatures. Nickel and cobalt fuse into alloys, and some lithium will volatilize along with the high-temperature flue gas. The remaining metal residues can be simply purified to obtain reusable metal raw materials.

3.3.2. Definition and working principle

Advantages: The pre-treatment steps in the early stage are simple. After the battery is crushed, it can be directly put into the furnace without the need for fine disassembly of the battery cells. It can handle a large quantity of waste batteries at one time, and the machine has a low operation threshold. It can receive dangerous batteries with leakage, damage and self-ignition risks, making it easier to control potential safety hazards during the production process.

However, among the three recycling methods, it has the most prominent shortcomings: First, high-temperature furnaces consume a large amount of electricity and fuel, with extremely high energy consumption and large carbon emissions, which does not meet the requirements of low-carbon development; Second, lithium is highly volatile when exposed to high temperatures, resulting in insufficient lithium recovery rate 60%， A large amount of precious lithium resources are wasted in vain. Thirdly, combustion can generate toxic waste gases such as hydrogen fluoride. The cost of waste gas purification equipment is high, and improper treatment can cause serious air

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pollution. High temperatures will also wear out the furnace equipment rapidly, and the maintenance costs in the later stage are large [11].

3.3.3. Actual usage scenarios

Early small-scale recycling plants generally used pyrotechnics and could also handle large quantities of damaged and easily self-igniting waste ternary batteries in an emergency. With increasingly strict environmental protection policies, simple pyrometallurgical recovery has gradually been phased out. Currently, most enterprises adopt a combined process of "pyrometallurgical pretreatment + hydrometallurgical purification": first, organic impurities are burned off at high temperatures, and then lithium, cobalt and nickel are precisely extracted through hydrometallurgical methods, making up for the poor recovery of lithium by the single pyrometallurgical method.

3.4. Comprehensive comparison and summary

Overall, among the three recycling methods, there is no absolutely best one. Factories should choose the appropriate solution based on the battery material, the degree of damage, and their own environmental protection supporting equipment. Complete lithium iron phosphate is given priority for secondary utilization, with low cost and less pollution, but it cannot completely recover the metal. Ternary batteries are suitable for hydrometallurgy, with high recovery rates of precious metals and low carbon emissions, but the pressure of wastewater treatment is huge. The pyrometallurgical treatment process is simple and highly safe, but it has high energy consumption and causes serious loss of lithium resources.

The current mainstream development direction of the industry is the combination of multiple recycling processes: batteries with slight degradation are first used for secondary energy storage, and then sent for wet metal extraction after their secondary life ends. For severely damaged batteries with safety hazards, impurities are first removed by high-temperature fire method, and then lithium, cobalt and nickel are separated by wet method. This combination mode strikes a balance among recycling efficiency, pollution treatment costs and production safety. Meanwhile, researchers at home and abroad have been developing new low-pollution recycled solvents and intelligent battery sorting machines, improving existing processes, reducing wastewater and waste gas, lowering carbon emissions throughout the recycling process, and promoting the development of the waste battery recycling industry towards a green, efficient and sustainable direction

4. Prospects

Nowadays, the number of new energy vehicles is continuously rising, and more and more power batteries are being phased out every year. Doing a good job in battery recycling can not only protect the environment and save rare metals, but also contribute to the country's low-carbon development. Combining the advantages and disadvantages of the current three mainstream recycling technologies, many new changes will occur in the battery recycling industry in the future.

First, recycling technology will be more advanced and environmentally friendly. There are obvious drawbacks to using the cascade, pyrometallurgical and wet methods alone. In the future, the industry will combine multiple processes: batteries with relatively low wear and tear will be used for energy storage and low-speed transportation first, and then the wet method will be used to extract metals after they are completely scrapped. For damaged batteries with safety hazards, impurities are first removed by high temperature, and then precious metals are separated by wet method, taking

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into account both recovery efficiency and production safety. Meanwhile, scientists will develop mild and pollution-free chemical solvents to replace highly corrosive strong acids and reduce sewage pollution. The fully automatic intelligent inspection machine will replace manual inspection of batteries one by one, saving manpower and time. Pyrometallurgical equipment will also be upgraded to reduce exhaust emissions and waste of lithium resources.

Second, the entire recycling industry will become more standardized, and highly polluting unlicensed small workshops will gradually disappear. The profit margin for recycling lithium iron phosphate is meager, and the enthusiasm of regular factories for recycling is low. A large number of used batteries flow into illegal black workshops, polluting land and water sources. In the future, car manufacturers and large battery enterprises will build a complete industrial chain from battery production, installation and use to scrapping and recycling, and code and track each battery to prevent the random loss of waste batteries. At the same time, expand the application scenarios of secondary batteries and increase the recycling income. Small processing plants should cooperate uniformly with large enterprises and phase out highly polluting simple equipment.

Thirdly, relevant laws, regulations and environmental protection standards will become increasingly strict. The state will introduce more detailed control standards, strictly limit the wastewater and waste gas generated from recycling, and shut down small recycling workshops that are high energy-consuming and heavily polluting. In response to the low profit margin in the recycling of lithium iron phosphate, supportive policies have been introduced to encourage enterprises to take the green recycling route. The recycled metal raw materials can be directly used to manufacture new batteries, with performance no different from that of newly mined ore raw materials, thus completing the entire circular industrial chain.

In the long run, battery recycling is an indispensable part of the development of new energy. New technologies can reduce carbon emissions during the recycling process, reuse recycled metals such as lithium and nickel, decrease mineral exploitation, and prevent the random discarding of waste batteries from polluting water and soil. In the future, more research will focus on low-cost and low-pollution recycling processes, enabling used power batteries to truly achieve resource recycling and promoting the long-term green development of the new energy vehicle industry.

5. Conclusion

By comparing two types of power batteries and three mainstream recycling technologies, this paper concludes that lithium iron phosphate contains almost no rare metals, has a low recycling rate, and is prone to flowing into illegal workshops, which can cause water and soil pollution. Ternary batteries are rich in lithium, cobalt and nickel, and are more suitable for metal extraction in hydrometallurgy. These three recycling methods each have their own advantages and disadvantages, and there is no perfect single process: Secondary utilization can select lithium iron phosphate batteries with intact casings and slight degradation, which is low-cost and causes less pollution, but it can only delay metal recycling and cannot achieve full element recycling. Hydrometallurgy has a high recovery rate for the most expensive metals and is suitable for damaged ternary batteries, but this method imposes a very heavy burden on wastewater treatment.

However, pyrometallurgical pretreatment is highly safe, but this treatment method is risky, can damage batteries, consume a lot of energy, and lead to the loss of lithium resources. There for, in the future, this industry cannot rely solely on a single recycling technology. All major enterprises need to combine various battery recycling processes based on different types and degrees of battery damage to achieve more efficient, safer and less polluting resource recovery.

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This article, from a realistic industry perspective, clarifies the serious environmental hazards caused by the random discarding of used batteries and emphasizes the necessity of establishing a standardized and systematic recycling system. Vigorously promoting multiple battery process combination recycling models and improving the complete battery recycling industrial chain can more effectively reduce heavy metal pollution in water and soil, thereby achieving the recycling and regeneration of scarce minerals such as lithium, cobalt and nickel, alleviating the pressure of ore mining, assisting the country in achieving the dual carbon green development goals, and promoting the long-term sustainable development of the new energy vehicle industry.

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