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DISSERTATION

JUSTIFICATION OF SCIENTIFIC PRINCIPLES OF WASTE BATTERY MANAGEMENT AND RECYCLING

183 – Environmental protection technologies

Submitted for the award of the academic degree of Philosophy Doctor

The dissertation contains the results of the author's own research. The use of ideas, results, and texts from other authors includes references to the respective sources.

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ABSTRACT

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This study systematically analyzes the environmental impact, classification, composition, legislative management, recycling, and pollution hazards of waste batteries.

The introduction substantiates the relevance of the dissertation topic and formulates the goal, and objectives of the research. Furthermore, it determines the scientific novelty and practical value of the results obtained, and presents the following: data on the personal contribution of the applicant, approval of the dissertation results, and the structure and scope of the work.

The **Chapter 1** is devoted to the classification standards of waste batteries, including classification by electrolyte type, working properties, positive and negative electrode materials, etc. The characteristics, applications and chemical reaction mechanisms of common batteries (such as zinc, alkaline, lithium, silver oxide, nickel-cadmium, nickel-hydrogen, and lithium-ion batteries) are analyzed. The specific hazards of waste batteries to the environment and humans are discussed, including heavy metal pollution and health risks. Improving the recycling system through legislation, promoting green design, strengthening technology research and development and public education are important ways to achieve the harmlessness and resource utilization of waste batteries. The composition of waste batteries is also discussed, pointing out that they contain heavy metals and acid-base electrolytes. If these substances are not handled properly, they cause long-term pollution of soil, water bodies and atmosphere, and endanger human health through the food chain. The study compares the content of typical elements in various batteries through tabular data, and analyzes the main components and environmental risks of lead-

acid batteries, lithium-ion batteries and nickel-cadmium batteries. In terms of legislative management, the study compares the legal systems and practical experience of Japan, the United States, Germany and other countries in the recycling and treatment of waste batteries, pointing out that China's current laws have strong principles but insufficient operability, unclear responsibilities of law enforcement departments, and lack of policy support. Foreign experience shows that a sound legal guarantee system, centralized management, public participation and clear subject responsibilities are the key to effective management of waste batteries.

The **chapter 2** examines the methods of waste battery management. A systematic analysis of the storage, collection, logistics system optimization and classification of waste batteries is carried out to propose a waste battery management system that conforms to China's national conditions. The storage requirements and methods of waste batteries are discussed in detail. For different types of waste batteries, corresponding storage facilities and safety protection measures are suggested. For example, lead-acid batteries need to be equipped with acid-proof ground isolation layers and wastewater collection systems, while lithium-ion batteries need to be equipped with explosion-proof facilities due to their explosion risks. In addition, international and domestic regulations must be followed during transportation to ensure sealed packaging and professional transportation to prevent leakage and environmental pollution. The current status and problems of China's waste battery collection system are analyzed. At present, it mainly relies on private recycling organizations, but the logistics system is imperfect, resulting in low recycling efficiency. By comparing the third-party logistics model in developed countries and China's electronic waste recycling system, it is proposed that the existing logistics resources can be used to design a low-cost, standardized waste battery recycling network. The study pointed out that it is difficult to implement paid recycling and trade-in strategies in China. It is recommended to combine waste battery recycling with convenient life services to enhance public participation. To optimize waste battery collection and treatment system, it is necessary to start from multiple dimensions of technology, industry, policy and international cooperation.

In terms of technology, a general intelligent disassembly and selective separation technology is needed to be developed. In terms of policy, a dynamic price adjustment mechanism and standardize market recycling channels should be established. Besides, it is recommended to strengthen public education, improve recycling facilities, promote reusable batteries, and strengthen supervision through laws and regulations.

In the **Chapter 3**, the resource recovery potential of waste batteries was evaluated, focusing on the analysis of waste battery generation, recycling status and metal resource value. Research shows that waste batteries, as an important renewable secondary resource, contain a large amount of valuable metals, such as cobalt, nickel, lead, lithium, etc. Their recycling can not only alleviate environmental pollution, but also realize the recycling of resources. Waste battery flows in China have been analyzed. China, as the world's largest battery producer and consumer, account for 57% of the total global waste battery generation. This study uses a quantitative analysis method, combined with China's battery production, sales, and import and export data (2014-2023), the data comes from the United Nations Commodity Trade Database and the China Battery Association report. The Weibull life distribution model is used to estimate the amount of waste batteries generated in China, and the calculation method is also based on the average life and recycling rate of batteries. According to our calculations, waste lithium batteries and lead-acid batteries are the main contributors to the growth of waste battery production, accounting for 99% of China's approximately 10.5 million tons of waste battery production. According to the Weibull life distribution model, the generation of waste batteries in China shows a significant upward trend, especially lithium-ion batteries and lead-acid batteries. The metal resources in waste batteries have important economic value. For example, cadmium and nickel in nickel-cadmium batteries, cobalt and lithium in lithium-ion batteries, and lead in lead-acid batteries can be recycled and reused to reduce dependence on primary minerals, reduce energy consumption and environmental pollution. The resource potential of metals in waste batteries in China was estimated. The study also pointed out that the

technical challenges and cost issues of waste battery recycling need to be addressed urgently, and policies, regulations and recycling systems need to be improved to increase the recycling rate. Overall, the resource recycling potential of waste batteries is huge, but its effective utilization needs to be combined with technological progress, policy support and economic incentives to achieve sustainable development of the environment and resources.

The **Chapter 4** analyzes the current status of waste battery recycling technology, focusing on the environmental impact of recycling cathode materials from waste lithium-ion batteries. By analyzing the composition of lithium-ion batteries, it assesses which components may pose environmental hazards. The sources of air, water, noise, solid waste, and toxic chemicals generated during the recycling process are also discussed. Furthermore, this chapter analyzes waste battery treatment methods, including pyrometallurgical, hydrometallurgical, and biological methods. Additionally, the recommendations are developed for the optimization of waste battery management in China.

Keywords: battery, pollution, environmental protection technology, resource recovery, waste battery management, recycling.

List of publications of the applicant

Publications in which the main scientific results of the dissertation are published:

[1] **Sun, X.**, & Ishchenko, V. (2025). Optimization of the collection system for waste batteries. *Environmental Safety and Natural Resources, 54*(2), 23–33. https://doi.org/10.32347/2411-4049.2025.2.23-33

[2] **Xiaodong, S.**, Ishchenko, V., & Polyvanyi, S. (2025). Environmental impact and flows of waste batteries in China. *Environmental Problems, 10* (2), 156-167. https://doi.org/10.23939/ep2025.02.156

[3] **Xiaodong, S.** & Ishchenko, V. (2024). Environmental impact analysis of waste lithium-ion battery cathode recycling. *Journal of Ecological Engineering, 25*(7): 352-358. https://doi.org/10.12911/22998993/189187

[4] **Xiaodong, S.** & Ishchenko, V. (2023). Waste Lithium-Ion Batteries Management in China. *Visnyk of Vinnytsia Politechnical Institute, 2*, 21–27. (in Ukrainian). https://doi.org/10.31649/1997-9266-2023-167-2-21-27

Publications confirming the approval of the dissertation materials:

[5] **Xiaodong, S.** & Ishchenko, V. (2025). Environmental Impact and Flows of Waste Batteries in China. In *Proceedings of the International Conference «European Green Dimensions: Fundamental, Applied, and Industrial Aspects»*, June 5−7, 2025 (p. 91). PMBSNU, Mykolaiv.

[6] **Xiaodong, S.** & Ishchenko, V. (2024). Analysis of current situation on recovery of used lithium-ion batteries in China. In *Proceedings of IX International Congress of Ecologists*, September 25–27, 2024 (pp. 84-55). Vinnytsia, VNTU.

[7] **Xiaodong, S.** & Ishchenko, V. (2024). Processing of waste lithium-ion battery cathode. In *Proceedings of LIII Conference of Vinnytsia National Technical University*, June 20–22, 2024 (pp. 1653-1654). Vinnytsia, VNTU.

[8] Ishchenko, V., **Xiaodong, S.**, Hlavatska, L., & Gritsuk, I. (2023). Hazardous Waste Generation and Management: a Case Study of Ukraine. In *Proceedings of International Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction*, October 8-11, 2023. Thessaloniki, Greece.

[9] **Xiaodong, S.** & Ishchenko, V. (2023). Study on waste batteries storage. In *Proceedings of International Conference "Energy efficiency in economies of Ukraine"*, November 21–23, 2023 (pp. 433-434). Vinnytsia, VNTU.

[10] **Xiaodong, S.** & Ishchenko, V. (2022). Waste batteries generation in China. In *Proceedings of All-Ukrainian Conference "Environmentally sustainable development of urban systems"*, November 2–3, 2022 (pp. 73-75). Kharkiv, BKNU.

CONTENT

INTRODUCTION

Justification of the choice of research topic. Recently, the issue of waste management has become very crucial due to the use of a large number of materials containing components harmful to the environment and human health. One such component is batteries, which are not collected separately in most countries and easily enter the environment together with household waste. The basis for the selection of the research topic is that with the rapid development of the global economy and the continuous improvement of people's living standards, batteries have become an indispensable necessity in modern life. The widespread use of batteries (household batteries and accumulators, car batteries) has allowed not only to improve the life quality, but also led to negative consequences for the environment and human health. This is associated with ineffective management of waste batteries. The content of waste batteries in household waste is known to be in the range of 0.02–0.06% and continues to grow. Waste batteries contain harmful substances such as heavy metals, acid-base electrolytes, etc.

Despite the fact that waste batteries contain both toxic components and valuable resources (primarily metals), they still end up in landfills. This leads to significant environmental consequences. Harmful substances contained in waste batteries are dangerous and toxic for human, and easily enter the environment while polluting the soil, water and air.

The appropriate disposal of waste batteries is not a sufficient solution, and this issue will become worse over time. Prevention and reduction of waste batteries generation, their reuse, recycling of resources require appropriate urgent solutions, in particular, the development of recycling technologies for environmentally sound management of waste batteries.

As a major battery producer and consumer, China is particularly prominent in the recycling and treatment of waste batteries. At present, China's waste battery recycling system is still imperfect, and the relevant laws and regulations are scattered and lack operability, resulting in a large number of waste batteries not being effectively treated, and resource waste and environmental pollution coexist. This study analyzes the classification, composition and environmental hazards of waste batteries, explores the legislative status and experience of waste battery management, and suggests recommendations on improving the legal system for waste battery recycling and treatment in combination with China's national conditions, providing a theoretical basis and practical path for achieving the coordinated development of resource recycling and environmental protection.

Goal and tasks of the research.

The goal of this research is to justify the environmentally friendly management of waste batteries and to study their resource potential and environmental impact. To achieve the goal, the following tasks were solved:

- analysis of battery types and composition, as well as legislation for waste batteries management;
- analysis of environmental pollution from waste batteries;
- analysis and optimization of the existing systems of collection and disposal of waste batteries;
- justification of the methods of waste batteries management for China;
- preparation of recommendations for the separate collection of waste batteries;
- estimation of generation and resource potential of waste batteries;
- optimization of the methods of processing and disposal of waste batteries.

Object of the research: the process of waste batteries management.

Subject of the research: environmentally friendly mechanisms of waste batteries management, chemical composition of its components, and environmental impact.

Research methods.

When conducting research, we adopted a comprehensive approach, including literature analysis, classification and comparative research, systematic analysis and summary. Based on data statistics and table summary, a data model for waste battery recycling was established. The research method focuses on the combination of theory and practice, and is both scientific and practical. The current status and problems of waste battery management were evaluated, and finally legislative suggestions and waste battery recycling optimization plans that are in line with China's national conditions were proposed. The research methods are diverse and targeted, providing comprehensive analysis and feasible suggestions for waste battery management.

Scientific novelty

For the first time:

- the scientific principles for the environmentally safe management of waste batteries in China have been substantiated, which makes it possible to reduce their negative impact on the environment and humans;

- the composition and resource potential of waste batteries in household waste has been defined, which will allow for a comprehensive assessment of their impact on the environment and humans, as well as for economic justification of waste battery recycling;

- the Weibull distribution model was applied for waste battery lifecycle assessment, which allows the estimation of the amount of waste batteries in household waste.

Further developed:

- conceptual approaches to assessing the environmental impact of waste batteries under different management methods that differ in that the material flow analysis and lifecycle assessment are applied, thereby ensuring reliable prediction of environmental consequences.

Improved:

- the waste battery management system based on China's waste processing technologies, which differs from existing approaches in that the principles of waste reduction, separate collection, sorting, and further processing are applied, thereby enabling rational resource use.

Practical significance of the results:

1. The recommendations have been developed to optimize the collection and disposal system and logistics for waste battery management.

2. Material flow analysis was done for waste batteries in China.

3. The component composition of waste batteries generated in China has been studied.

4. Amounts of waste batteries generation in China has been assessed.

5. Environmental impact analysis of waste batteries has been provided for the case study of lithium-ion battery.

The applicant's personal contribution

All the main results of the dissertation work were obtained independently. In the co-authored publications, the applicant contributed the following:

- the recommendations on separate collection of different types of waste batteries were also developed;
- waste batteries collection system has been optimised based on the suggestions for developing countries, while providing efficient waste management;
- waste battery generation in China was calculated;
- composition of lithium-ion battery was analyzed in order to estimate which components are potentially dangerous to the environment;
- sources of air, water, noise pollution, solid waste, and toxic chemicals generated in the recycling process were identified.
- the current state and existing problems of recycling and disposal of the waste lithium-ion batteries in China was analyzed from the point of view of input materials for batteries, production processes, recycling and disposal technologies;
- environmental impact of waste batteries was assessed;
- the recycling system for waste batteries in China was analyzed;
- environmental impact pathways during the recycling process of waste lithium-ion battery cathode were analyzed;
- the data on hazardous waste generation were collected;

- the requirements have been proposed for different storage methods in terms of average storage capacity per unit area, maximum storage capacity in a single storage area, storage area spacing, channel width, wall spacing width, etc.;
- waste batteries generation in China was estimated.

Approval of the results

The key results of the work were presented and discussed at the following scientific conferences:

- International Conference «European Green Dimensions: Fundamental, Applied, and Industrial Aspects», June 5−7, 2025, Mykolaiv, Ukraine;
- IX International Congress of Ecologists, September 25–27, 2024, Vinnytsia, Ukraine;
- LIII Conference of Vinnytsia National Technical University, June 20–22, 2024, Vinnytsia, Ukraine;
- International Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, October 8-11, 2023, Thessaloniki, Greece;
- International Conference "Energy efficiency in economies of Ukraine", November 21–23, 2023, Vinnytsia, Ukraine;
- All-Ukrainian Conference "Environmentally sustainable development of urban systems", November 2–3, 2022, Kharkiv, Ukraine.

Connection of the work with scientific programs, plans, topics, and grants

The dissertation was elaborated according to research projects of the Department of Ecology, Chemistry and Environmental Protection Technologies at Vinnytsia National Technical University: «Assessment of technogenic environmental impact of hazardous waste and resource potential for their recycling» (State project No.0123U101999); «Development of the recommendations on the determining the rates of municipal solid waste collection in Turbiv municipality (project No.0123U103253), «Improving the management system for waste electrical and electronic equipment (project No.16K8)».

Publications

The main contents of the thesis have been published in 10 scientific works, including 2 articles in peer-reviewed journals from Scopus/Web of Science database, 2 articles in Ukrainian journals of category B, 6 conference papers.

Structure and scope of the work.

The paper consists of an introduction, four chapters, a conclusion, a reference list (194 items), and 3 annexes. The total volume of the dissertation is 199 pages of printed text, containing 43 figures and 29 tables.

CHAPTER 1

ANALYSIS OF WASTE BATTERIES

1.1 Classification of waste batteries

Waste batteries can be classified into three categories according to different classification standards (Fig. 1.1).

1. According to the type of battery electrolyte:

- alkaline battery, the electrolyte of this battery is mainly based on potassium hydroxide solution; examples: alkaline zinc-manganese battery (commonly known as alkaline manganese battery or alkaline battery), nickel-cadmium battery, nickel metal hydride battery, etc.
- acid battery, this battery contains mainly sulfuric acid aqueous solution as the medium; examples: zinc-manganese dry battery (some consumers also called acid battery), seawater battery.
- organic battery, this kind of battery mainly uses organic solution as the medium; examples: lithium battery, lithium-ion battery, etc.

2. According to the operating nature and storage mode [1]:

- primary battery, also known as dry battery, this battery is characterized by discharge and can not be recharged; examples: zinc-manganese dry battery, lithium battery, etc.
- secondary battery, also known as rechargeable battery, this battery is characterized by the fact that charge and discharge cycles can be repeated many times; examples: nickel metal hydride battery, lithium battery, nickel-cadmium battery, lead-acid battery.
- fuel cell, also known as continuous battery, this kind of battery is characterized by the active material continuously injected into the battery, so that it continuously discharges the battery; examples: hydrogen and oxygen fuel cells.

- reserve battery, also known as activated battery, in this battery storage is not directly in contact with the electrolyte, until the battery is used, the electrolyte is not added; examples: magnesium silver battery, zinc silver battery, etc.

3. According to the positive and negative electrode materials used in the battery [2]:

- zinc series battery; examples: zinc-manganese battery, zinc silver battery, etc.
- nickel series battery; examples: nickel-cadmium battery, nickel metal hydrid battery, etc.
- lead battery; examples: lead-acid batteries.
- lithium battery; examples: lithium-ion battery, lithium manganese battery.
- manganese dioxide battery series; examples: zinc-manganese battery, alkali manganese battery, etc.
- air (oxygen) series battery; examples: zinc air batteries, etc.

Battery Classification is shown in Figure 1.1.

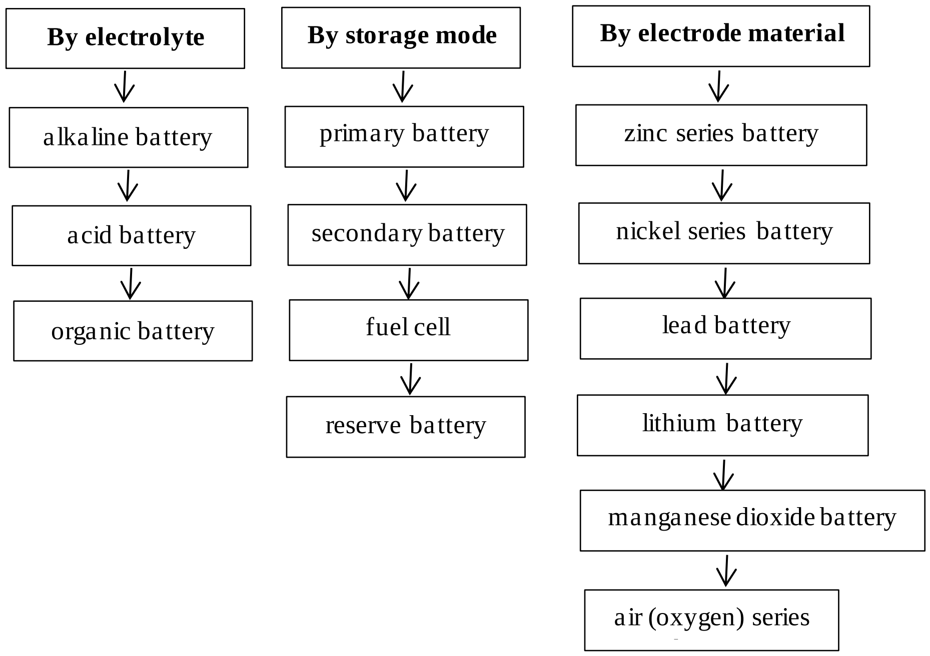

Figure 1.1 – Battery classification

Below is a detailed introduction to several types of batteries most widely used in daily life.

Zinc battery

Zinc-carbon battery is a very common type of dry battery that had been commercialized as early as 1900. There are several types of zinc-carbon batteries in terms of size, shape, and service life. If the strength of its function is not taken into account, zinc-carbon battery is a safe and economical battery with a wide range of raw materials.

A zinc-carbon (Zn-C) battery is an electrochemical system with zinc as the anode (which sends electrons into the circuit, hence the name negative electrode) and a mixture of manganese dioxide powder and other materials as the cathode (positive electrode). An electrolyte solution of ammonium chloride and zinc chloride serves as the electrolyte. Electrons are transferred from the external circuit back to the positive electrode [3].

If the current used is very small and the usage time is not long, then zinc-carbon batteries are the most efficient. If a large current is used and the battery is used for a long time, the hydrogen gas generated by the chemical reaction to release electrical energy will accumulate on the carbon rod, hindering its ability to conduct electrons and thus reducing the efficiency of the battery.

There are many different types of carbon-based batteries, with variations in the electrolyte mixture and carbon rod size. Batteries for radio applications contain a high proportion of electrochemically active materials. These batteries have a higher capacity and therefore last longer even at low currents [4].

The service life of zinc-carbon batteries is closely related to their usage. When the required current decreases, the chemical efficiency of the battery will be improved. Replacing one battery with two parallel batteries can increase its service life by three times. The estimated capacity of zinc-carbon battery's service life is closely related to the size of the battery and the current used. Other factors affecting battery's service life include ambient temperature and shelf life. At a room temperature of 20°C, the capacity of the battery decreases by about half, while it almost drops to zero at –20°C. If a special electrolyte is added to the battery, it will slightly improve the low-temperature function. If the battery is stored in an environment with a temperature of 70°C for a long time, its service life will be shortened by about half. If the battery is stored at a higher temperature, its deterioration rate will be faster.

Typical zinc-carbon battery models and performance are shown in the Table 1.1 [5].

Table 1.1. Typical zinc-carbon battery models and performance

Battery name	**Battery size**	**Chinese model**	**Current, mA**	**Capacity, A·hr**	**Energy density, W·hr/kg**
Zn-C R20	D	No.1	10	4.2	25
			50	4.4	27
			100	3.8	23
Zn-C R6	AA	No.5	3	0.88	29
			15	0.50	17
			30	0.37	12
Zn-C R03	AAA	No.7	2	0.45	30
			10	0.37	25
			20	0.28	19

Alkaline battery

This is a primary battery with zinc as the negative electrode, manganese dioxide as the positive electrode, and potassium hydroxide solution as the electrolyte. In this battery, electrolyte does not participate in chemical reactions. Its capacity is 3–7 times that of a regular battery of the same size, and it can continuously discharge high currents. It has good anti-leakage performance and is the best zinc-manganese battery. It is represented by the letter "LR" followed by the number indicating the battery model.

The alkaline manganese battery, which first appeared in German patents, is a type of wet battery. In 1912, another type of dry battery obtained a German patent. It was not until 1949 that the "Crown" type battery of Yuehua Company in the United States was put into the market. After the successful development of cylindrical structures in 1960, alkaline manganese batteries were able to develop rapidly.

Alkaline zinc-manganese batteries are mainly used as portable power sources. Ordinary zinc-manganese batteries (commonly referred to as zinc-carbon batteries) have poor high-current continuous operating ability, while alkaline zinc-manganese batteries can operate continuously with high current, making them most suitable for equipment that requires high current power supply, such as cameras, radio-controlled aircraft and sea models, electric tools, electric toys, radio recorders, etc. [6].

It has high capacity and low internal resistance, and can provide smoother operating voltage and longer operating time than ordinary zinc-manganese batteries. It is suitable as a supporting power supply for devices such as remote controllers, laptops, testing instruments, radios, handheld walkie talkies, etc.

In addition, rechargeable alkaline zinc-manganese battery not only has a good charge retention ability, but also the active materials of the battery can be recycled, thus saving resources, protecting the environment, reducing the cost of use[7]. Further improving the performance–price ratio (cost efficiency ratio) of alkaline zinc-manganese battery, without memory effect, makes alkaline zinc-manganese battery more competitive and more widely used.

In military equipment, alkaline zinc-manganese batteries have been used as supporting equipment due to their convenient use, excellent performance, and long shelf life. Especially in military communication equipment, it is widely used as a supporting power source for tactical radios, field telephones, terminal equipment, instruments. Under field conditions, there is no mains power, and charging is extremely difficult relying solely on battery power [8]. The radio station is working 24 hours a day and consumes a lot of power when sending messages. To ensure uninterrupted communication, it is necessary to equip batteries that can provide long operating hours and have good continuous operating ability. Alkaline zinc-manganese batteries can better meet these requirements. Therefore, a large number of primary batteries used for tactical radio stations are still alkaline zinc-manganese batteries. High quality alkaline zinc-manganese batteries have a shelf life over 5 years, which is difficult for other batteries to achieve. That makes them excellent to use in military as reserve batteries.

In alkaline battery, electrode reaction equations are as follows .

Button cell

Cathode reaction:

$$2MnO_2 + 2H_2O + 2e^- \rightarrow 2MnOOH + 2OH^- \qquad (1.1)$$

Anode reaction:

$$Zn + 2OH^- + 2e^- \rightarrow Zn(OH)_2 \qquad (1.2)$$

Total reaction:

$$Zn + 2MnO_2 + H_2O \rightarrow Zn(OH)_2 + Mn_2O_3 \qquad (1.3)$$

General battery

Cathode reaction:

$$MnO_2 + H_2O + e^- \rightarrow MnOOH + OH^-, \qquad (1.4)$$

$$MnOOH + H_2O + e^- \rightarrow Mn(OH)_2 + OH^- \qquad (1.5)$$

Anode reaction:

$$Zn + 2OH^- \rightarrow Zn(OH)_2 + 2e^-, \qquad (1.6)$$

$$Zn(OH)_2 + 2OH^- \rightarrow [Zn(OH)_4]^{2-} \qquad (1.7)$$

Total reaction:

$$Zn + MnO_2 + 2H_2O + 2OH^- \rightarrow Mn(OH)_2 + [Zn(OH)_4]^{2-} \qquad (1.8)$$

Classification of alkaline batteries

1. Cylindrical battery structure

Alkaline zinc-manganese batteries have a representative cylindrical structure, which is exactly opposite to the structural layout of cylindrical ordinary zinc-manganese batteries. In alkaline zinc-manganese batteries, the circular positive electrode is adjacent to the inner wall of the container steel cylinder, and the negative electrode is located in the middle of the positive electrode. There is a nail shaped negative current collector, which is welded to the top cover as the negative electrode of the battery, and the steel cylinder is the positive electrode.

The specifications of commonly used cylindrical alkaline manganese batteries are shown in the Table 1.2 [9].

Table 1.2. Types of alkaline battery

Alkaline battery Chinese model	International model of alkaline battery	English code	Diameter/Height, mm
No.1	LR20	D	34.2/61.5
No.2	LR14	C	26.2/50.0
No.5	LR6	AA	14.5/50.5
No.7	LR03	AAA	10.5/44.5

2. Roll type battery structure

Its structure uses a metal mesh as the carrier, pressing the positive and negative electrodes into thin ribbons, and then folding them together with a diaphragm to form a spiral (capacitive) structure of the battery. This structure is characterized by a large positive and negative electrode area, low overpotential, and can achieve higher capacity during low temperature and high current discharge.

3. Square single cell (button) battery structure

The positive and negative electrodes of a square single cell battery adopt a pole group structure, and the positive and negative electrodes are pressed into square thin plates, with a metal current collector network sandwiched between the plates.

The charge of button type alkaline manganese dioxide batteries is approximately 55% of that of zinc-silver button type batteries of the same size. Commonly used models include LR41, LR43, LR44, LR54, and LR55, with the same dimensions and specifications as corresponding zinc-silver button batteries [9].

Lithium battery

Lithium batteries generally use manganese dioxide as the positive electrode material, lithium or its alloy as the negative electrode material, and use non-aqueous electrolyte solutions.

Discharge reaction is as follows:

$$Li + MnO_2 \rightarrow LiMnO_2 \quad (1.9)$$

Lithium batteries were first used in cardiac pacemakers. The advantages of lithium battery, such as extremely low self-discharge rate and gentle discharge voltage, enable the pacemaker implanted in the human body to operate for a long time without recharging [10]. Lithium batteries generally have a nominal voltage higher than 3 volts, making them more suitable for use as integrated circuit power supplies. Lithium batteries are widely used in calculators, digital cameras, and watches.

The lithium battery model naming standard applies to various types of lithium primary batteries and lithium secondary batteries with lithium as the negative electrode, compound as the positive electrode, and electrolyte [11].

The system letter names of the single lithium battery model are presented in the Table 1.3.

Table 1.3. Single lithium battery models

Letter code	**Positive and negative electrode materials**	**Voltage**	**Letter code**	**Positive electrode materials**	**Voltage**
B	Lithium fluoride carbon	3.0	I	Lithium iodine	2.8
C	Lithium manganese dioxide	3.0	K	Lithium copper sulfide	2.1
D	Lithium bismuth trioxide	1.5	Q	Lithium titanium sulfide	2.1
E	Lithium thionyl chloride	3.6	U	Lithium chromium oxide	3.0
F	Lithium iron sulfide	1.5 or 2.2	V	Lithium thirteen oxide hexavanadium	2.4
G	Lithium copper oxide	1.5	W	Lithium sulfur dioxide	2.8
H	Lithium lead bismuth oxide	1.5	Y	Lithium molybdenum dioxide	1.9

Lithium manganese dioxide battery, which belongs to the lithium manganese dioxide structure, uses manganese dioxide with very stable chemical properties as the positive electrode material, uses lithium metal as the negative electrode material, and uses ethylene glycol dimethyl ether, propylene carbonate and lithium chlorate as the electrolyte of lithium battery, which is shaped like a button, referred to as button lithium battery or lithium manganese button battery [12]. Its naming (e.g., for CR2032 type) is based on IEC standards. Among them, *C* represents a chemical battery system with lithium as the negative electrode and manganese dioxide as the positive electrode, *R* or *F* represents the shape of the battery as cylinder or square; *20* represents a diameter of 20 mm for the battery, and *32* represents a height of 3.2 mm for the battery.

With the requirements of new industries, there are also special improvements to batteries, whose capacity will be very different, mainly to improve their high current output capacity, such as those used for flashing lights or RF products [13]. The shelf life of typical lithium battery of CR2032 type is usually 5 years. If the usage environment is ideal (sealed, room temperature, no moisture interference, etc.), its lifespan will be further extended, up to 8 years, or even 10 years.

Silver-oxide battery

Silver-oxide battery, also known as silver-zinc battery or zinc-silver oxide battery, is a type of battery that uses silver oxide as the positive electrode, zinc as the negative electrode, and alkaline solution as the electrolyte.

Silver-oxide batteries are disposable batteries. The voltage of silver-oxide battery is relatively high – 1.55V, higher than 1.5V of alkaline battery and 1.35V of mercury battery. During the discharge process, the curve of voltage versus discharge time is flat, which means it can maintain a voltage close to the same for a long time. Thus is unlike alkaline batteries, where the voltage gradually decreases as the battery level decreases. Therefore, it is suitable for applications that require miniaturization. Its energy density per unit volume is high, and its capacity is almost twice that of similar alkaline button cell.

Silver-oxide battery is durable for long-term storage, with almost no degradation over time, making it suitable for devices that can be driven for a long time, such as watches, or devices that can be stored for a long time.

If the silver oxide battery is stored for a long time, the terminal part may be in a powder spraying state. This is a phenomenon called salinization, when a small amount of alkaline liquid evaporates and crystallizes. If it is cleaned with a dry cloth, it can be reused, but due to repeated occurrences, it may corrode the equipment.

However, because of the high cost of silver, it is generally used as a button cell, or in some special cases with high requirements. Most of the products are button shaped, and because of their excellent characteristics (such as long-term storage), they are also used for special purposes. It is widely used in small electronic devices, such as hearing aids, electronic watches, torpedoes, or submarines.

The composition of this battery varies with different applications. Silver-oxide batteries used for hearing aids (requiring low leakage current and long service life) have a positive electrode made of depolarized oxides: silver oxide and manganese dioxide, and a negative electrode made of zinc. Its electrolyte is strongly alkaline potassium hydroxide to enhance its energy density. And for silver-oxide batteries used in electronic watches (with very low discharge current and extremely long service life), the electrolyte is sodium hydroxide with better stability.

The name of common models of silver oxide batteries usually start with SR, which is a standard code developed by IEC, where *S* represents silver oxide batteries and *R* represents circular (including cylindrical) types [14].

Cathode reaction:

$$Ag_2O + H_2O + 2e^- \rightarrow 2Ag + 2OH^- \qquad (1.10)$$

Anode reaction:

$$Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^- \qquad (1.11)$$

Total electrode reaction equation:

$$Zn + Ag_2O \rightarrow ZnO + 2Ag \qquad (1.12)$$

Rechargeable battery

Ordinary batteries are disposable, while rechargeable batteries can be charged and reused. Rechargeable batteries vary in production materials and processes, including lead-acid batteries, nickel-cadmium batteries, nickel-iron batteries, nickel-metal hydride batteries, and lithium-ion batteries. Its advantage is long lifecycle, they can fully charge and discharge more than 200 times, and some rechargeable batteries have a higher load capacity than most of disposable batteries.

According to the IEC standard, the identification of nickel-cadmium and nickel-metal hydride batteries consists of five parts:

(1) Battery type: *KR* identify nickel cadmium battery, *HF* represents nickel hydrogen battery *HR* represents nickel-metal hydride battery.

(2) Battery size information includes the diameter, height, width, and thickness of circular batteries, separated by slashes in millimeters.

(3) The symbol for high-temperature batteries is represented by T.

(4) *HB* represents the connecting piece used for parallel series connection of the battery. For example, HF18/07/49 represents a square nickel hydrogen battery of 18mm width, a thickness of 7 mm, and a height of 49 mm.

Typical rechargeable battery characteristics are shown [15] in the Table 1.4.

Table 1.4. Typical rechargeable battery characteristics

Battery type	**Ni-Cd**	**Ni-MH**	**Li-ion**	**Lithium polymer**
Voltage, V	1.2	1.2	3.6	3.7
Service life, times	500	1000	500	500
Discharge temperature, ℃	-20℃～60℃	-10℃～45℃	-20℃～60℃	-20℃～60℃
Charging temperature, ℃	0℃～45℃	-10℃～45℃	0℃～45℃	0℃～45℃

Nickel-cadmium battery

The active substance on the positive plate of a nickel-cadmium battery is nickel oxide powder, while the active substance on the negative plate is cadmium oxide powder. The active substance is wrapped in perforated steel strips, and after pressure forming, it becomes the positive and negative plates of the battery. The plates are made by methods such as slurry pulling, rolling, sintering, forming or pasting, drying, and pressing. Materials such as polyamide non-woven fabric are used as isolation layer. As an electrolyte, potassium hydroxide solution is usually used. The electrodes are wound or stacked and assembled in plastic or nickel-plated steel shells.

There are various types of cadmium nickel batteries, including cylindrical sealed (KR), button sealed (KB), and square sealed (KC). It is the earliest type of battery used in mobile phones, medical devices, and other devices. It has the characteristics of wide temperature range, long cycle and storage life, and can discharge at a large current. However, it has a "memory" effect and often leads to a decrease in electrical performance due to regular incorrect use [16]. The battery is not fully discharged before charging, which will lead to the reduction of the battery capacity over time. In the process of charging and discharging the battery (the discharge is more obvious), a few small bubbles will be generated on the battery plate. Over time, these bubbles reduce the area of the battery plate and indirectly affect the battery capacity. Of course, we can reduce the "memory effect" by mastering reasonable charging and discharging methods. Besides, cadmium is toxic, so nickel-cadmium batteries are not conducive to the environmental protection. Numerous shortcomings have led to the basic elimination of nickel-cadmium batteries from the application range of digital device batteries.

The hydroxide ions (OH^-) in cadmium (Cd) and sodium hydroxide (NaOH) located at the negative electrode are converted into cadmium hydroxide, which adheres to the anode and also emits electrons. Electrons travel along the wire to the cathode, reacting with nickel dioxide from the cathode and water in the sodium hydroxide solution to form nickel hydroxide and hydroxide ions. Nickel hydroxide will adhere to the anode, and hydroxide ions will return to the sodium hydroxide solution. Therefore, the concentration of the sodium hydroxide solution will not decrease over time.

The active substance on the positive electrode plate of a nickel cadmium battery is composed of nickel oxide powder and graphite powder. Graphite does not participate in chemical reactions and its main function is to enhance conductivity. The active substance on the negative electrode plate is composed of cadmium oxide powder and iron oxide powder. The function of iron oxide powder is to provide cadmium oxide powder with high diffusion, prevent agglomeration, and increase the capacity of the electrode plate. Compared with other batteries, the self-discharge rate of Ni-Cd batteries (that is, the rate at which the batteries lose charge when not in use) is moderate. During use, if the Ni-Cd battery is not fully discharged, and then charged again, the next time it is discharged, you will not be able to fully charge the battery [17].

Nickel-metal hydride battery

The positive plate material of nickel-metal hydride battery is nickel oxide powder, the negative plate material is hydrogen absorbing alloy (e.g., intermetallic compounds such as $LaNi_5$ and FeTi), and the electrolyte is potassium hydroxide solution.

Nickel-metal hydride batteries are divided into high-voltage and low-voltage batteries. The positive active material of NiMH battery is $Ni(OH)_2$ (called NiO electrode), the negative active material is metal hydride, also called hydrogen storage alloy (called hydrogen storage electrode), and the electrolyte is 6 mol/L potassium hydroxide solution. A high-pressure hydrogen is stored in thin-walled containers.

The process modes of active substances to form electrode plates mainly include sintering, slurry drawing, foam, fiber and infiltrating. The electrodes prepared by different processes have great differences in capacity and large current discharge performance. In general, the battery is produced according to the processes with different use conditions. Civil batteries such as communication batteries mostly use slurry cathode and foam nickel anode to form batteries. The chemical reactions of charge and discharge are as follows.

Positive electrode:

$$Ni(OH)_2 + OH^- \rightarrow NiOOH + H_2O + e^- \tag{1.13}$$

Negative electrode:

$$Me + H_2O + e^- \rightarrow MeH_{ab} + OH^- \tag{1.14}$$

Total reaction:

$$Ni(OH)_2 + Me \rightarrow NiOOH + MeH \tag{1.15}$$

Note: Me is metal alloy; H_{ab} is adsorbed hydrogen.

During charging, $Ni(OH)_2$ and OH^- of the positive electrode react to generate NiOOH and H_2O, while releasing e^- to generate MeH and OH^- together. The total reaction is $Ni(OH)_2$ and Me to generate NiOOH, and the metal alloy stores hydrogen. On the contrary, during discharge, MeH_{ab} releases H^+, while H^+ and OH^- generate H_2O and e^-, while NiOOH, H_2O and e^- regenerate $Ni(OH)_2$ and OH^- [18].

Li-ion battery

According to the IEC61960 standard, the identification of secondary lithium batteries is as follows [19]:

(1) The battery identification consists of 3 letters followed by 5 numbers (for cylindrical type) or 6 numbers (for square type).

(2) The first letter represents the negative electrode material of the battery. *I* represents lithium ions built-in, *L* represents lithium electrodes or lithium alloy electrodes.

(3) The second letter represents the positive electrode material of the battery, *C* stands for cobalt electrode, *N* for nickel electrode, *M* for manganese electrode, *V* for vanadium electrode.

(4) The third letter represents the shape of the battery, *R* represents a cylindrical battery, and *L* represents a square battery.

(5) Five numbers of cylindrical battery represent the diameter and height of the battery. The diameter is measured in millimeters and the height is measured in tenths of a millimeter. When any dimension of diameter or height is greater than or equal to 100 mm, a diagonal line should be added between the two dimensions. Six numbers of square battery represent the thickness, width, and height of the battery (in millimeters).

Like all chemical batteries, lithium-ion batteries are also composed of three parts: positive electrode, negative electrode, and electrolyte. The electrode materials are all lithium ions that can be embedded (inserted)/deembedded (deinserted).

The lithium-ion battery uses $LiCoO_2$ composite metal oxides to form an anode on aluminum plate, and lithium carbon compounds to form a cathode on a copper plate. There are submicron sized microporous polyolefin film separators between the plates, and the electrolyte is an organic solvent.

Table 1.5. Performance of different positive electrode materials [20]

Cathode material	**Average output voltage**	**Energy density**
$LiCoO_2$	3.7 V	140 mA·h/g
Li_2MnO_3	3.7 V	100 mA·h/g
$LiFePO_4$	3.2 V	130 mA·h/g
Li_2FePO_4F	3.6 V	115 mA·h/g

Positive electrode material: There are many optional positive electrode materials, and mainstream products mostly use lithium iron phosphate. The performance of different positive electrode materials [20] is shown in the Table 1.5.

Positive electrode reaction: lithium ions are embedded during discharge, and lithium ions are deembedded during charging.

When charging:

$$LiFePO_4 \rightarrow Li_{1-x}FePO_4 + xLi^+ + xe^- \qquad (1.16)$$

When discharging:

$$Li_{1-x}FePO_4 + xLi^+ + xe^- \rightarrow LiFePO_4 \qquad (1.17)$$

Lithium-ion batteries with lithium cobalt oxide as the positive electrode material are not suitable for high current discharge. Excessive current discharge can reduce the discharge time (resulting in high internal temperature and energy loss) and may cause danger. But lithium iron phosphate cathode material can be charged and discharged at a high current of 20C or even greater (C is the battery capacity, such as C = 800 mA·h, 1C charging rate is the charging current of 800 mA), which is particularly suitable for electric vehicles. Therefore, the maximum discharge current provided by the battery production factory should be less than the maximum discharge current during use. Lithium-ion batteries have certain temperature requirements, and the factory provides charging temperature range, discharge temperature range, and storage temperature range. Overvoltage charging can cause permanent damage to lithium-ion batteries [21].

Negative electrode material: mostly graphite is used. New research shows that titanate may be a better material. Negative electrode reaction: lithium ion insertion during charging, lithium ion detachment during discharge.

When charging:

$$xLi^+ + xe^- + 6C \rightarrow LixC_6 \qquad (1.18)$$

When discharging:

$$LixC_6 \rightarrow xLi^+ + xe^- + 6C \qquad (1.19)$$

Petroleum coke and graphite as anode materials are non-toxic and have sufficient resources. Lithium ion is embedded in carbon, which overcomes the high activity of lithium and solves the safety problems existing in traditional lithium batteries.

Lithium batteries that have not been used for a long time should be stored in a cool and dry place, preferably in a half-charged state (70–80% of full charge). Full charge storage is dangerous and the battery may be damaged, while no charge storage can damage the battery.

Polymer category

Polymer lithium-ion battery is the latest generation of rechargeable lithium-ion battery developed on the basis of liquid lithium-ion battery. It uses conductive material as the positive electrode, carbon material as the negative electrode, electrolyte is composed of solid or gelled organic conductive film, and aluminum plastic film is used as the outer packaging. The electrolyte of polymer lithium-ion batteries is colloidal and does not flow, so there is no leakage problem and it is safer [22].

High storage category

In order to break through the storage neck of traditional lithium batteries, a new iron-carbon storage material that can store more electricity in a very small storage unit is developed. However, the obvious drawback of this material before was the unstable charging cycle, which significantly reduced storage capacity of the battery after multiple charge cycles. To this end, a new synthesis method is used. Researchers mixed several raw materials with a lithium salt and heated them to produce a completely new nanostructured material with carbon nanotubes. This method creates storage cells and conductive circuits on nanoscale materials in one fell swoop.

1.2 Study on composition of waste batteries

The main pollutants contained in batteries include heavy metals and electrolyte solutions such as acids and alkalis [23]. The main heavy metals include mercury, cadmium, lead, nickel, zinc, etc. Mercury, cadmium, and lead are substances that pose significant risks to the environment and human health. Nickel, zinc, and other substances are beneficial within a certain concentration range, but exceeding a certain amount in the environment will cause harm to the human body. Electrolytes such as waste acid and alkali may cause soil acidification or alkalization [24]. Waste batteries containing acid, alkali, and other components of waste electrolyte may cause environmental pollution through heavy metals. This kind of pollution has both immediate and long-term effects. Table 1.6 shows the content of typical elements in various portable batteries, while main components of waste lead-acid batteries [25] are shown in the Table 1.7.

Table 1.6. Typical element content in portable batteries, mg/kg

Element	**Zinc-manganese**	**Alkaline manganese dioxide**	**Nickel-cadmium**	**Mercury oxide battery**	**Zinc silver battery**	**Lithium-ion battery**
As	3-236	2-239				
Cr	69-677	25-1335				1.3-12920
Cu	5-4539	5-6739			40720-47110	
In	3-101	9-100				
Fe	34-307000	50-327300				75-311700
Pb	14-802	16-58				5-37
Mn	120000-414000	28800-460000			13830-226000	30-395000
Hg	3-4790	118-8201		229300-908000	629-20800	
Ni	13-595	12.6-4323	116000-556000		186-30460	17000-41050
Ci	9900-130000					12-5300
K		2560-56700	13684-34824	11960-50350	19270-99350	
Sn	26-665	4-492				
Zn	18000-387000	2090-172500		8140-141000		
Cd			11000-173147	1.4-30		
Na				154-2020	294-2250	
Ag					37590-353600	1-63
Li						12500-77500
S						82-3470
F						96-98000
pH	4.8-6.27	11.9-14.0	12.6-13.5	10.7-13.3	10.8-12.7	4.62-10.17

Table 1.7. Main components of waste lead-acid batteries, %

Pb	S	$PbSO_4$	PbO	Sb	FeO	SiO_2	CaO
5.0	5.0	42.1	38.0	2. 2	0.75	0.88	0.18

The huge consumption of lithium batteries consumes a considerable amount of non-renewable metal resources. The reserves of raw materials such as cobalt and lithium required for the production of lithium-ion batteries are limited. The reserves of materials required for lithium-ion batteries are shown in the Table 1.8 [26].

Table 1.8. Natural reserves of metals needed for lithium-ion battery

Metal	Reserve capacity, ppm	Density, g/cm^3
Cd	0.2	8.64
Co	25	8.9
Pb	12.5	11.34
Li	20	0.53
Hg	0.08	13.55
Mn	950	7.2
Cr	100	7.2
Ni	75	8.9
Zn	70	7.14

Below is the composition of each battery type.

Alkaline manganese battery

Indicative chemical composition (vary depending on battery size and manufacturer, Fig. 1.2):

MnO_2 – 37%; Fe–23%; Zn – 16%; H_2O–9%; KOH–5%; C–4%; brass–2%; others – 4%.

Zinc-carbon battery

Indicative chemical composition (vary according to battery size and manufacturer, Fig. 1.3):

MnO_2–27%; Zn – 23%; H_2O–18%; C – 10%; ZnCl / NH_4Cl – 5%; Fe – 4%; others – 13%.

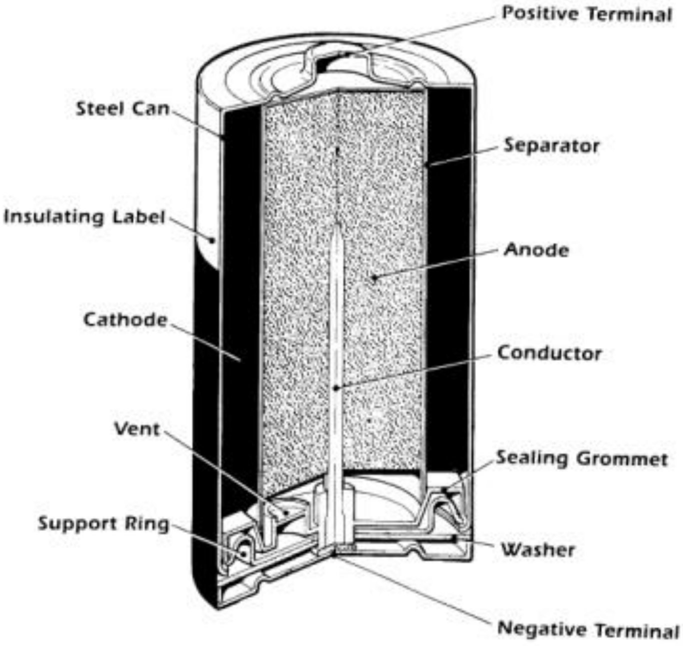

Figure 1.2 – Alkaline manganese battery

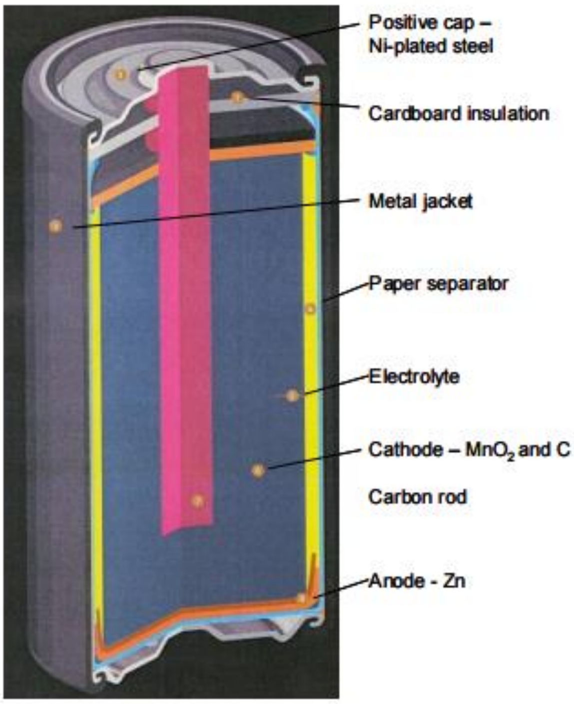

Figure 1.3 – Zinc carbon battery

Lithium manganese dioxide major battery

Indicative chemical composition (vary according to battery size, Fig. 1.4): Fe – 50%; MnO_2 – 30%; plastic – 7%; dimethoxyethane – 6%, Li – 3%; C – 2%; Ni – 2%.

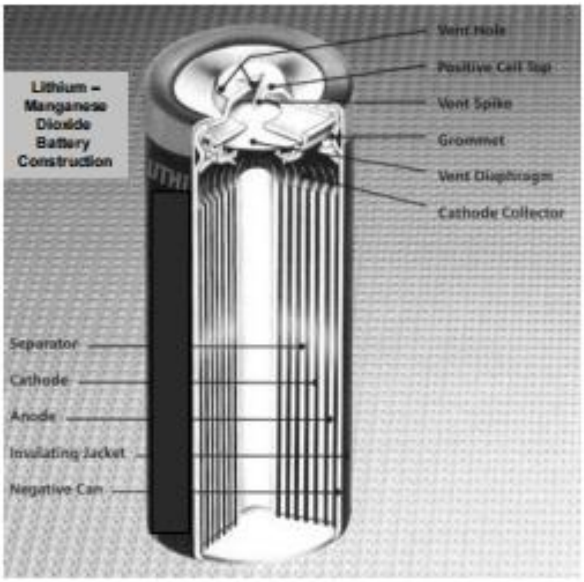

Figure 1.4 – Lithium manganese dioxide major battery

Lithium manganese dioxide button battery

Indicative chemical composition (vary according to battery size, Fig. 1.5): Fe – 50%; MnO_2 – 28%; Cr – 10%; plastic – 3%; Li – 3%; dimethoxyethane – 2%, C – 2%; Ni – 2%.

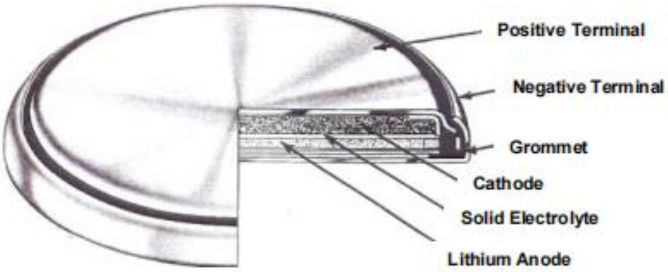

Figure 1.5 – Lithium manganese dioxide button battery

Silver oxide battery

Indicative chemical composition (vary according to battery size, Fig. 1.6): Fe – 42%; Ag_2O – 33%; Zn – 9%; Cu – 4%; MnO_2 – 3%; H_2O – 2%; plastic – 2%; Ni – 2%; KOH – 1%; C – 0.5%; Hg – 0.4%; others – 1,1%.

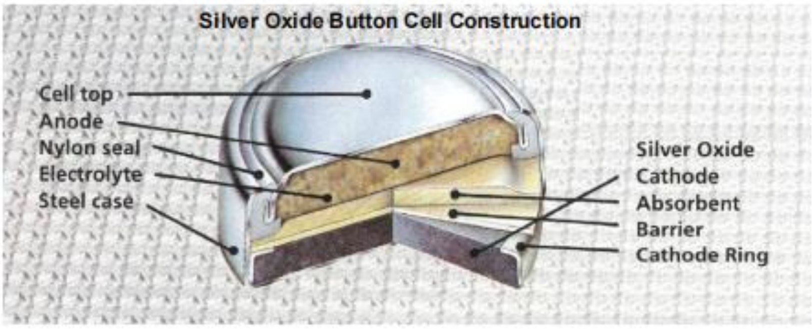

Figure 1.6 – Silver oxide battery

Zinc air battery

Indicative chemical composition (vary according to battery size, Fig. 1.7): Fe – 42%; zinc – 35%; H_2O – 10%; plastic – 4%; KOH – 4%; C – 1%; Hg – 1%; others – 3%.

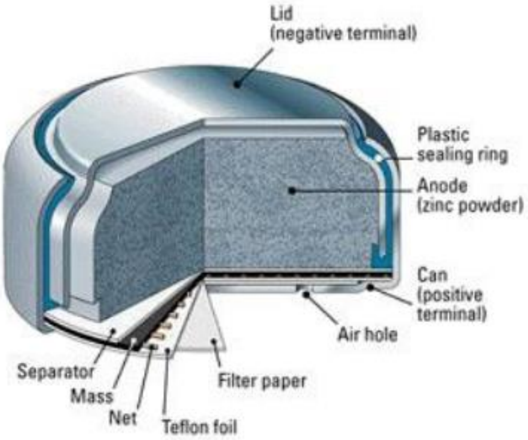

Figure 1.7 – Zinc air battery

Nickel-cadmium battery

Indicative chemical composition (vary according to battery size, Fig. 1.8): Fe – 40%; Ni – 22%; Cd – 15%; plastic – 5%; KOH – 2%; others – 16%.

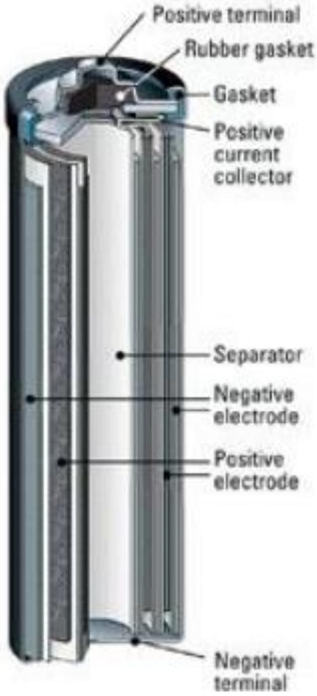

Figure 1.8 – Nickel-cadmium battery

Lead acid battery

Indicative composition (vary according to battery size): lead (incl. lead oxides) – 72%, electrolyte (H_2SO_4) – 17%, plastics – 9%; others – 2%.

Li-ion battery

The components are as follows.

1. Positive electrode: the active substance is generally lithium manganese oxide or lithium cobalt oxide, with nickel cobalt lithium manganese oxide materials. Electric bicycles generally use nickel cobalt lithium manganese oxide (commonly known as ternary) or ternary + a small amount of lithium manganese oxide. Pure lithium manganese oxide and lithium iron phosphate gradually fade out due to their large volume, poor performance, or high cost. Conductive collector uses electrolytic aluminum foil with a thickness of 10–20 microns.

2. Diaphragm, a specially formed polymer film with a microporous structure that allows lithium ions to pass freely, while electrons cannot.

3. Negative electrode: the active material is graphite or carbon with a similar graphite structure, and the conductive current collector uses electrolytic copper foil

with a thickness of 7–15 microns.

4. Organic electrolyte: carbonate solvent dissolved with lithium hexafluorophosphate, and gel electrolyte used for polymer.

5. Battery shell: divided into steel shell (rarely used in square shape), aluminum shell, nickel plated iron shell (used in cylindrical batteries), aluminum plastic film (soft packaging), etc., as well as the battery cover, which is also the positive and negative terminal of the battery.

Negative electrodes can be roughly divided into the following types.

1. Carbon anode materials: the anode materials actually used in lithium-ion batteries are basically carbon materials, such as artificial graphite, natural graphite, mesophase carbon microspheres, petroleum coke, carbon fiber, pyrolysis resin carbon, etc.

2. Tin based negative electrode materials: tin based negative electrode materials can be divided into two types: tin oxide and tin based composite oxide. Oxides refer to the oxides of various valence metal tin.

3. Lithium containing transition metal nitride negative electrode material.

4. Alloy based negative electrode materials, including tin based alloys, silicon-based alloys, germanium based alloys, aluminum based alloys, antimony based alloys, magnesium based alloys, and other alloys.

5. Nanoscale negative electrode materials: carbon nanotubes, nano alloy materials.

6. Nano oxide material: according to the latest market development trends in the new energy industry of lithium batteries, many companies have started using nano titanium oxide and nano silicon oxide to add to traditional graphite, tin oxide, and nano carbon nanotubes, greatly improving the charging and discharging capacity and frequency of lithium batteries.

Electrolytes contain solutes and solvents. Solute: lithium salts are often used, such as lithium perchlorate ($LiClO_4$), and lithium tetrafluoroborate ($LiBF_4$). Solvent: due to the working voltage of the battery being much higher than the decomposition voltage of water, organic solvents such as ether, ethylene carbonate, propylene carbonate, diethyl carbonate, etc. are often used in lithium-ion batteries. Organic solvents often disrupt the structure of graphite during charging, causing it to peel off and form a solid electrolyte interphase on its surface, leading to electrode passivation. Organic solvents also pose safety issues such as flammability and explosiveness.

1.3 Legislation on waste batteries management

1.3.1 Analysis of legislation on waste battery management in developed countries

Developed countries mainly adopt the following measures to control waste battery pollution:

1. Control the use of harmful elements during battery production, or replace batteries containing harmful elements with new types, such as mercury-free batteries. This method is called “redesign”.

2. Extend the battery life or use rechargeable batteries that can be reused. This method is called “reuse”.

3. Recycling waste batteries for reuse is called “recycling”.

4. Harmless disposal of collected waste batteries.

The following is the legislative situation of waste battery management in some developed countries [27].

Japan

Through the enactment and revision of a series of laws and regulations, Japan has gradually established a sophisticated and mature system for the recycling of used batteries. The Waste Disposal Act, enacted in 1970, focused on addressing the pollution caused by waste, with the legislative focus on "how to safely dispose of it." This is the foundational law for waste management in Japan. Initially, it primarily stipulated treatment standards and penalties for industrial and general household waste, aiming to prevent illegal dumping and environmental pollution.

With rapid economic development, resource shortages and insufficient landfill space became increasingly prominent, and Japan's policy focus shifted from "how to dispose of" to "how to reduce and reuse." The Law for Promoting the Effective Utilization of Resources was enacted in 1991. This marked a pivotal moment in Japan's waste battery recycling management. A 2000 revision introduced the concept of "extended producer responsibility." Thus, Japan established a mandatory recycling system for small rechargeable batteries.

Small electronic products such as mobile phones, laptops, and digital cameras are rapidly replaced, containing large amounts of valuable metals and rare earth elements, as well as used batteries. The Small Home Appliance Recycling Act was implemented in 2013. Since the late 2010s, Japan's resource recycling policy has been elevated to a national strategic level, and it has begun to address new challenges. While the "Plastic Resource Recycling Strategy" and the "Green Growth Strategy" don't directly target batteries, these national strategies emphasize the overall societal transition toward a circular economy and a decarbonized society. Batteries, particularly automotive power batteries, as critical resources and high-value products, are placed at the core of this strategy.

With the widespread adoption of electric vehicles, the large number of used automotive power batteries has become both a new challenge and an opportunity. Japan's Ministry of Economy, Trade and Industry is actively promoting the establishment of a system for the recycling, cascade utilization, and resource extraction from automotive power batteries. This goes beyond simple "recycling" to build a comprehensive value chain throughout the entire life cycle.

United States

The recycling and treatment of waste batteries in the United States also leads the world, with a recycling rate of almost 100%. Taking New York State as an example, state law stipulates that car batteries that are not used in discarded batteries can be returned to retailers, sent to specialized recycling stations, or placed in the cleaning agency's exclusive garbage disposal site, and are prohibited from being mixed with ordinary garbage and thrown away casually. State laws also stipulate that automotive battery retailers have the obligation to recycle two batteries per person per month for free. When consumers purchase car batteries, they must pay an additional $5 as future recycling costs. In addition to automotive batteries, lead-acid batteries and nickel-cadmium batteries also have designated recycling locations. Consumers can give their used batteries to manufacturers, retailers, or wholesalers. In addition, some businesses also offer free battery recycling services. The regulations related to batteries in the United States are as follows: firstly, regulations to limit the mercury content in batteries and the recycling and disposal of mercury free zinc-manganese batteries. From late 1989 to early 1991, the United States passed regulations to limit the mercury content in batteries. In 1993, the US battery manufacturing industry voluntarily reduced the mercury content in batteries. By the end of 1993, battery manufacturers in the United States no longer added mercury to all alkaline manganese batteries and ordinary zinc-manganese batteries (carbon-based batteries). The Management Measures for Mercury Containing Batteries and Rechargeable Pools were implemented on May 13, 1996. The Battery Law stipulates that in order to facilitate effective recycling and appropriate disposal of waste nickel-cadmium batteries, small sealed lead-acid batteries, and other batteries that need to be controlled, battery manufacturers must use unified regulatory labeling and encourage voluntary manufacturers to invest in the recycling and appropriate disposal of waste batteries. It is prohibited to sell batteries without markings or with markings that do not meet the requirements, as well as electrical appliances that cannot or are inconvenient to disassemble batteries. And specify the content and style of the identification. Regulations prohibit the sale and use of alkaline batteries, zinc-manganese batteries containing mercury (with the intention of adding mercury to batteries), and mercury oxide batteries, and encourage the research and production of new types of batteries. It requires manufacturers of rechargeable batteries and manufacturers of charging battery equipment to organize public education and participation in the collection of waste batteries, improve the collection rate of waste nickel-cadmium batteries, small sealed lead-acid batteries, and other batteries that need to be controlled, or effectively treat and dispose of waste batteries. For this reason, the United States has launched a nationwide nickel-cadmium battery recycling program and some state recycling programs, while the recycling program for waste small lead-acid batteries is carried out by the Portable Rechargeable Battery Association (PRBA) and the Battery International Council (BCI). In this plan, the wholesale, retailers, and public organizations of nickel-cadmium batteries collect waste nickel-cadmium batteries, and PRBA bears the collection cost and sends the waste nickel-cadmium batteries to the International Metal Recycling Company (INMETCO) in Pennsylvania. The recovered steel is used to manufacture stainless steel, and 99.95% purity cadmium is reused for the production of nickel-cadmium batteries.

In addition, some states have also established their own recycling plans for waste nickel-cadmium batteries. For example, the recycling rate of waste nickel-cadmium batteries in Massachusetts had reached one-third before 1997. In 1995, the Environmental Protection Association of the United States formulated the "Management Measures for Ordinary Waste and Garbage (UWR)", which was revised in July 1999. Legislation stipulates that all waste batteries must comply with the provisions of the "Management Measures for Ordinary Waste and Garbage (UWR)". In this regulation, the government has made detailed labeling requirements for batteries. The battery product and its packaging materials must be labeled with the words “Batteries must not be discarded at will and must be properly disposed of”. The establishment of networks for the collection, recycling, and treatment of waste batteries is encouraged. And in the form of legal regulations, the United States Environmental Protection Agency is required to establish a public education plan to promote and educate the public about the collection, recycling, and reasonable work of waste batteries, encourage residents to use rechargeable batteries more, and automatically participate in waste battery collection and treatment activities. Special regulations prohibit battery manufacturers from intentionally adding mercury to ordinary batteries.

The United States also has demands for ensuring the safety and environmental protection of the battery supply chain. The “National Lithium Battery Development Blueprint 2021–2030” in the United States mentions the need to achieve the recycling of lithium batteries and the large-scale recovery of key raw materials, establish a complete and competitive lithium battery recycling value chain in the United States, and invest in scientific research and training.

Germany

In 1994, Germany successively promulgated the “Circular Economy and Waste Treatment Law” and the “Waste Dry Batteries and Battery Treatment Law”. In April 1998, Germany also introduced the “Waste Dry Batteries and Battery Management Law”, which regulates the design, production, and sales of battery products in the form of regulations, and encourages battery production enterprises to actively develop batteries that do not contain or contain less harmful substances. In 2001, according to the EU 98/101/EC guidelines, Germany revised the “Waste Dry Batteries and Battery Management Law”. The “Waste Battery Management Law” established strict regulations for battery products imported to Germany: firstly, battery manufacturers or importers must have a complete waste battery recycling and treatment system in Germany to sell batteries. Secondly, it is prohibited to produce and sell button cell with mercury content more than 2% and other batteries with mercury content more than 0.0005%. Once again, batteries integrated internally in instruments, meters, and other product equipment must not contain batteries containing hazardous substances. Button cell with mercury content less than 2% is an exception. With the promulgation of the Waste Battery Management Law, Germany has established multiple comprehensive waste battery recycling and treatment system [28].

1.3.2 Chinese legislation on waste battery management

Currently, there is no specific legislation in China for the management and treatment of waste batteries. China has already introduced 9 laws related to the environment, among which the legal provisions related to waste batteries are scattered and mostly principled, without formulating detailed rules for waste batteries management. Moreover, the current legal and regulatory documents on waste batteries in China are mainly standard laws and regulations, such as environmental standards, component content, appearance labeling, and waste battery treatment standards [29]. However, the deep issues related to the recycling and disposal of waste batteries cannot be explained or addressed. Especially regarding the collection and disposal of waste batteries, there is no corresponding reward or punishment mechanism for collection or non-collection. The reuse of waste batteries, the cost of waste batteries recycling, how to recycle them, how to reuse them, and related issues in the process (such as organization, supervision, form), the materials, processes in batteries, the content of harmful substances in batteries, and legal responsibilities for violating requirements all need specific and detailed explanations and is determined by specialized laws and regulations.

Below are some Chinese laws regarding the waste batteries management [30].

Environmental Protection Law

Some principled provisions and public participation principles in the Environmental Protection Law of the People's Republic of China apply to the treatment of electronic waste. Among them, provisions such as “units and individuals who have made significant achievements in protecting and improving the environment shall be rewarded by the government” can encourage public participation in preventing electronic waste pollution. At the same time, the law also stipulates that the environmental protection authorities of local governments at or above the county level have the obligation to report to the local government, and the government takes measures, which is essentially the monitoring and reporting responsibilities of the environmental protection department. That is to say, when electronic waste seriously pollutes the environment and threatens the safety of residents’ lives and property, this clause can be applied.

Clean Production Promotion Law

The Clean Production Promotion Law of the People's Republic of China came into effect in 2003. Its main legal provisions related to the recycling and treatment of waste batteries are Articles 38 and 41. However, they only have guiding significance for battery manufacturers, and have played an auxiliary role in waste battery management with weak operability.

Law on the Prevention and Control of Environmental Pollution by Solid Waste

The Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste came into effect in 2005. The provisions related to batteries and their management include Article 30, which states that enterprises and institutions shall reasonably select and utilize raw materials, energy, and other resources, adopt advanced production processes and equipment, and reduce the amount of industrial solid waste generated. This is reflected in the fact that waste batteries also belong to solid waste, and the scope of adjustment in this law includes principled provisions for the recycling and utilization of waste batteries, without specific content. Although extended producer responsibility is stipulated, there are no corresponding punishment measures or corresponding recycling measures. At the same time, the law stipulates certain administrative management functions of the government, but does not pay attention to the management of industry self-discipline, and the role of social organizations cannot be fully played.

Circular Economy Promotion Law

The Circular Economy Promotion Law was officially implemented in 2009. Article 15 stipulates that products included in the mandatory recycling list should be recycled by producers or entrusted to others for recycling. This article reflects the extended producer responsibility system, which means that electronic waste producers, as polluters, should control the pollution they generate or potentially generate. Article 19 regulates the green design and production of electronic products. Article 38 stipulates that “the state implements a multi-channel recycling and centralized disposal system for electronic waste. Government agencies, organizations, enterprises, institutions, and individuals are not allowed to discard or dispose of electronic waste at will. When selling old electronic products, they should undergo maintenance or testing to meet the standards for reusable products, and affix reusable product labels in prominent positions”. This law clearly sets out specific requirements for circular economy. However, these regulations are mostly principled and still need to be examined at the operational level [31].

China currently does not have specific indicators similar to those of the European Union for battery management, but as a guiding document, the 14th Five Year Industrial Green Development Plan states that a relatively complete power battery recycling and utilization system should be established by 2025.

Shortcomings in the Chinese legislation

1. Strong principle and lack of operability. There is still a lack of detailed regulations and systems in the overall work of waste battery recycling and treatment, and the main bodies in each link have not formed a strong sense of responsibility and enthusiasm, making it difficult to carry out comprehensive pollution prevention and control work. The existing relevant legal norms only declare the principle that the state supports the recycling and utilization of batteries and that products should use environmentally friendly raw materials, but do not specify how the state provides that. For example, although enterprises have the obligation to use raw materials that are easily recyclable, easy to handle, or capable of being decomposed in the environment, there is no corresponding legal responsibility established, which means that those who do not use them do not receive the necessary sanctions, and those who use them do not receive the corresponding compensation, resulting in de facto unfairness. Moreover, the circulation, disposal, and recycling of batteries are quite complex, and cannot be solved solely by the word “should”. It involves a series of circulation links, waste reduction, and the operation of recycling institutions and organizations, directly related to the vital interests of market entities. It cannot be solved solely by the environmental awareness and morality of citizens and enterprises. The law is very weak in regulating waste battery management [32].

2. The rights and responsibilities of law enforcement management agencies are unclear, and there are many drawbacks in end management. The provisions on the scope of responsibilities between management agencies and departments in relevant legislation are very unclear, especially the provisions on how to carry out cooperation between departments, which creates too much space for administrative

discretion. However, due to improper considerations of the interests of the administrative body, different departments compete to claim jurisdiction over profitable affairs and unfavorable matters in areas where the legal provisions are not clear. When there is a lack of coordination from superiors, the phenomenon of shifting blame among law enforcement departments has seriously affected the enforcement of the law. In addition, the overlapping functions of environmental planning, monitoring, and protection may lead to the overlapping of dispute resolution functions, while the unreasonable powers and division of labor of environmental protection administrative management departments can also lead to inaction or injustice in the process of environmental law enforcement. The Deqing blood lead exceeding event is a good example. The serious inaccuracy in the evaluation by the environmental impact assessment unit is a significant reason for this incident. It once again illustrates the problems in the enforcement and management of waste batteries in China. Besides, currently, China's management methods for waste batteries are still focused on the treatment of environmental safety damage, which is not only difficult and costly to treat, but also completely deviates from the national policy of sustainable development.

3. Lack of government policy support system. China's waste battery management industry currently lacks legal and policy support. The profits from waste battery treatment are generally reflected in two aspects: government subsidies and resources generated during the treatment process, such as zinc, manganese, mercury, etc. The common practice abroad is to implement a “government subsidy” for the recycling and treatment of waste batteries. But there are no relevant policies in China yet. For example, in the United States and Japan, waste batteries are recycled and handed over to enterprises for treatment, and the government provides a certain subsidy for each ton of treated batteries. Korean manufacturers of batteries must pay a certain amount of deposit for each ton produced, which is used for the expenses of recyclers and processors, and designate a specialized factory for processing. Some countries impose environmental governance taxes on battery production enterprises or offer tax reductions or exemptions for waste battery

treatment enterprises. However, China's efforts in this area appear to be somewhat weak. Experts and scholars call on the country to accelerate the development of relevant laws and regulations, improve the waste battery recycling and treatment system as soon as possible, develop waste battery treatment technologies, and achieve harmless treatment and resource utilization of waste batteries. In the continuous exploration and practice of various regions, there are also successful cases. For example, Wuhan Greenmei Resource Recycling Co. has established recycling networks in 13 prefecture level cities in Hubei Province. More than 200 Zhongbai Convenient Supermarkets in Wuhan alone repurchase 50000 waste batteries per day, which has received good economic and environmental benefits. Shenyang has established the only waste battery recycling and disposal center in Northeast China, with 8 production lines for treating waste batteries and 2 production lines for new batteries. Its capacity for treating waste batteries can reach 22000 tons per year, equivalent to over 700 million batteries, which can basically meet the waste battery treatment requirements of Liaoning Province [33].

1.3.3 Implications for China due to other countries' legislation

The legislative work on the recycling and treatment of waste batteries in China is still in its early stages, and there is still a significant gap compared to developed countries such as the United States, Japan, and Germany. China currently lacks a comprehensive legislation that can lead the clean production of battery products, as well as the collection, recycling, and harmless disposal of waste batteries. The lack of comprehensive and unified legislation has led the waste battery management being in a situation of multiple government departments, overlapping functions, and conflicting policies. Drawing on the legislation of waste battery recycling and treatment in developed countries, China's waste battery recycling and treatment legislation should pay attention to the following aspects [34].

1. An efficient legal system

From the experience of developed countries, an efficient legal system is the foundation for the healthy development of waste battery management system. Many countries have formulated a series of policies and measures related to waste batteries. The sustainable, scientifically-based, and environmentally friendly development of waste battery management can be achieved only with legal protection. As a developing country, China is not only the “birthplace” of battery products, but also the distribution center of waste batteries. Its legislative work on the recycling and treatment of waste batteries started relatively late, and it is even more necessary to intensify legislation to turn waste batteries into resources as soon as possible. The author believes that the key to legislation is to address two fundamental issues. Firstly, to address high-level legislative issues, it is necessary to formulate and introduce specialized regulations for the recycling and treatment of waste batteries. Secondly, to address the systemic issues of legislation, corresponding supporting measures must be introduced in order to completely solve the problem of waste battery pollution.

2. A reliable management system. Many countries that have already legislated for the recycling and treatment of waste batteries have a governmental department to supervise the normal operation of the waste battery management system. For example, Germany has an effective recycling system for waste batteries with an official body – German Battery Recycling Association established to coordinate the operation and implementation of battery manufacturers, distributors, and legislators.

3. Extensive public participation. Developed countries give a great importance to the participation of residents, and citizens have the right to participate in the formulation of institutional policies. In this way, the public feel that they have made a commitment to sustainable development and become more actively involved in policy implementation. For example, in Japan, laws are used to strengthen public awareness, and a large number of laws and regulations are formulated to compel citizens, including individuals, businesses, and local governments to follow suit. In addition, before and after the introduction of laws, Japan also conducted extensive publicity and explanations to its citizens, explaining the environmental problems and waste crisis that Japan is currently facing through the publications, forums, speeches, and other forms, and calling on people to consciously reduce emissions to protect

the environment. By seeking the maximum understanding of the people and obtaining the conscious cooperation of the majority, people can have a sense of pride while following the rules for waste disposal, without feeling forced by others. The United States explicitly requires the Environmental Protection Agency to establish a public education plan in the "Management Measures for Ordinary Waste and Garbage", to educate the public about the collection, recycling, and reasonable disposal of various types of waste batteries, and to encourage public participation in the collection and utilization of waste batteries.

4. Different subjects with different responsibilities. The legislation of developed countries clearly stipulates the responsibilities and obligations of governments (including local authorities), enterprises and institutions, and individuals (producers, consumers, etc.). Generally speaking, the government is mainly responsible for formulating basic plans or policies, formulating relevant policies, and implementing incentive and punishment measures. Enterprises mainly have producer responsibility and polluter payment responsibility, etc. For example, the EU Battery Directive clearly stipulates that the EU has been mandating the recycling of waste batteries since 2008, and the cost of battery recycling will be borne by the manufacturer. Starting from 2009, all batteries sold within the EU must indicate their specific service life. Individuals are mainly responsible for collection and sorting, paying for emissions, and using recycled products.

1.4 Environmental pollution from waste batteries

Waste battery pollution is not as concentrated as wastewater and exhaust gas pollution generated by industry, with obvious short-term effects, easy to monitor, and easy to attract people's attention.

The pollution pathways of waste batteries

Generally speaking, if the components of a battery are sealed inside the battery shell during use, they will not have an impact on the environment. However, if long-term mechanical wear and corrosion cause the leakage of heavy metals, acids and alkalis inside, entering the soil or water sources, they will enter the human food chain through various channels.

Battery users are scattered, and pollution sources are also scattered. The pollution is caused by long-term pollution of water and soil, followed by the accumulation effect in plants and animals, and ultimately enters the human body through the food chain, affecting human health and even leading to serious diseases. For this low toxicity and long-term pollution, it is often difficult to evaluate its potential toxicity using chemical analysis methods. Traditional tests using indicator organisms, such as acute toxicity experiments and determination of lethal concentrations, are also difficult to achieve ideal results. This kind of pollution is actually present in nature, the pre-occurrence rate of this sublethal effect of pollution is much greater than that of acute effects (such as the mass death of animals). Therefore, it is necessary to seek more sensitive toxicological evaluation indicators for reasonable evaluation of this low toxicity, long-term pollutant [35].

Hazards to the environment

When waste batteries are discarded in nature or mixed with household waste for landfilling, the outer metal of the waste batteries will be corroded, causing the leakage of heavy metals, acids, and alkalis inside, which may enter the soil or water through infiltration. Besides, due to the current lack of economically effective recycling technologies in China, a portion of waste batteries are usually disposed of along with household waste by incineration and landfilling. When incinerating waste batteries, on the one hand, they may adhere to the equipment, causing blockage and corrosion. On the other hand, heavy metals such as mercury, arsenic, and zinc are easily vaporized and volatilized at high temperatures. Some heavy metals react in the furnace to generate chlorides, sulfides, or oxides, which are more easily vaporized and volatilized than the original metal elements. After entering the atmosphere with the tail smoke, they will cause pollution to the atmosphere and soil. A large amount of heavy metals are enriched in the bottom ash, and the resulting ash residue is also difficult to treat.

Hazards to human health

Zinc-manganese batteries contain many heavy metals, which can cause various illnesses when absorbed by the human body to a certain extent. The main harm of heavy metals in waste batteries to human health is that mercury has carcinogenicity and can cause central nervous system diseases. The symptoms of zinc poisoning are gastrointestinal dysfunction and diarrhea, and zinc salts can cause dermatitis and skin ulcers. Metal copper salts are highly toxic and can cause damage to the gastrointestinal system, leading to hemolytic anemia, dysfunction of bile excretion, and liver damage. The main toxic effect of metal lead is to cause anemia, damage the nervous system, cardiovascular system, and kidneys, damage the digestive system, and affect children's development. The harm of the main metals contained in waste batteries to human health is shown in the Table 1.9 [36].

Table 1.9. Hazard of waste battery

Element Name	**Hazard**
lead	It causes anemia, neurological dysfunction and kidney injury, acting on the nervous system, hematopoietic system, digestive system and organs such as liver and kidney, and inhibiting the anabolism of hemoglobin
nickel	Dissolve in the blood, participate in the body circulation, damage to the central nervous system, cause vascular variation
cadmium	Make bone softening, bone deformation, serious formation of natural fracture, so that death
zinc	The salt of zinc is protein precipitation and can stimulate the skin mucosa
manganese	Cause neurological dysfunction, comprehensive functional dysfunction, more serious people appear mental symptoms
$LiMO_2$ (M for cobalt, manganese, and nickel)	Skin contact can cause allergies, respiratory contact can cause lung symptoms, and produce toxic gases after burning
Carbon or graphite	Skin contact can cause allergies, respiratory contact can cause lung symptoms, combustion will produce CO, CO_2
$LiPF_6$	Through the skin, respiratory contact will cause stimulation, combustion will produce HF, P_2O_5 and other toxic gases

1.4.1 Harm of waste lithium-ion batteries

In waste lithium-ion batteries, there are both existing components and new substances generated by chemical reactions during charging and discharging [37]. Abandoned batteries are discarded into the environment, and due to various reasons, they are damaged, causing substances in the batteries to enter the environment and causing environmental pollution. Lithium-ion batteries have the characteristic of high dispersion in disposal, so their pollution to the environment is long-term and slow .

The positive and negative electrode materials, electrolytes, etc. of lithium-ion batteries can have adverse effects on human health, and their hazards are shown in the Table 1.10 [38].

Table 1.10. Lithium-ion battery components harm

Material types	**Material name**	**Harmfulness; perniciousness**
Anode material	Li Co O_2	Skin contact can cause allergies, respiratory contact can cause lung symptoms, and produce toxic gases after burning
	Li Ni O_2	Skin contact can cause allergies, respiratory contact can cause lung symptoms, and produce toxic gases after burning
	Li Mn O_4	Skin contact can cause allergies, respiratory contact can cause lung symptoms, and produce toxic gases after burning
Cathode material	Carbon, graphite	Skin contact can cause allergies, respiratory contact can cause lung symptoms, combustion will produce CO, CO_2
Electrolyte solution	$LiPF_6$	Skin and respiratory contact can cause irritation, and it will produce toxic gases such as HF and P_20_5 after combustion
	$LiBF_4$	Corrosive, breathing, skin contact can cause irritation, combustion will produce HF and other toxic gases
	$LiCLO_4$	Breathing and skin contact can cause irritation, and burn in Li Cl and O_2
Electrolyte solvent	EC, PC, DMC	Skin and respiratory contact will cause irritation, and after burning will produce CO, CO_2

1.4.2 Harm of waste nickel-cadmium batteries

Nickel-cadmium batteries contain heavy metals such as cadmium, nickel, and strong alkaline electrolytes. If not properly treated after disposal, it may cause serious harm to the environment and human health. Especially cadmium is a toxic substance that can cause significant harm to human health when released into the environment. If waste batteries are mixed into the composting process, it will seriously affect the quality of the composting product. During the incineration process, the large amount of cadmium volatilization can pollute the atmosphere and soil environment, and also produce a large amount of ash that is difficult to treat due to the enrichment of heavy metals. Where landfills do not meet the requirements, cadmium and nickel from waste nickel-cadmium batteries may contaminate water or soil through infiltration.

Once cadmium enters the environment, especially in the soil, it is difficult to eliminate it, and it will undergo organic transformation in organisms, making the harm of heavy metal pollution even greater. Excessive cadmium can be accumulated in the roots, stems, leaves, and fruits of plants, not only seriously affecting their growth and development, but also endangering animals and humans through the food chain. Cadmium can bind to polymer organic compounds containing hydroxyl and amino groups, inhibiting many enzyme systems and affecting the normal function of enzyme systems in organs such as the liver and kidneys [39].

Nickel can also have a significant impact on human health. People with nickel allergies can develop contact rashes when their skin comes into direct contact with nickel. Inhaling a large amount of nickel-containing air can lead to chronic bronchitis and decreased lung function, and even cause lung cancer and sinus cancer. Eating or drinking large amounts of nickel-containing food and water can cause lung diseases, as well as affect the animal’s stomach, liver, kidneys, immune system, and metabolic system. According to the investigation of the U.S. Department of Health and Human Services (DHHS), nickel and some nickel-containing compounds belong to carcinogen [40].

1.4.3 Harm of lead-acid batteries

According to both the Basel Convention and the China Hazardous Waste List, waste lead-acid batteries are classified as hazardous waste. The main components that have an impact on the environment are sulfuric acid and heavy metals such as lead, antimony, arsenic, and zinc. A waste battery generally contains 20% to 25% electrolyte, including 15% to 20% sulfuric acid and suspended lead compounds.

During the use of lead-acid batteries, their harm is minimal. However, if the used lead-acid batteries are not collected and recycled according to operating standards, it will cause serious environmental problems and harm human health.

Lead and sulfuric acid are the main sources of environmental impact in lead-acid batteries. If waste lead-acid batteries are directly placed in the environment, they may break and release toxic substances and produce corrosiveness (approximately 2–3L of sulfuric acid is released from each waste car lead-acid battery). In batteries using colloidal electrolytes, the associated risks may be slightly reduced due to the high viscosity of the colloid, but they still exist. For batteries with encapsulated electrolyte, although the direct risk is small, it is also a potential source of pollution.

During the collection process, due to the highly corrosive waste acid contained in lead-acid batteries, dumping into the surrounding environment can cause its flowing into soil and groundwater, and the severity of its pollution is self-evident [41]. Sulfuric acid is extremely danger, while the metals contained in lead-acid batteries have certain toxicity. Inhaling its dust, smoke, or ingesting water or food containing this substance can harm human health.

The purpose of lead refining is to remove almost all copper, antimony, arsenic, and tin from it, in order to meet the standard of soft lead. The potential sources of environmental pollution that this process may generate are: lead smoke caused by excessive heating of lead; release of sulfur dioxide; formation and removal of scum; removal and recovery of chlorine and tin; removing tin with oxygen-rich air.

The lead-containing waste generated during the regeneration of waste lead-acid batteries, as well as the waste residue generated during the smelting process, can seriously pollute the surrounding soil and water bodies if not properly treated, thereby posing serious harm to human health.

In summary, used batteries can cause environmental pollution due to leakage or improper disposal, and often contain various toxic chemicals and heavy metals. The following are some potential impacts of waste batteries on the environment:

1. Soil pollution. If batteries are mishandled, their contents can seep into the soil and contaminate with toxic chemicals and heavy metals such as lead, cadmium, and mercury. This will damage soil fertility and affect the growth and development of plants.

2. Water pollution. If waste batteries are not properly treated, their contents can also contaminate water bodies through leaching or runoff. This can harm aquatic organisms and affect water quality, making it unsafe for human consumption.

3. Air pollution. When batteries are burned, they release toxic smoke into the air, including heavy metals and other harmful substances. This may cause respiratory and other health issues for nearby residents.

4. Resource depletion. Batteries contain a variety of materials, including metals and rare earth elements, which are limited in supply and expensive to extract. Properly recycling these materials can reduce the demand for new mining operations and protect natural resources.

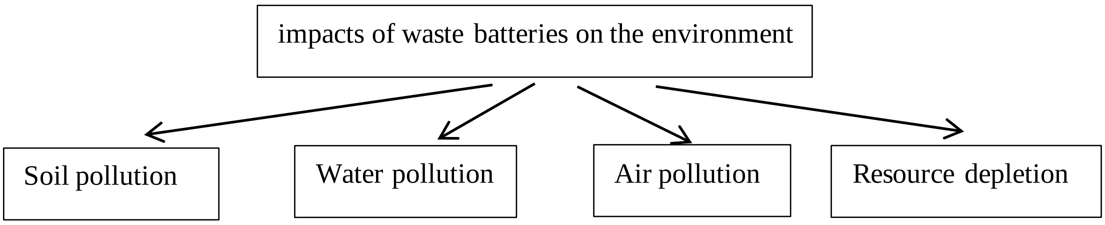

Figure 1.9 – waste batteries on the environment

Overall, if mishandled, waste batteries may pose significant environmental risks. Batteries must be recycled and disposed of in accordance with local regulations to prevent environmental pollution and protect human health.

1.5 Conclusion to the Chapter 1

This chapter systematically explains the classification, composition, environmental impact, and current domestic and international legislation and management of waste batteries. The following is a summary of this section.

The chapter details several common battery types used in daily life, including zinc batteries, alkaline batteries, lithium batteries, silver oxide batteries, rechargeable batteries (nickel-cadmium and nickel-metal hydride batteries, lithium-ion batteries), and other types.

Waste batteries contain a variety of heavy metals (such as mercury, cadmium, lead, nickel, and zinc) and acidic and alkaline electrolytes. If improperly handled, these substances can pollute soil and water, and harm human health through the food chain. The article provides detailed tables listing the typical element content of various battery types.

Learning from international experience in waste battery management legislation, China currently lacks legislation specifically addressing waste battery recycling and disposal. Chinese laws suffer from a lack of principled principles, poor operationalization, unclear responsibilities, and insufficient policy support. A sound legal framework should be established, management responsibilities clarified, public participation promoted, and the responsibilities of all parties enforced.

Environmental pollution from used batteries occurs through corrosion of the battery casing, which can lead to the leakage of heavy metals and electrolytes into the soil and water, ultimately harming humans through the food chain.

If used batteries are not properly handled, they can cause serious and long-term harm to the environment and human health. China is still in its infancy in waste battery management and urgently needs to learn from established international experience, accelerate legislation, establish a comprehensive recycling system, promote technological innovation, achieve harmless disposal and resource utilization of used batteries, and promote sustainable development.

CHAPTER 2

JUSTIFICATION OF WASTE BATTERIES MANAGEMENT METHODS

2.1 Analysis of existing methods of waste batteries storage

2.1.1 Storage requirements for waste batteries

According to different storage requirements and whether they belong to hazardous waste, waste batteries are divided into ordinary waste batteries, explosive waste batteries and hazardous waste batteries. According to the latest national hazardous waste inventory implemented by various countries, mercury containing waste, cadmium containing waste, and lead containing waste belong to hazardous waste [42]. Therefore, waste batteries containing mercury, cadmium containing waste batteries, lead-acid waste batteries, and their scraps can be classified as hazardous waste batteries. Lithium primary batteries, especially lithium thionyl chloride batteries, are prone to explosion, so these types of batteries are classified as separate type, explosive waste batteries. Other waste batteries are classified as ordinary waste batteries [43].

For ordinary waste batteries, according to the requirements for general solid waste, storage warehouses and places should have warning signs for ordinary solid waste. For hazardous waste batteries, they must be stored in accordance with the requirements for hazardous waste, and warning signs for hazardous waste should be affixed to storage warehouses and locations.

2.1.2 Storage methods

There are several ways to store used batteries, including isolated storage and stacked storage. Considering the environmental pollution control and safety protection during the storage process of waste batteries, requirements have been proposed for different storage methods in terms of average storage capacity per unit area, maximum storage capacity in a single storage area, storage area spacing, channel width, and wall spacing width. A common method is to place each battery separately in an insulating bag and store it in a dry, well-ventilated, dark, and cool fireproof container, away from flammable materials and high-temperature environments. Different types of batteries or new and old batteries should not be mixed [44]. For lithium batteries, one should avoid storing them in high-temperature and humid environments. It can be temporarily stored in sand or water and then taken to a recycling point as soon as possible.

2.1.3 Waste battery storage facilities

Primary batteries (zinc-manganese, alkaline, lithium primary) and secondary batteries (lithium-ion, nickel metal hydride) are general waste batteries (if not disassembled) and can be stored in PET plastic tanks or iron drums. Waste electrode materials, leftover materials, waste residue, etc. are in the form of scrap or slag. For convenience, they can be stored in plastic woven bags or iron barrels. Mercury containing batteries, nickel-cadmium batteries, and scraps can be stored in PET plastic tanks or iron drums as well. Waste lead-acid batteries should first be emptied into a waste liquid collection container, and then stored in a PET plastic tank, with hazardous waste labels attached.

Due to the unique nature of waste lead-acid batteries, the following requirements are also proposed for storage facilities:

1. The storage unit must have an acid resistant ground isolation layer to facilitate the interception and collection of any leaked liquid.

2. There should be efficient wastewater collection systems to collect spilled solutions.

3. There should be only one entrance, and in general, this entrance should be closed to avoid the spread of dust.

4. It should have an air collection and exhaust system to filter lead-containing dust in the air and refresh the air.

5. Suitable fire protection devices should be installed.

The safety protection and pollution control of waste batteries during storage mainly involve regular inspections of facilities, communication equipment, lighting facilities, safety protective clothing, and other tools.

2.1.4 Storage of waste batteries during transportation

The transportation of waste batteries should consider both environmental pollution and safety factors. The cross-border transfer of waste batteries belonging to hazardous waste should comply with the requirements of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal. The transfer of waste batteries in China should comply with the "Management Measures for Hazardous Waste Transfer Coupons" and relevant regulations. During transportation, waste batteries are not allowed to be arbitrarily discarded in the environment, and there are special requirements for transportation vehicles and personnel [45].

Mercury containing batteries, cadmium containing batteries, lead-acid batteries, etc. must be transported as hazardous waste. Regardless of the transportation method used, they must be transported in sealed containers to prevent leakage. During transportation, it is necessary to correctly label according to relevant requirements and use common symbols, colors, and meanings to warn of their corrosiveness and danger.

Drivers and transportation personnel should be trained: those managing hazardous waste should receive training in emergency rescue, including fire prevention, leak prevention, and how to contact emergency response personnel. In addition, they should know what type of hazardous materials they are transporting and how to handle them. Personal protective equipment should be equipped during transportation. Personal protective equipment should be provided to transportation personnel and they should also be trained on how to use this equipment in the case of an accident. Transport should follow a predetermined route and schedule, and provide early warning for potential accidents or special issues that may occur during the transportation of hazardous waste.

The main problem during the transportation of waste lead-acid batteries is possible electrolyte leakage. The electrolyte may leak out of waste batteries, and measures need to be taken to avoid accidents, and emergency actions should be taken in the case of an accident. Transportation may cause the battery to be positioned upside down, including damage to the casing, which may cause electrolyte to flow out. Therefore, it is required to provide a sealed container that is resistant to bumps and acid. The container must be placed properly during transportation, not sliding. Therefore, in order to avoid this problem, it is necessary to tie it tightly and code it properly.

2.1.5 Storage requirements for waste batteries in China

The following requirements are applied for waste battery storage in China:

1. The storage of waste batteries should comply with the relevant provisions of the Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution (Order No. 31 of the President of the People's Republic of China) and the Technical Policy for the Prevention and Control of Waste Battery Pollution No. 163 .

2. Waste batteries should be stored in a cool and dry place, and should not be stored in an open area. They should not be stored in direct sunlight, high temperature, or damp places [46].

3. The storage and transportation unit of waste batteries should obtain approval from the local environmental protection department and obtain corresponding business qualifications. For hazardous waste batteries, a hazardous waste business license should be obtained.

4. During the storage and transportation process, waste batteries should not be disassembled, rolled, or subjected to other crushing operations to ensure the integrity of waste battery shell and reduce and prevent the leakage of harmful substances.

5. The storage warehouse and location of waste batteries should be managed by dedicated personnel, who must possess relevant professional knowledge.

6. Waste batteries should be discharged during storage and transportation.

2.1.6 Case study of lithium battery

Lithium batteries have complex components, poor biodegradability, are not easily biodegradable, and have certain toxicity. Once a lithium battery is damaged, it may release a relatively large amount of current, which may lead to fire or other safety issues. Therefore, lithium batteries are classified as hazardous waste. However, lithium batteries can also be classified as solid waste. Because lithium batteries are structurally solid and contain a certain amount of metal and other materials, they are also classified as solid waste.

Due to the high risk of explosion accidents caused by lithium batteries, the hazardous waste temporary storage room must have explosion-proof facilities and relevant explosion relief devices. Additionally, a fire extinguishing and alarm systems are required, as well as lightning protection, static electricity prevention, and leakage prevention facilities need to be complete.

2.2 Analysis of existing system of waste batteries collection

In China, the investment cost of government supervision and management mechanism is too high, private recycling organizations are still in a weak position, and the market regulation system is incomplete.

This section proposes that waste battery collection should be run as a system, and studies the key factors affecting the current situation of waste battery collection in China.

Waste collection logistics refers to the process of transferring items that have lost their original use value in economic activities, based on actual circumstances. The physical flow of items formed when they need to be collected, classified, processed, packaged, transported, stored, and sent separately to specialized processing facilities. Through the company's own logistics and distribution system, the waste battery used by consumers will be collected and transported to the starting point step by step. After collection, it will be recycled as raw materials or reasonably degraded. In the process of collection, the logistics advantages and distribution network of the company have their own brand characteristics. On the one hand, the collection logistics system of each company is driven by mandatory national policies, and on the other hand, it is driven by their own demands for brand image.

2.2.1 Logistics of waste battery collection

At present, the main waste battery collection method in China is the collection by one private organization.

The large amount of waste batteries z destination of product transportation. The intersection of logistics nodes and logistics endpoints forms a logistics network. Through the collection logistics network, waste electronic products ultimately flow to logistics nodes (processing factories).

Based on the analysis of these four methods of electronic waste collection, it can be seen that the logistics network of China's electronic waste collection system is complex, with multiple logistics nodes, causing regulatory difficulties, and the issue of electronic waste collection is equally challenging. Due to the inherent value and market prospects of electronic waste, the processing technology is already very advanced. Through different logistics systems, various electronic waste from different regions are transported to factories for processing. In case of waste battery collection, the cycle is long, the risk is high, and the return on investment is not as good as electronic waste, so the waste battery treatment facilities are relatively few, and there are almost no logistics nodes, and the logistics network is also relatively poor. Therefore, collection of waste batteries is different from electronic waste under the current situation. In order to be more stable, logistics nodes must be relatively fixed and easy to manage the characteristic of low transportation costs. The current situation of electronic waste collection also reflects the advantages and disadvantages of logistics in China's waste industry. Public welfare investments are still very difficult in the market, and companies are generally profit-oriented. For markets with high risks and low returns such as waste battery management, there is insufficient participation and no complete logistics system. On the other hand, currently, there are abundant human resources and multiple collection channels involved in waste collection logistics.

2.3 Optimization of waste battery collection system

After studying the waste battery collection system, it has been concluded that a waste battery collection system based on the actual situation of each country needs to have certain characteristics, such as reasonable pricing, targeting densely populated cities, and closely integrating with logistics management, in order to form a circular and long-term effective collection system. Combining these factors, the waste battery collection system can be optimized.

1. Paid collection of waste batteries

The paid collection system for waste batteries in Europe, America, and Japan is mainly aimed at the battery production industry. The cost of waste battery collection and treating is directly deducted from the profits of enterprises, or added to the retail sales volume. By gradually phasing out environmentally friendly battery types through market regulation, the collection rate of waste batteries is rising.

This monetary strategy is not suitable for China's national conditions, and there have been many studies on the paid collection system for waste batteries, which has not been implemented [55]. Unlike developed countries, the Chinese waste trading industry has been preserved for a long time in Chinese consumer awareness. The paid collection system that directly converts waste batteries in users' hands into currency through the sale of waste products is more suitable for China's national conditions.

Direct paid collection of waste batteries is not in line with the actual situation in China, and the specific reasons are as follows:

- direct offsetting the price of waste batteries requires a large amount of investment from companies, which can be described as a risk investment, while the return rate is unknown;

- converting waste batteries into currency will accumulate a large amount of waste batteries in a short period of time, suddenly increasing the difficulty of disposing of waste batteries;
- converting waste batteries into currency will make it difficult for a small number of users to pass them off as real, making collection more difficult and causing economic losses for companies;
- sudden emergence of a large number of waste batteries that cannot be disposed of can cause environmental pollution and harm.
- direct offsetting waste batteries requires a large amount of human resources (setting up collection stations).

2. Method of exchanging waste batteries for other items

Battery manufacturers implement the practice of exchanging used batteries for new ones for customers who purchase batteries. Each used battery can be offset by a certain amount, mainly implemented in supermarkets or large stores, which has achieved certain results, but still cannot comprehensively solve the problem [56].

The strategy of exchanging used batteries for new ones has achieved some success because companies do not require prior investment and reduce risks. Employees at waste battery sale points can take on the role of sorting and collection. Besides, the policy of replacing used batteries with new ones ensures a balance between used and new batteries, without causing short-term imbalance. However, due to the widespread distribution of waste batteries, exchanging them for new ones still cannot increase the rate of waste battery collection. The collection of waste batteries requires a balanced system that can continuously provide a certain amount of waste batteries, while reducing investment risks for enterprises and facilitating national policy adjustments. Reasonably offsetting waste batteries is suitable for the current situation in China.

For example, if 4 dry batteries have a recycling value of 1 yuan, it means that 4 dry batteries can be converted into 1 yuan for convenience. For college students, this convenience involves washing clothes and taking the school bus. For citizens, it corresponds to taking a bus once and subscribing to some magazines. For the community, it may be purchasing drinks from vending machines. If waste batteries are converted into a convenient way of life, it will be much better, such as for cola vending machines, public phone booths, laundry coins, public transportation, and so on. Unmanned vending machines do not require the investment of too much human resources in management, and the collection of waste batteries is not directly converted into profits. Users using waste batteries is nothing more than taking a bus, purchasing a bottle of drink, or washing clothes, without direct transaction amount, which can greatly reduce the rate of counterfeit products. In addition, waste battery recycling industry has incorporated more convenience and public welfare, increasing citizens' awareness. The method of converting waste into a convenient way of life is not yet common in China, but it has certain targeted characteristics for the distribution of waste batteries, and users have also expressed recognition and support for this method.

Suggestions for standardization of waste battery collection

Based on the comparison of standardization of waste battery collection in China and abroad, the following suggestions are proposed.

1. Take the lead in formulating standards that are urgently needed and technologically mature within the industry. Quantitative subsystem or specific standard revision work. Priority should be given to researching and establishing important basic standards such as urgently needed terms and definitions, safety requirements, etc. in the field of waste batteries.

2. Strengthen technological research and innovation, promote the transformation of scientific and technological achievements into technical standards. Technological innovation is the key to improving the collection rate and quality of waste batteries. Only by overcoming the challenges of green collection and treatment of waste battery resources can the recovered.

3. Improve the market-oriented construction of the collection system, clarify the responsible parties and collection goals. Under the guidance and constraints of relevant legal frameworks such as environment protection and resource recycling, in accordance with the laws of economic and social development, a sound market-

oriented system for waste battery collection should be established. Combined with the extended producer responsibility system, the responsibilities and obligations of all parties involved in waste battery collection should be further clarified, and reasonable collection targets should be set to guide companies to increase the proportion of collected batteries, which is used to better meet market demand. At the same time, we will accelerate the construction of a standard support system for the development of circular economy, give full play to the normative leading role of standards, strengthen the traceability management of waste batteries, promote upstream and downstream cooperation in the industrial chain, and promote the healthy development of the waste battery management.

4. Integrate standard systems and certification systems such as environmental footprint and resource recycling, and promote international cooperation and mutual recognition. Actively participate in ISO. IEC and other international standardization activities closely monitor the new trends and directions in the standardization of waste battery collection internationally, and fully draw on advanced collection and recycling technologies and management experience from abroad. Timely conduct applicability analysis and comparison of key technical indicators of international standards, increase the adoption of international standards, and enhance the consistency between Chinese standards and international standards. Actively participate in and lead the formulation of international standards and rules for certification of recycled materials, power battery cascade utilization products, deepen international cooperation and mutual recognition, and promote the "going global" of Chinese standards.

5. Pay attention to publicity and guidance, and enhance the awareness of waste battery collection in the whole society. At important days and periods such as National Ecology Day, National Energy Conservation Promotion Week, and World Environment Day, various forms of publicity and education activities should be carried out with themes such as "Green Recycling into Communities" and "Resource Recycling into Schools" to widely promote the dangers of waste batteries, the importance of collection, recycling and reusing waste batteries, and related policy

measures. Other measures include innovating publicity methods, enriching publicity means, making full use of media, the Internet and other information platforms, popularizing the knowledge about waste battery collection through multiple channels and dimensions, spreading the concept of green and low-carbon, improving the initiative of the public to participate in waste battery collection, and striving to create a good atmosphere for the participation of the whole society.

The flow chart of the waste battery management system standardization is shown in Fig. 2.1.

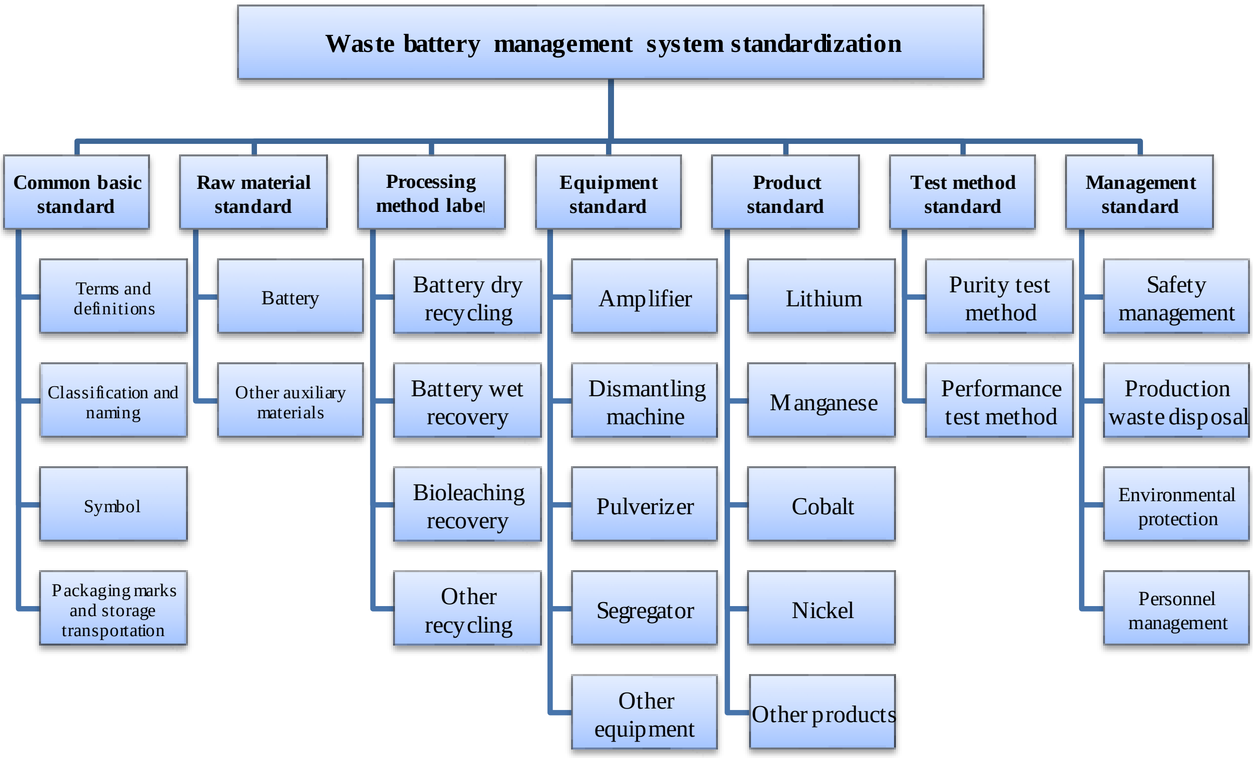

Figure 2.1 – The flow chart of waste battery management system standardization

The logistics of waste battery collection cannot rely on traditional waste collection logistics. Building such a logistics system requires a large amount of human and financial resources, and requires the participation of other logistics systems. In traditional collection systems, waste batteries go through distributors to manufacturers and finally arrive to treatment facilities. Many developed countries also adopt this method to form a certain standardized process, but it is not suitable for the current situation in China. Individual businesses and private organizations have high collection efficiency and low logistics costs, but there is no standardization and may cause environmental pollution in local areas. The environmental protection company has installed waste battery collection bins inside the community to recycle and undertake logistics work, which has achieved initial results. However, the laying of such waste battery collection channels takes too long and may encounter resistance from unknown factors at any time, such as community administrators and a few residential users. These current logistics methods have their own advantages and disadvantages. In summary, China currently needs a standardized and relatively low-cost logistics network [57].

There is no unified standard transportation vehicle or standard storage conditions in China. The current amount of waste batteries generated in the daily lives of residents in Sichuan Province is about 4000 tons per year. Due to the lack of a disposal site, Chengdu alone currently hoards nearly 400 tons of waste batteries, which have been stored for 9 years and still cannot be disposed of. Taking Chengdu as an example, establishing a waste battery disposal factory can improve the current situation. This means that there will be a logistics endpoint for waste battery collection, and the selection of logistics nodes will affect the entire logistics cost. Waste battery collected in all areas will be transported to logistics nodes for accumulation. After reaching a certain quantity, they will be transferred to the logistics endpoint, which is the waste battery treatment factory, which forms a logistics network for waste battery collection. Private collection organizations set up waste battery collection bins in schools, communities, and streets, encouraging citizens to collect and transfer waste batteries through publicity (Fig. 2.2). Through this method, a certain amount of waste batteries can be accumulated in a short period of time. Environmental protection companies set up waste battery collection bins in the community, transport it to logistics nodes, and finally send it to the logistics endpoint [58].

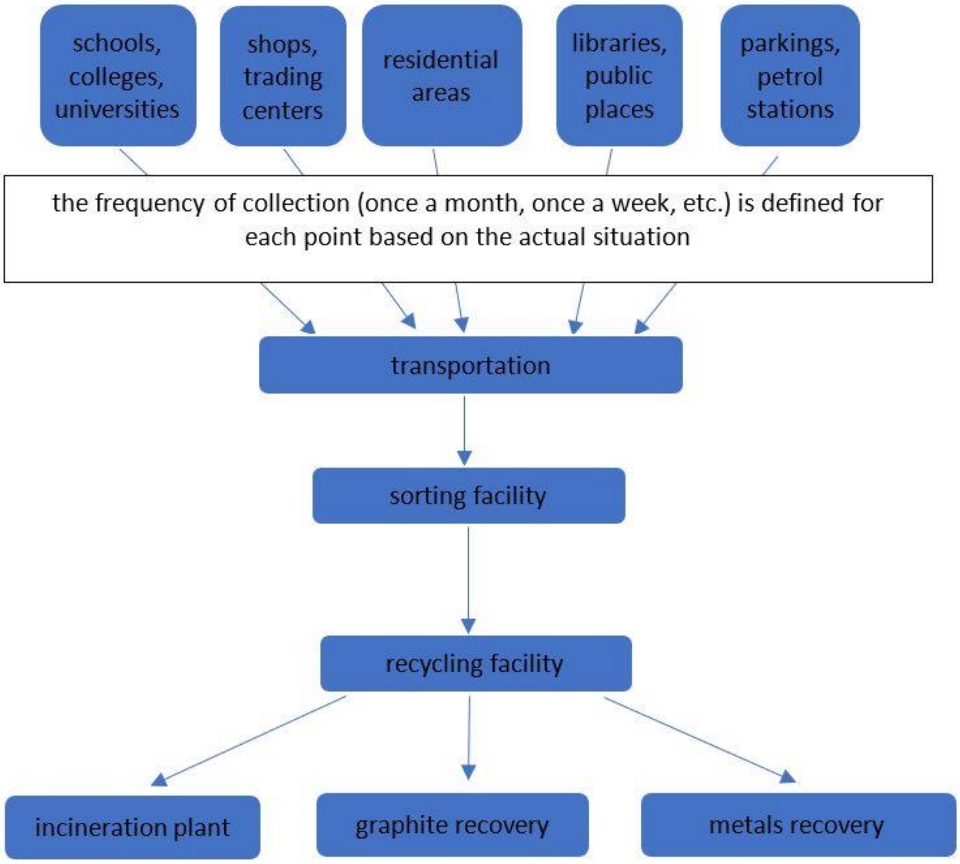

Figure 2.2 – Waste battery collection process

Overall, the main problem in the current waste battery management industry is the lack of smooth circulation and the inability to form an effective resource loop.

1. The destination of the end consumer is unknown, and the market entities are irregular.

Currently, other business models such as battery banks and battery swapping in China are still in the stage of small-scale application. In the on-board sales model, the ultimate right to use and ownership of the battery belongs to the consumer. Consumers can sell waste batteries to enterprises through trade in or directly dispose of them. But the reality is that a large number of used batteries flow into illegal channels, even causing a phenomenon of "inverted" prices for new and used batteries. It is understood that according to current policies, enterprises have the main responsibility for collection, and battery manufacturing and recycling enterprises have corresponding responsibilities. However, due to the high prices of upstream raw materials in recent years, the high profit margins have driven informal market entities to purchase scrapped batteries in a form similar to "auctions". At the same time, Chinese regulations have not clearly defined the responsibility of consumers for collection, and consumers have no responsibility or obligation to dispose of waste batteries, lacking effective binding force. According to market estimates, only about 30% of waste batteries enter formal collection channels. At the same time, the industry is filled with a large number of small enterprises that lack technical capabilities, production conditions, and environmental protection capabilities. According to statistics, as of July 2022, the number of waste battery collection companies in China has exceeded 15000, with over 50% of them having a registered capital of less than 5 million. The market pattern for the collection of waste batteries has not yet emerged, and the market order has not yet formed, which is in the early stage of development.

2. Poor domestic transportation and circulation

The transportation requirements and packaging costs for waste batteries are high, and the phenomenon of non-standard transportation often occurs. In terms of regulatory standards, the "List of Dangerous Goods" classifies waste batteries as Class 9 dangerous goods and requires Class II packaging, which has high requirements for packaging strength and cost. According to the "Regulations on Road Transport of the People's Republic of China" and the "Regulations on the Administration of Road Transport of Dangerous Goods", transport units and vehicles are required to have corresponding licenses, the condition of the vehicles must meet the first level standards, and vehicle drivers, loading and unloading management personnel, and escort personnel must obtain corresponding professional qualification certificates. The "Management Regulations for Battery Recycling and Utilization Part 1: Packaging and Transportation" also requires that if there are dangerous situations such as leakage, deformation, fire, and water immersion in batteries (Class B batteries), special protective measures should be taken for their packaging and transportation. At present, professional battery transportation vehicles are not only rare, but also quite expensive. In the absence of strict supervision, enterprises lack the willingness to seek compliant transportation.

Besides, the procedures for waste batteries transportation across provinces are cumbersome and costly. According to the "Management Measures for the Transfer of Hazardous Waste", the cross-provincial transfer of hazardous waste requires joint approval from the environmental authorities of the two provinces where the hazardous waste is transferred and received, and can only be transferred after approval. The procedures are cumbersome and the cost is high. At the same time, based on the current industrial situation, some provinces and regions in China have not yet established strong collection bases, making it difficult to effectively dispose of waste batteries in their own provinces. This has led to a large number of waste batteries having to be processed into powder before transportation, further reducing production efficiency and increasing enterprise costs.

3. Overseas waste batteries cannot be collected and recycled

Currently, there are certain policy barriers to the export of waste batteries from abroad, and China's import policies are becoming increasingly strict. In November 2017, the European Commission passed the proposal for a new regulation on the transportation of waste in Europe, which, in conjunction with the requirements of the New Battery Law, clarifies that waste batteries can be transported out of the EU if permitted by the receiving country and provided that they can be proven to be non-toxic after import and meet relevant safety requirements. Currently, the vast majority of countries comply with the Basel Convention, allowing the export of waste batteries to countries with processing capabilities. As a member of the Organization for Economic Cooperation and Development (OECD) and a contracting party to the Basel Convention, Japan complies with the Basel Convention and does not allow the export of waste (including used batteries) to countries that are unable to process waste, especially developing countries. The United States signed the Basel Convention in 1992, but has not yet ratified and implemented it domestically. Currently, the United States complies with the requirements of the OECD Council Decision C (2001) 107 on the Control of Transboundary Movements of Waste Destined for Recovery Operations, which prohibits the cross-border transportation of hazardous waste, including scrapped batteries. In contrast, in recent years, China has become increasingly strict in its import policies for used batteries, gradually tightening the import of all solid waste.

In summary, this section proposes an optimization plan for the waste battery collection system. Through improved pricing strategies and reasonable logistics systems, the waste battery collection system is standardized, which is easy to be managed by the national and macro level, forms an industrial scale, avoids environmental pollution, and can increase user enthusiasm. In order to improve the current situation of waste battery collection, the following aspects can be taken into consideration:

1. Enhance public awareness. Through various means such as publicity, lectures, community activities, etc., raise public awareness of the importance of waste battery collection. Let everyone understand that protecting the environment is protecting ourselves.

2. Establish collection channels. The government can establish specialized collection points or cooperate with relevant companies to establish effective collection mechanisms. At the same time, encourage communities, schools, enterprises and institutions to establish their own collection systems and form a collection network that covers the entire society.

3. Promote reusable batteries. Encourage companies to develop and produce reusable batteries to reduce environmental pollution. At the same time, rewards will be given to users who use reusable batteries to increase their enthusiasm for collection.

4. Technological innovation. Increase research and development efforts on waste battery treatment technology, and find more environmentally friendly and efficient collection / recycling methods. For example, developing an intelligent collection system to achieve automatic battery classification through IoT technology.

5. Strengthen the laws and regulations. Develop and improve relevant laws and regulations to regulate the collection and disposal of waste batteries. Violations of regulations should be punished in accordance with the law to form an effective

deterrent force.

2.4 Recommendations on separate collection of waste batteries

Waste batteries should be separated from other waste in the collection process in order to be sent for processing. If it is put together with other household waste, the fermentation process during composting treatment will be affected by the metals contained in battery [59]. If waste is incinerated, the high mercury content in the flue gas will affect the quality of the air pumping environment and pollute the air. If waste is landfilled, the heavy metals in the battery will penetrate into the underground and pollute the soil and groundwater.

Waste batteries must be collected separately so that the battery can be recycled and prevented the spread of harmful substances.

Current collection methods for waste batteries

1. For common dry batteries: one should put them directly into the official garbage bin and does not collect them in a centralized manner (along with alkaline batteries, lithium batteries, and nickel metal hydride batteries).

2. For batteries with high levels of harmful substances, including most button batteries, nickel-cadmium batteries, etc.: if there is a waste battery recycling agency nearby, one should deliver it to them (such as some neighborhood committees, university environmental protection associations, etc.); if there are no recycling agencies for waste batteries nearby (like in most cities and rural areas), one should contact the local environmental protection bureau or send waste batteries to recycling agencies in other cities.

3. Specifically, if a large number of dry batteries have been collected, one should classify them first and then dispose of separately according to the aforementioned suggestions. All types of waste batteries should not be managed together [60]. In the absence of effective recycling technology and economic conditions, the government does not encourage centralized collection of waste disposable batteries that have met the national low mercury or mercury free

requirements.

The recommendations for the efficient management of waste batteries are as follows:

1. Strengthen the classification, collection and management of waste batteries.

In the engineering analysis of environmental impact assessment for newly built, renovated, and expanded battery manufacturers, not only should the raw materials, processes, and finished products containing heavy metals and harmful substances meet the emission standards, but also the after-sales recycling and utilization of products should be evaluated and analyzed. Manufacturers should achieve clean production to facilitate the recycling and utilization of their products. Environmental protection and relevant departments should increase their supervision and management efforts, regularly or irregularly monitor the recycling and utilization situation. In the environmental impact assessment, based on the production scale, it is recommended to establish a production line for the treatment of used battery resources, effectively promoting the recycling and utilization of renewable resources.

2. Encourage the production of environmentally friendly batteries.

Batteries containing heavy metals and mercury should have relevant labels for easy collection, recycling and classification. The government should relax policies in tax or other areas to encourage the production of green and environmentally friendly batteries. Adopting computer network control and utilizing system functional module data transmission technology to sort broken waste batteries [61].

3. Improve the people's awareness on waste batteries collection.

Enhance the environmental awareness of the entire society, carry out education on environmental protection from kindergarten onwards, and make the collection, recycling and utilization of waste batteries habitual and standardized. Besides, research efforts on the harmless treatment process of used batteries must be increased, and authorities should provide policy or financial support for treatment processes and achievements that are pollution-free or less polluting, low-cost, less energy consuming, and have quick results, so that discarded used batteries can enter a virtuous cycle of production – consumption – regeneration.

The flow chart of optimization of waste battery management logistics is shown in Fig. 2.3.

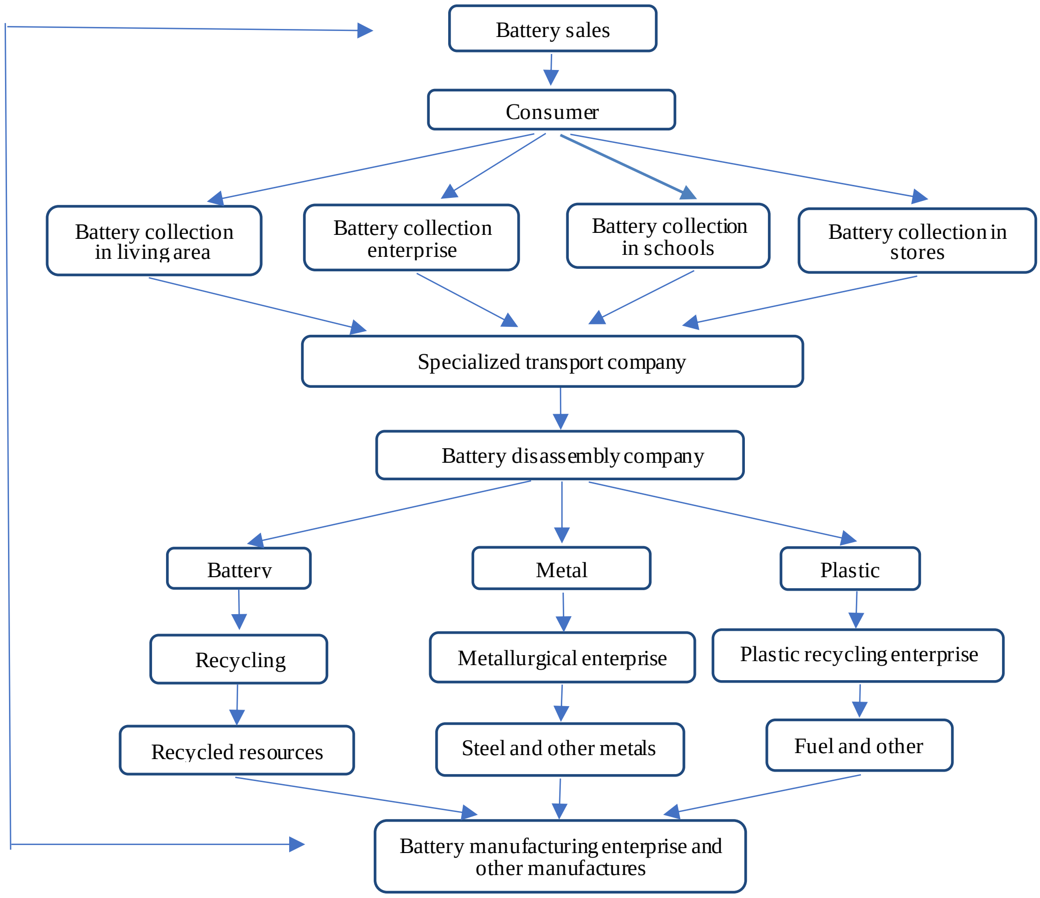

Figure 2.3 – The flow chart of waste battery management logistics optimization

2.5 Conclusion to the Chapter 2

This chapter first outlines the classification standards and corresponding storage requirements for different types of waste batteries (ordinary, explosive, and hazardous waste batteries). It emphasizes that hazardous waste batteries must be stored according to hazardous waste standards and clearly labeled; storage methods should be moisture-proof, fire-proof, and high-temperature-proof, avoiding mixing different types of batteries; storage facilities should have seepage-proof, acid-proof, dust-proof, ventilation, and fire-fighting systems.

This chapter points out that China's waste battery collection rate is low, mainly due to: high government regulatory investment and weak private recycling organizations; a lack of a sound market mechanism and logistics system; low public environmental awareness; and inadequate collection channels. China's collection system is still in its early stages of public welfare operation, lacking a profit mechanism and unified standards.

This chapter summarizes the collection of waste batteries, aiming to raise public awareness of this issue and promote the improvement of waste battery collection and environmental awareness. The chapter explains the comprehensive sources of waste batteries and the current specific collection methods. In response to the current situation of waste battery collection and the situation of the battery industry, the collection and treatment of waste batteries is solely based on government policies the efforts of governments, enterprises, or non-governmental organizations are difficult to achieve significant results, and it is necessary to provide waste battery collection as a system. The success of the paid collection system and the logistics system are key factors in the waste battery collection system.

This chapter proposes several improvement measures: it suggests exploring monetization or a points-based incentive system, combining it with China's tradition of "exchanging waste for money," but cautions against high costs, counterfeit goods inflows. Unified standards, technical specifications, and accountability systems should be established, and technological innovation, market mechanisms, and alignment with international standards should be strengthened. Media and community activities should be utilized to raise public awareness and foster an atmosphere of shared participation across society.

This chapter emphasizes that waste batteries should be sorted and collected separately at the source: avoiding mixing with household waste for incineration or landfill to prevent heavy metal pollution; strengthening environmental assessments of battery manufacturers; encouraging the production of green and environmentally friendly batteries; raising public environmental awareness; and promoting a circular economy model of "production-consumption-recycling."

CHAPTER 3

EVALUATION OF RESOURCE RECOVERY POTENTIAL OF WASTE BATTERIES

3.1 Volume of waste batteries generation

The generation of waste batteries is mainly related to their usage and lifecycle. Here are some of the main ways in which used batteries are generated [62]:

1. End of product lifecycle

Consumer electronics products, such as mobile phones, laptops, tablets, etc., will have their batteries replaced or discarded as technology updates and product lifespan comes to an end. After a certain period of electric vehicles use (usually 8–10 years), the performance of electric vehicle batteries will decline and eventually need to be replaced, resulting in waste batteries [63].

2. Battery malfunction or damage

Accidental damage: during use, the battery may malfunction due to collisions, overcharging, short circuits, and other reasons, rendering it unusable.

Natural aging: after long-term use, the internal chemicals of the battery will gradually degrade, leading to a decrease in battery performance and ultimately unable to function properly.

3. Replacement and upgrade

Technological progress: with the emergence of new technologies, consumers may choose more efficient or longer lasting batteries for replacement, resulting in old batteries being discarded.

Design update: some products may require battery replacement due to design upgrades, such as new models of mobile phones or electric vehicles.

4. Improper use

Incorrect charging methods, such as using inappropriate chargers or overcharging, may lead to decreased battery performance and shortened lifespan.

Environmental factors: extreme temperature, humidity, and other environmental conditions can also affect the lifespan of batteries, leading to premature failure.

5. Industrial and commercial use

Backup power supply: in some industrial applications, backup power supplies (such as lead-acid batteries) are replaced after a period of use, resulting in waste batteries.

Renewable energy storage: with the popularity of solar and wind energy, energy storage batteries (such as lithium-ion batteries) will also become waste after their service life ends.

6. Losses during the recycling

In the process of battery recycling and disposal, some waste may be generated due to improper operation or insufficient technology.

7. Legal and policy impacts

Laws and regulations in some regions may require regular replacement of specific types of batteries to ensure safety and performance, which can also lead to the generation of waste batteries.

As of 2020, there are approximately 200000 metric tons of battery materials available for recycling worldwide. It is expected that by 2030, this number will increase sevenfold, reaching 1.4 million tons. By 2040, it is expected that there will be over 7 million tons of batteries at the market.

It is expected that by 2030, 100–120 GWh of electric vehicle batteries will be retired globally, which will contain a large amount of valuable metals and toxic chemicals. By 2030, it is expected that the cumulative amount of discarded electric vehicle battery modules worldwide will reach 4 million tons, which is higher than the current global recycling capacity.

The global battery recycling market is expected to reach 21 billion US dollars by 2030. It is expected that by 2030, China will contribute 57% to the world's waste battery generation. As of December 2023, China is far ahead in global battery recycling capacity, exceeding 500000 metric tons. The United States and Europe each have a recycling capacity of approximately 200000 metric tons [64].

3.1.1 Analysis of waste battery generation in Japan

In Japan, only 20% of all used batteries in the country are collected through official channels, with 93% collected through private environmental organizations and 7% collected through manufacturers. A large portion of used batteries have not been collected in a timely manner.

Most manufacturers set the recommended lifespan of cylindrical zinc carbon batteries to 2 to 3 years, and cylindrical alkaline batteries to 5 years. However, the recent advanced alkaline batteries have a shelf life of up to 10 years after the manufacturing date, as can be seen in the figure, with a shelf life exceeding 2020 [65].

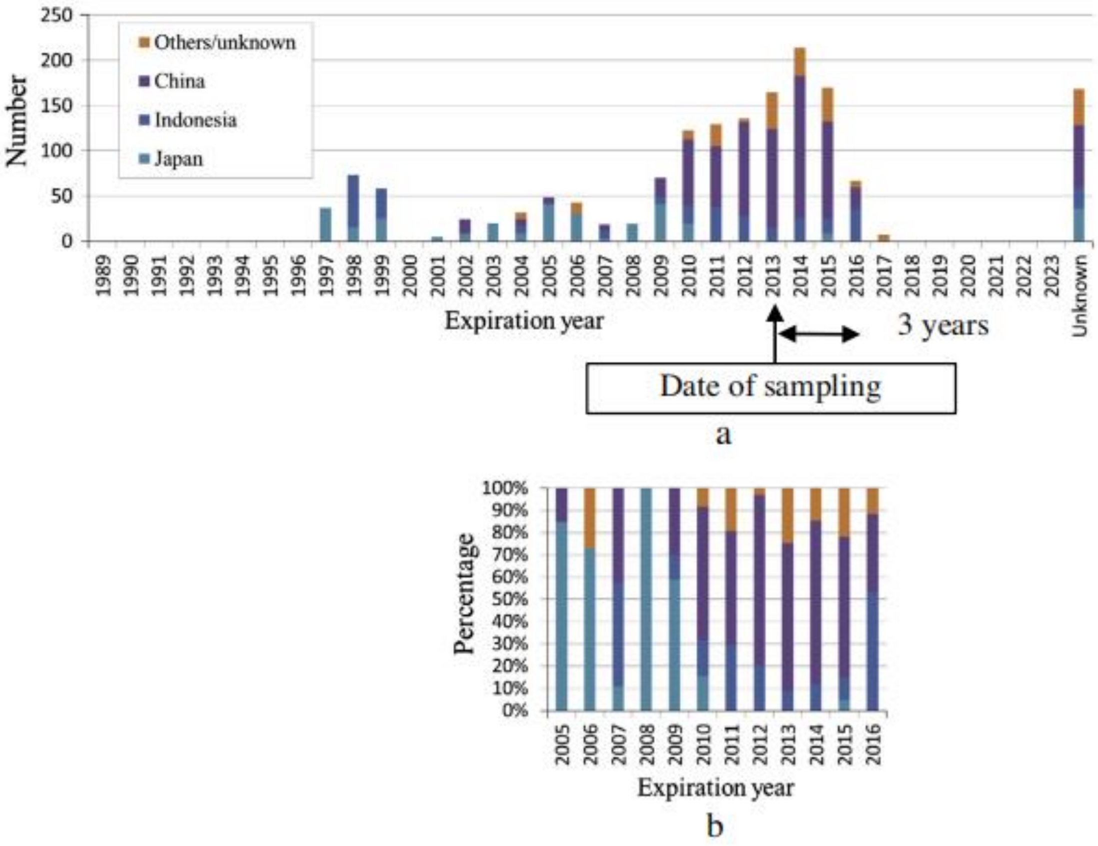

Figure 3.1 – Distribution of expiration dates of zinc-carbon batteries: number (a) and percentage (b)

Figures 3.1 and 3.2 [66] also provides information on the production location. The production of zinc-carbon and alkaline batteries discarded in Japan have shifted from Japan to China and other countries.

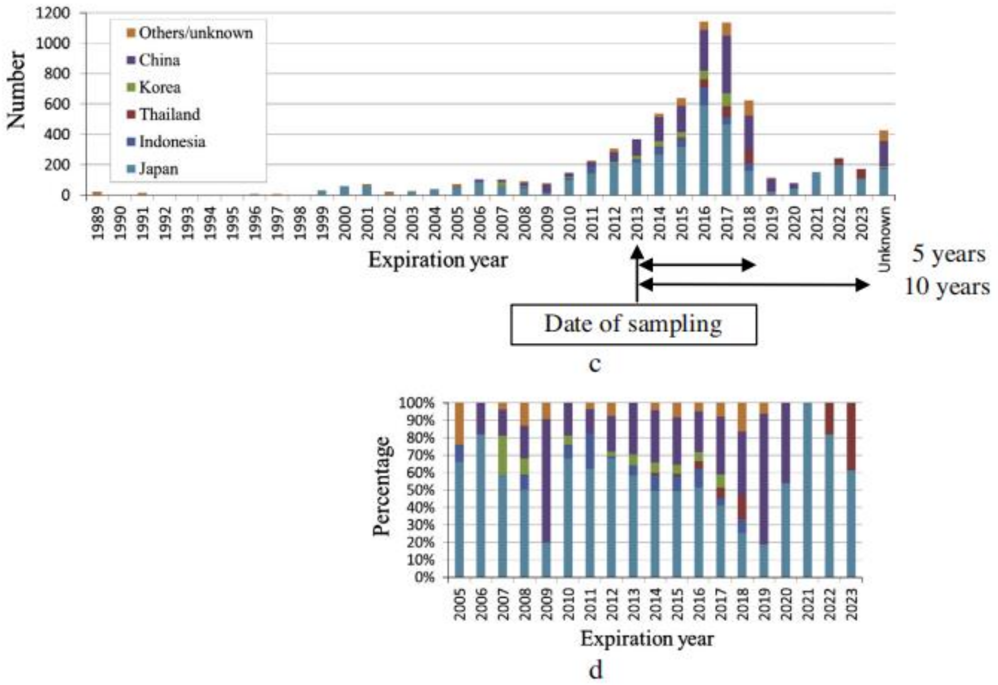

Figure 3.2 – Distribution of expiration dates of alkaline batteries: number (c) and percentage (d)

3.1.2 Analysis of waste batteries generation in the USA

The generation of used batteries in the United States is a constantly changing number, influenced by various factors including the sales of consumer electronics, the popularity of electric vehicles, and the enforcement of relevant regulations. Here is some background information and trends regarding the production of used batteries in the United States.

Source of waste batteries

The popularity of consumer electronics such as mobile phones, laptops, and tablets has led to the use of a large number of small lithium-ion batteries. With the rapid growth of the electric vehicle market, the use of lithium batteries has significantly increased, and it is expected that a large amount of waste electric vehicle batteries will be generated in the coming years. Industrial and household batteries, such as lead-acid batteries used in automobiles and other industrial applications, also contribute to the total amount of waste batteries.

Collection rate

According to data from the US Environmental Protection Agency (EPA), although the United States generates a large amount of waste batteries every year, the collection rate is relatively low. Many consumers may not know how to properly dispose of used batteries, resulting in some batteries being discarded in regular garbage. In recent years, with the improvement of public environmental awareness and the increase of recycling facilities, the collection rate of waste batteries has raised.

Statistical data

According to some industry studies, it is estimated that the number of waste batteries generated in the United States each year reaches hundreds of millions, but the specific amount varies depending on research institutions and statistical methods. For example, some reports indicate that the United States generates approximately 10 million tons of lead-acid battery waste annually.

Future trends

With the popularization of electric vehicles and renewable energy storage systems, it is expected that the generation of waste batteries will continue to increase. The government and businesses are promoting more efficient recycling technologies and infrastructure to address the challenges of future waste batteries. The generation of waste batteries in the United States is a complex and constantly changing field, involving multiple sources and recycling channels. With the increasing awareness of environmental protection and the improvement of regulations, the future management and collection system for waste batteries is expected to be further improved.

3.1.3 Analysis of waste batteries generation in the EU

According to the European Commission, the EU currently imports about 800,000 tons of car batteries, 190,000 tons of industrial batteries and 160,000 tons of consumer batteries per year. At the same time, more than 1.9 million tons of waste batteries are generated in Europe every year. According to statistical studies, automotive lead-acid batteries have the highest collection and recycling rate (99%). However, the collection rate of lithium-ion batteries in Europe is very low because lithium battery recycling is technically challenging and expensive. The number of used batteries in Europe far exceeds the local recycling capacity, and a large number of waste batteries are difficult to deal with or flow to unknown channels [67].

In Germany, it is estimated that 32 billion waste batteries are discarded globally every year, and in Germany alone, an average of 10 batteries per person are consumed every year, totaling about 30,000 tons, resulting in a serious damage to the soil environment caused by a large number of discarded used batteries [68].

In Poland, the Waste Battery Law stipulates that the mandatory waste battery collection fee is targeted at manufacturers, importers, and end-users of batteries. Users should dispose of these wastes free of charge to special suppliers. Manufacturers and importers have an obligation to achieve a certain minimum level of collection and reuse. According to the number of batteries introduced, if they fail to meet the mandatory minimum level, they must pay the fees to the Polish government. This money will be accumulated in a dedicated account of the National Environmental Protection and Water Management Fund, and will be used for social environmental education and promoting the separate collection of waste batteries [69]. This obligation can be fulfilled by the manufacturers itself or by a special organization.

Sales and collection of portable batteries in the EU from 2009 to 2022 are presented in Table 3.1 and Fig. 3.3 [71]. In 2022, around 244,000 tons of portable batteries were put on the market (sales) in the EU, while around 111,000 tons of used portable batteries were collected as recyclable waste. Thus, slightly less than half (46%) of the average annual sales of portable batteries (calculated for 2020–2022) were collected in 2022 [70].

Table 3.1. Sales of portable batteries, 2009–2022, tons [71]

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
EU, thousand tons	162	176	173	173	169	172	177	177	188	191	206	229	245	244
Belgium	4061	4351	4401	4259	4398	4222	4566	4585	4785	4920	5413	5611	6239	6024
Bulgaria	520	1052	624	602	677	730	700	750	815	690	942	940	1002	1045
Czechia	2638	3281	3393	3716	3672	4000	3985	4047	4064	4048	4293	4963	5206	5209
Denmark	3613	3062	3347	3704	3132	3637	3762	3944	3698	4475	4034	4932	5114	4598
Germany	37298	42531	43334	43549	42441	43979	43902	45511	50643	52159	55905	65368	63211	63133
Estonia	408	411	475	525	403	417	464	479	489	483	475	542	520	653
Ireland	2017	2181	2096	1951	1913	2378	2703	1968	2991	2336	2666	3543	3692	3528
Greece							1657	1599	1692	1646	1798	1850	2872	2732
Spain	12090	13023	11331	10514	10662	10815	12669	11915	12017	12774	12949	14364	15547	14842
France	29921	32914	33458	33458	32227	31330	31383	29936	31482	31329	33003	35268	37694	
Croatia			332	407	394	347	266	395	568	674	906	1052	1049	1355
Italy	27843	30313	29507	29407	27939	26944	28440	25197	25268	24807	24829	27859	32356	31812
Cyprus	180	280	272	237	226	189	206	211	233	202	175	203	197	189
Latvia	289	412	478	483	516	553	509	628	490	512	562	666	685	788
Lithuania	734	831	708	782	796	686	700	748	832	762	750	817	929	1088
Luxembourg	214	159	183	185	192	171	172	196	201	209	242	261	285	273
Hungary	2087	1858	1798	1046	1192	1726	1804	1684	2357	2842	2920	2519	3173	3302
Malta		108	87	104	89	103	74	75	68	81	172	143	164	137
Netherlands	7672	7824	7971	7322	6786	7687	8031	8830	8890	9578	8762	10889	11871	11140
Austria	3272	3642	3614	3717	3892	4087	4547	4708	4745	5449	5760	6347	6139	7153
Poland		9868	9771	10599	11264	11799	12304	12813	13426	13338	19400	19557	20846	21845
Portugal	3630	1317	1381	1615	1727	1807	1547	1778	2241	2456	2598	2623	2922	2700
Romania	2079	3447	2696	2740		2730	2646	2340	3625	2802	4276	4964	6874	
Slovenia	915	1053	670	722	720	719	663	872	790	823	833	826	884	890
Slovakia	900	950	950	1000	950	842	939	1236	1460	1534	1748	2030	2270	2430
Finland	2569	2814	2763	2752	2703	2651	2864	3026	3180	3460	3615	3626	4066	3738
Sweden	5168	6197	5708	5641	5602	6046	5812	7634	6913	6834	7386	7558	8875	
Norway		1940	1980	2015	2025	1965	1955	2230	3599	3122	4367	3526	3530	3976

The amount of portable batteries put on the market varies strongly across the EU countries, with sales in some EU countries ranging from 137 tons (Malta) to more than 63,000 tons (Germany). Overall, country-specific sales have increased over the period from 2009 to 2022, with volumes increasing for most countries. Only 2 countries (Portugal and Slovenia) reported a decrease over this period.

The amount of waste portable batteries collected is lower than the average sales over the last three years. Between 2009 and 2022, collection of waste batteries increased steadily in almost all countries. Only 1 country, Portugal, reported a smaller collected tonnage in 2022 than in 2009 [71].

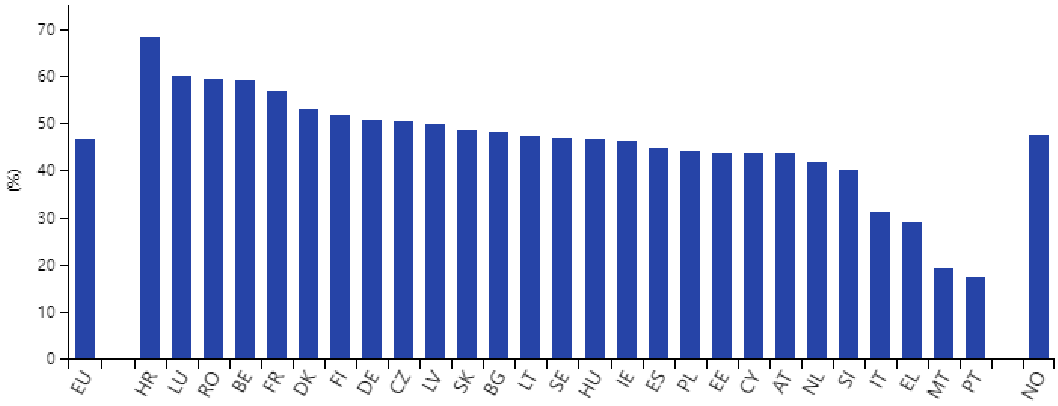

Figure 3.3 – Portable batteries collected for recycling, 2022

By contrast, the collection of waste batteries in the EU has increased steadily since 2009. Starting from around 50,000 tons in 2009, collection increased to around 111,000 tons in 2022. The tonnage collected increased each year, except for between 2019 and 2020.

3.1.4 Analysis of waste battery generation in China

China's battery production is about half of the world's total battery production. A large number of batteries are produced and consumed every year, which leads to a large number of used batteries that need to be recycled. China's primary battery, alkaline secondary battery and lithium-ion secondary battery collection and recycling system is particularly weak, waste battery recycling enterprises simply use waste batteries as raw materials, generally will suffer economic losses. Increasing the profitability of waste battery recycling systems is a key issue to consider.

According to preliminary statistics, the production of primary batteries in China reached 24.603 billion in 2003, an increase of 24.1% over 2002. In 2003, China's battery exports were 20.4 billion, an increase of 20% over 2002, and battery exports accounted for 78.8% of the total battery production. In 2003, the export volume of disposable batteries was 18.811 billion, an increase of 18.68% over 2002.

Exports amounted to $877 million, an increase of 25.6% over 2002. Among them, the export volume of zinc-manganese batteries was 18.15 billion, an increase of 19.76% over 2002 [72]. In 2003, China imported 5.736 billion batteries, an increase of 13.15% over 2002. Among them, the import volume of disposable batteries was 4.5243 billion, an increase of 10.15% over 2002. Imports amounted to $428 million, up 34.66 percent from 2002 [73]. Primary batteries was the largest and most dispersed battery products, with a total consumption of more than 8 billion in 2003, and the amount of waste reaching 400,000 tons.

In 2023, China's battery production reached 7.58 million tons, a year-on-year increase of 25%, with a total industry output value exceeding 1.4 trillion yuan [74]. Furthermore, in November 2024, China's total output of power batteries and other batteries was 950,000 tons, a month-on-month increase of 4.2% and a year-on-year increase of 33.3%, with lithium iron phosphate batteries accounting for 79.3%.

Table 3.2 shows the production of various battery types from 2018 to 2023 [75].

Table 3.2. Production of various battery types from 2018 to 2023, billion pcs.

Type of battery	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Alkaline batteries	0.66	0.86	0.9	0.43	0.37	0.4
Lithium ion batteries	5.6	7.8	11.1	14	15.7	18.9
Primary batteries and primary battery packs	38.1	42.3	46.4	40	40.1	40.8

The current standard for automotive batteries in China is that the capacity degradation should not exceed 20% of the rated capacity after driving for 8 years or 120000 kilometers. Therefore, the service life of power batteries is relatively short, usually only 5–8 years, and the effective life is even as short as 4–6 years [76]. As an example, based on the 4–6-year service life, power batteries produced in 2014 entered the retirement period in bulk starting from 2018, and China ushered in the first batch of power battery retirement peak starting from 2021.

According to the data from the China Automotive Technology Research Center, the cumulative total amount of waste power batteries in China was about 200,000 tons in 2020, and by 2025, this number raised to about 780,000 tons. Waste power batteries are likely to exceed the annual target of 1 million tons around 2027 [77].

With the continuous increase in waste power batteries and the soaring prices of metal resources such as nickel, cobalt, manganese, and lithium, the market size of China's power battery recycling industry continues to expand, rising from 5.83 billion yuan in 2018 to 20.4 billion yuan in 2022, with an annual growth rate of 36.8%. It is expected to grow to 55 billion yuan by 2027 (Fig. 3.4) [78].

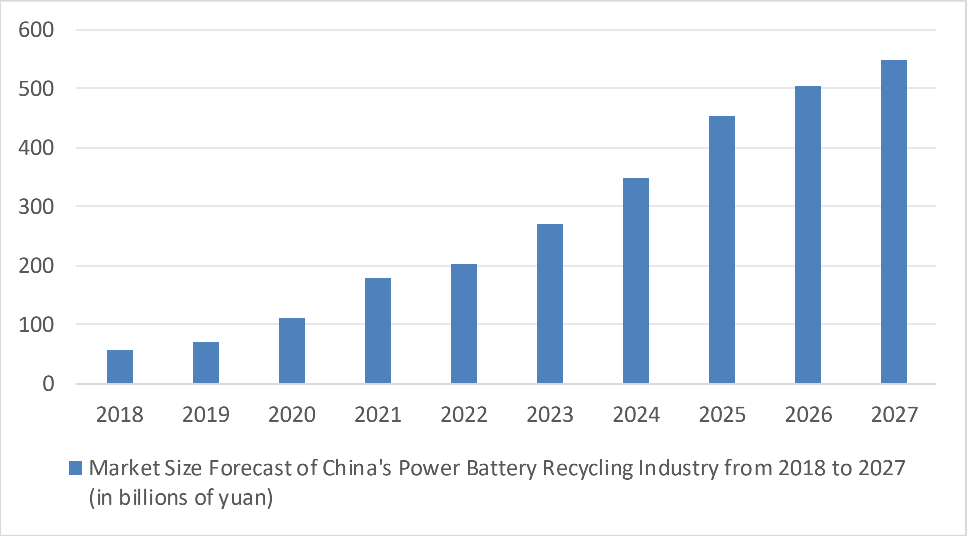

Figure 3.4 – Market size forecast of China's power battery recycling industry from 2018 to 2027

From 2018 to 2022, with the gradual retirement of power batteries used in early new energy vehicles and the continuous increase in the amount of power battery recycling in China, the power battery recycling industry has developed rapidly. Meanwhile, with the booming development of China's new energy industry, power battery companies are accelerating their expansion, and the strong demand for upstream metal resources such as nickel, cobalt, and lithium is further driving the development of the power battery recycling industry. In the future, as China's power battery recycling policies become more environmentally sound and the recycling system becomes more comprehensive, the market size of the power battery recycling industry will increase.

The service life of car lithium batteries is usually 3 to 5 years. China has vigorously promoted new energy vehicle batteries since 2016. With the centralized retirement of this batch of batteries, the Chinese power battery recycling industry has entered a period of development. From 2018 to 2022, the theoretical amount of waste car batteries in China has increased from 241,000 tons to 750,000 tons, but the actual amount has increased from 112,000 tons to 300,000 tons, which is lower. The main reason is that the development time of China's car battery recycling industry is short, and there is a lack of a sound regulatory system, resulting in a low collection rate. Theoretical and actual collection of car batteries in China, as shown in Fig. 3.5 [78] from 2018 to 2022.

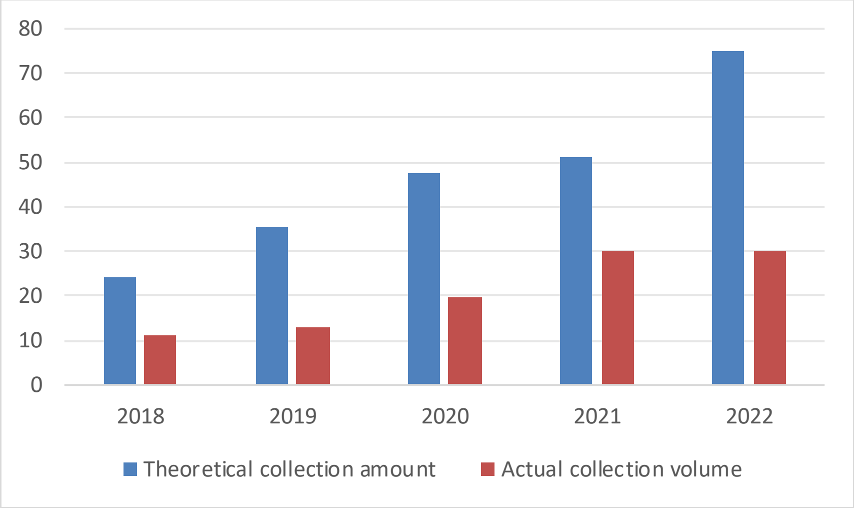

Figure 3.5 – Theoretical and actual collection of car batteries in China, 2018-2022 (unit: 10000 tons)

Due to the explosive growth of downstream application scenarios such as new energy vehicles and energy storage, the global power battery industry is thriving. It is expected that by 2030, the global demand for lithium batteries will reach 4 TWh. Among them, China, as the largest demand and supply market for the global lithium battery industry, will continue to lead the industry transformation. At the same time, Europe and the United States will contribute more incremental drivers under strong demands such as emission reduction targets and energy transformation, and reshape the global market supply and demand pattern. Emerging markets represented by

Southeast Asia, India, and the Middle East are also entering a rapid growth stage and actively participating in the global lithium battery supply chain system.

Currently, China still plays a leading role in various key links of the lithium battery industry chain, but is facing market competition. Figure 3.6 [79] shows the comparison of annual power battery production in various countries in 2023.

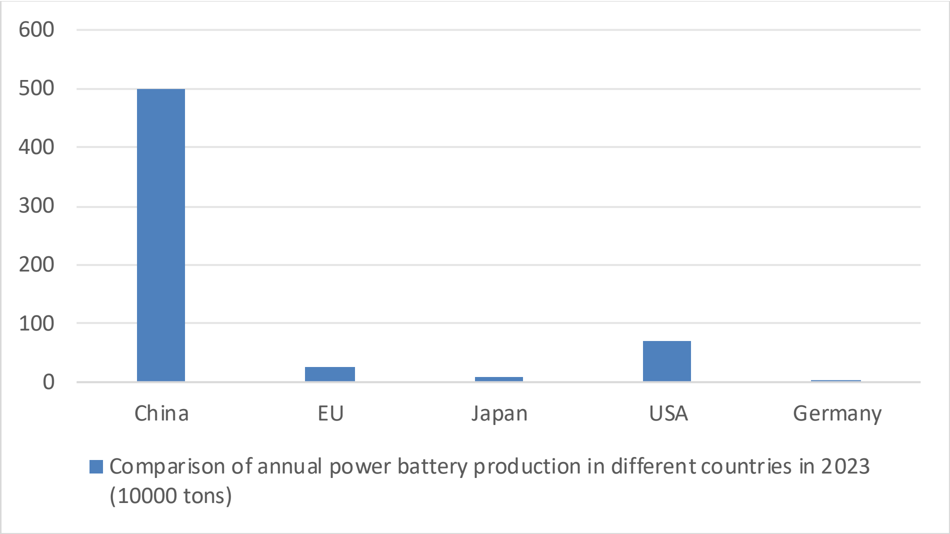

Figure 3.6 – Comparison of annual power battery production in different countries in 2023 (unit: 10000 tons)

3.2 Evaluation of waste batteries flows in China

China is the world's largest producer and consumer of dry cell batteries, accounting for one-third of the world's annual battery production and consuming about 7 to 8 billion batteries per year. However, the battery collection rate is less than 2% [80]. Although China has made relevant provisions on hazardous waste in the Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste , due to the variety of battery types and the lack of clear definition of their hazardousness, most of China's waste batteries are not managed as hazardous waste. On December 31, 1997, the China National Light Industry Council, the Ministry of Economic Affairs and Trade, the Ministry of Trade, the State Administration for Industry and Commerce, the State Environmental

Protection Administration [81], the General Administration of Customs, the State Administration of Technical Supervision, and the State Administration for Market Regulation jointly issued a document prohibiting the production of batteries with a mercury content over 0.025% of their weight from January 1, 2001, and prohibiting the production and sale of batteries with a mercury content over 0.0001% of their weight from January 1, 2006. The Ministry of Construction, the Ministry of Science and Technology, and the Ministry of Commerce jointly issued the “Technical Policy for the Prevention and Control of Waste Battery Pollution” [82]. This policy is a guiding document that provides guidance for the entire process of waste battery classification, collection, transportation, comprehensive utilization, storage, and treatment, as well as other pollution prevention and control measures. It also stipulates the technical conditions, planning, projects, site selection, facility construction, and operation management for the collection and treatment of waste batteries. It also stipulates that the focus of waste battery collection is on waste rechargeable batteries such as cadmium nickel batteries, nickel hydrogen batteries, lithium-ion batteries, and lead-acid batteries, and waste button-type primary batteries such as silver oxide batteries and other button batteries.

3.2.1 Trends in battery production

In China, the "Technical Policy on the Prevention and Control of Hazardous Waste Pollution" provides for the prevention and control of special hazardous waste pollution: the state and local governments at all levels should formulate technical and economic policies to phase out mercury- and cadmium-containing batteries. The manufacturers should adjust the product structure in accordance with the state laws and industrial policies, and phase out the mercury- and cadmium-containing batteries on schedule. Before the mercury- and cadmium-containing batteries are phased out, household waste disposal units should establish classified collection, storage and treatment facilities for the effective management of waste batteries. Separate collection of waste batteries is promoted to avoid waste batteries containing mercury and cadmium mixed with household waste incineration facilities. Waste lead-acid batteries must be collected, and must not be disposed of by other means, and their collection and transportation must be included in the management of hazardous waste.

Battery industry development and adjustment is focused on mercury-free alkaline zinc-manganese batteries, nickel-metal hydride rechargeable batteries, lithium-ion batteries, fully sealed lead-acid batteries, fuel cells, solar cells and other new high-energy batteries [83].

The average annual growth of primary batteries is 200 million pcs. The focus should be on adjusting the product structure, increasing the proportion of alkaline zinc-manganese batteries, and accelerating the process of low-mercury and mercury-free batteries.

Nickel-cadmium batteries gradually phase out of production. Instead, non-mercury and non-cadmium batteries are increased: nickel-metal hydride batteries (0.8 billion pcs/year, annual growth of 45%), lithium batteries (200 million pcs/year, annual growth rate of 108%), lead-acid batteries (annual growth rate of 5%) [83].

3.2.2 Estimation of waste batteries generation in China

Estimation of waste batteries generation usually involves several steps as follows.

1. Assessment of batteries quantity placed on the market. A combination of two sources were used:

a) Analysis of domestic production and net import/export of batteries. The annual batteries amount data can be calculated according to the following equation:

$$POM(t) = P(t) + I(t) - E(t), \tag{3.1}$$

where $POM(t)$ is the amount of batteries placed on the market in the year t, $P(t)$ is the domestic production of batteries in the year t, $I(t)$ is the amount of batteries imported in the year t, and E(t) is the amount of batteries exported in the year t [84]. Import and export data for time period of 2014 to 2023 were retrieved from the

United Nations Commodity Trade Statistics [85]. The production data were searched for in open access sources.

b) Data analysis of battery circulation in China. Mainly based on sales data at Chinese market, have been obtained through statistical analysis of sales data from battery manufacturers, market research, etc.

2. Estimation of the average lifespan of batteries. Different types of batteries have different lifespans. Generally speaking, the lifespan of lead-acid batteries is about 3–5 years, while the lifespan of lithium-ion batteries is about 2–10 years. The manufacturers' characteristics of batteries and literature data were analyzed to estimate the lifespan of various batteries.

3. Calculation of waste batteries generation. A Weibull lifetime distribution has been used many times for estimation of waste generation [84]. It is calculated based on Weibull function, and then the annual waste generation is calculated according to the annual sales and the Weibull lifetime distribution. The density function of the Weibull distribution is given as follows (Equations 3.2–3.4):

$$\left(\frac{T_{\mathrm{average}}}{\mathrm{T}_{\mathrm{max}}}\right)^{\beta} = \frac{\beta-1}{-\beta\cdot ln0.01}; \tag{3.2}$$

$$\eta = \mathrm{T}_{\mathrm{average}}\cdot\left(1-\frac{1}{\beta}\right)^{-\frac{1}{\beta}}; \tag{3.3}$$

$$\mathrm{f(T)}=\frac{\beta}{\eta}\cdot\left(\frac{T}{\eta}\right)^{\beta-1}\cdot e^{-\left(\frac{T}{\eta}\right)^{\beta}}, \tag{3.4}$$

where $f(T)$ is the Weibull lifetime distribution function, in which β is the shape parameter ($\beta > 0$), η is a scale parameter ($\eta > 0$), $T_{average}$ is the average lifetime of the battery corresponding to the median of the Weibull distribution curve, namely, the maximum density of the function, and T_{max} corresponds to the time when 99% of the batteries have been scrapped. In this study, we assume that the T_{max} of the batteries is twice the corresponding $T_{average}$.

The quantity of waste generated in a specific year is calculated by a collective sum of discarded products that were placed on the market in all historical years multiplied by the appropriate lifespan distribution. The lifespan distribution reflects the probability of a product batch being discarded over time [86]. That means each product (each battery type) has its own lifespan distribution based on lifetime. Therefore, Weibull parameters were calculated for each battery type according to Eqs. 3.2–3.3, followed by lifespan distribution calculation according to Eq. 3.4.

Calculations

Assessment of batteries quantity placed on the market

Relevant tables are placed in the Annex C.

Primary batteries import/export

1. Silver oxide batteries (UN code 850640-Cells and batteries; primary).

China's imported and exported amount of silver oxide primary cells and batteries between the years 2014 and 2023 are shown in Fig. 3.7.

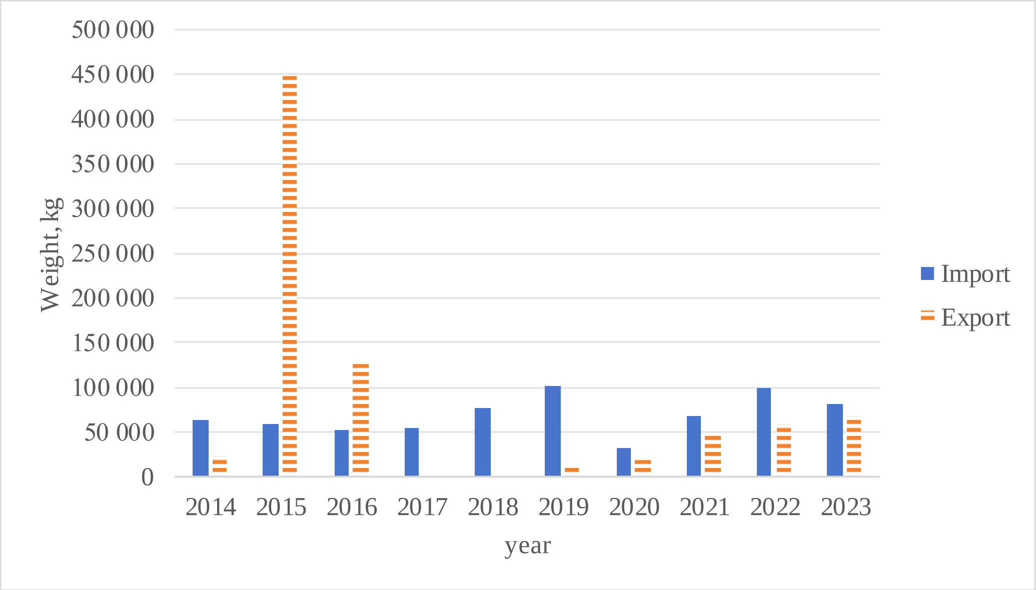

Figure 3.7 – Silver oxide primary batteries import and export

2. Lithium primary batteries (UN code 850650-Cells and batteries; primary, lithium).

China's imported and exported amount of lithium primary cells and batteries between the years 2014 and 2023 are shown in Figure 3.8.

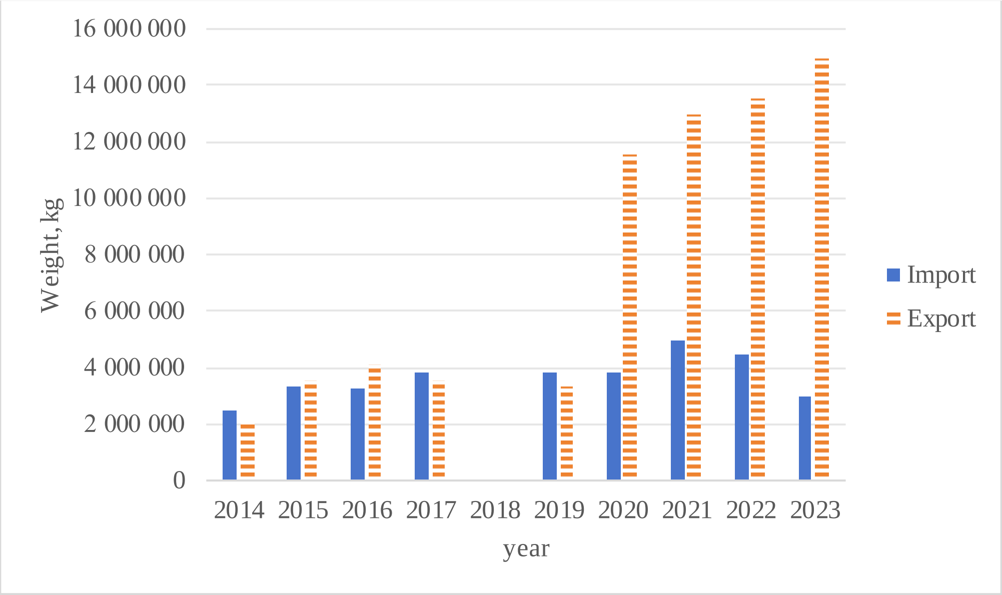

Figure 3.8 – Lithium primary batteries import and export

3. Air-zinc batteries (UN code 850660-Cells and batteries; primary, air-zinc).

China's imported and exported amount of air-zinc batteries primary cells and batteries between the years 2014 and 2023 are shown in Figure 3.9.

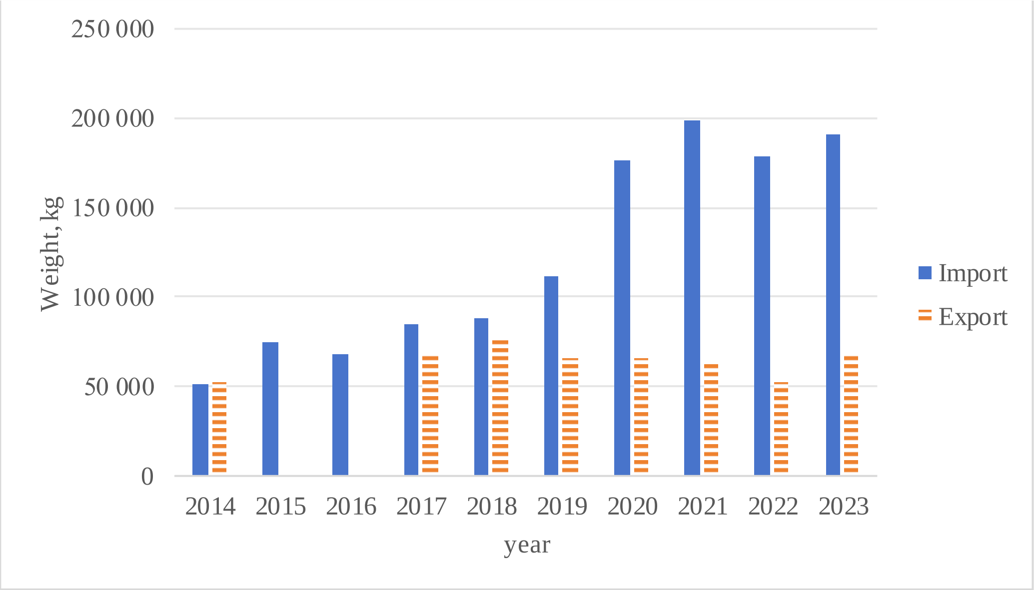

Figure 3.9 – Air-zinc primary batteries import and export

Rechargeable batteries import/export

4. Lead-acid batteries (UN code 850710 and 850720-Electric accumulators, lead-acid).

China's imported and exported amount of lead-acid batteries between the years 2013 and 2023 are shown in Figure 3.10.

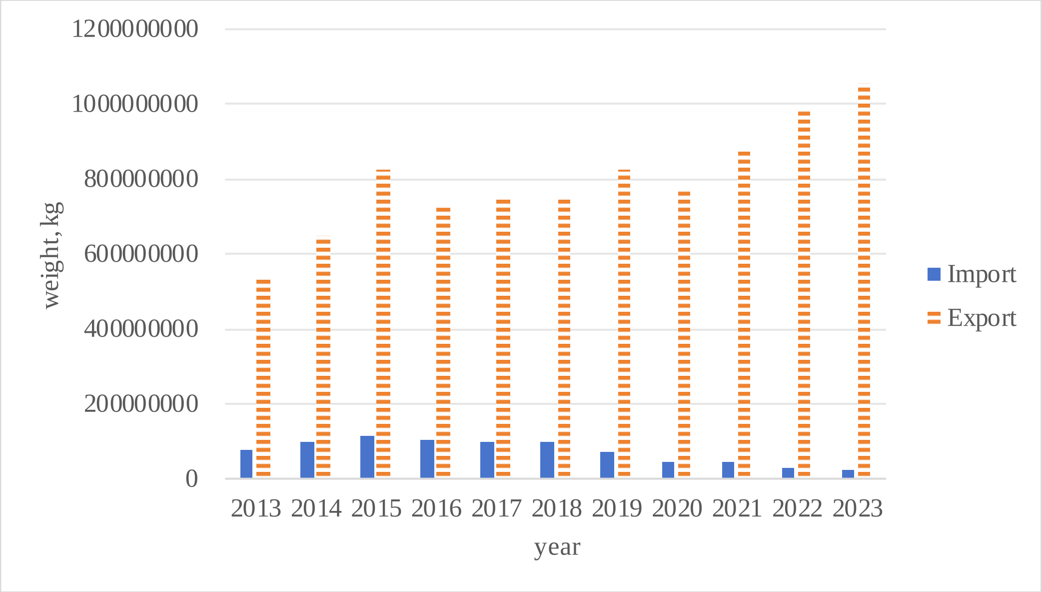

Figure 3.10 – Lead-acid batteries import and export

5. Nickel-cadmium batteries (UN code 850730-Electric accumulators, nickel-cadmium).

China's imported and exported amount of nickel-cadmium batteries between the years 2013 and 2023 are shown in Figure 3.11.

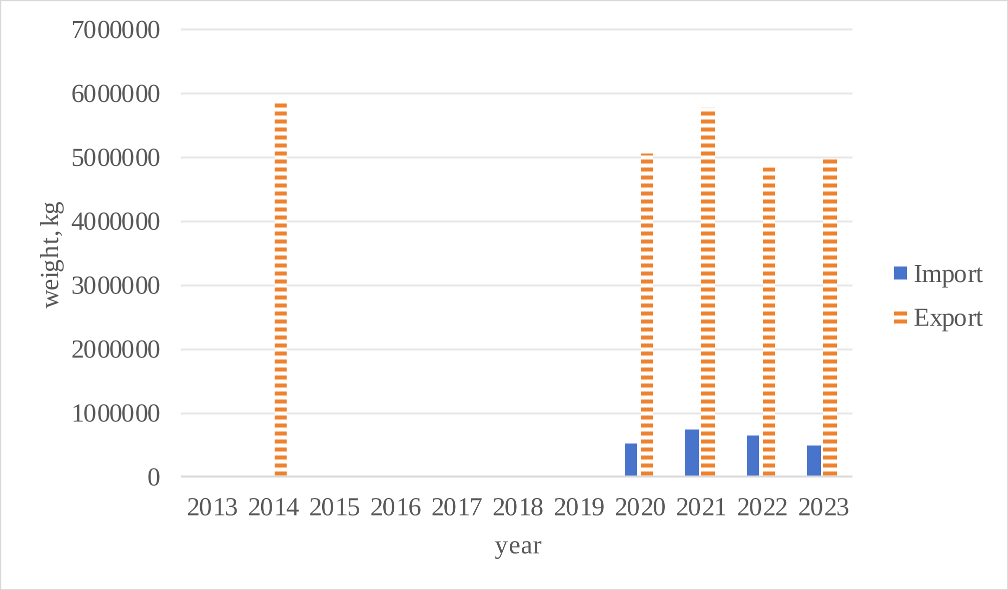

Figure 3.11 – Nickel-cadmium batteries import and export

6. Lithium-ion batteries (UN code 850760-Electric accumulators, lithium-ion).

China's imported and exported amount of lithium-ion batteries between the years 2013 and 2023 are shown in Figure 3.12.

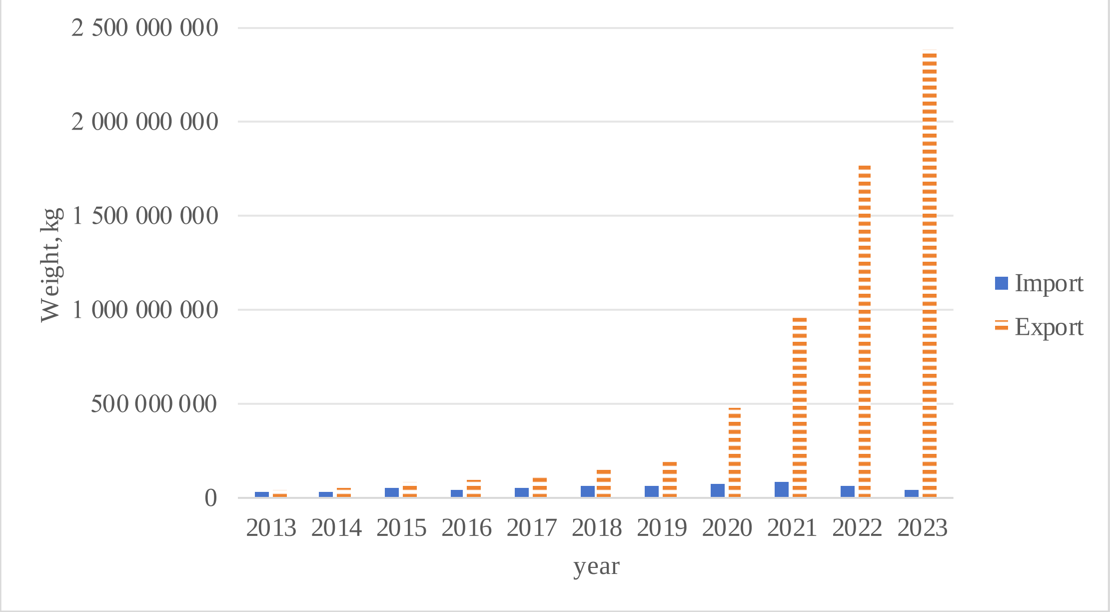

Figure 3.12 – Lithium-ion import and export

According to the Fig. 3.6–3.12, the following analysis is inferred based on common industry trends and battery type characteristics. Actual changes need to be further verified in combination with chart data.

Silver oxide batteries had a small number in the early stage of technology replacement from 2014 to 2015, an increase in number due to the growth in demand for medical equipment from 2016 to 2019, a decrease in the supply chain due to the impact of the epidemic in 2020, and an increase in the number of medical recovery after the epidemic from 2021 to 2023. The import and export volumes show a fluctuating trend. The demand for silver oxide batteries in the high-end field may be relatively stable, but the total amount is small, which may be related to the demand for medical equipment, precision instruments, etc.

Lithium batteries showed an overall upward trend from 2014 to 2023, especially after 2017 (consumer electronics outbreak) and from 2020 to 2023 (new energy equipment demand). Supply chain disruptions briefly declined in the early stage of the epidemic in 2020. Especially in the context of the rapid popularization of electronic products and smart devices, China, as a major global lithium battery producer, may dominate exports, but imports may be concentrated on high value-added products.

The import and export volumes of zinc-air batteries are low, which may be related to the limitations of its application areas (such as hearing aids and military equipment). It may have potential in the development of environmentally friendly battery technology in the future. The number was small due to technical limitations from 2014 to 2016. The number increased from 2018 to 2020 apparently due to the expansion of the hearing aid market, and decreased in 2021 due to lithium battery competition. The new increase in 2022–2023 is related to demands in the emergency field.

Lead-acid batteries export increased gradually in recent 10 years, while import had a peak in 2015 (due to the growth of automobile and energy storage demand) followed by the substantial decrease. It may be affected by environmental protection policy restrictions (such as lead pollution control) and substitution by lithium-ion batteries. Besides, the replacement of lead-acid batteries was accelerated in 2020–2023 due to electric cars expansion.

The import and export volume of nickel-cadmium batteries has been declining year by year, mainly due to its environmental pollution problems and its replacement by more efficient nickel-metal hydride batteries and lithium-ion batteries. China gradually reduces the production and export of such batteries. The overall reduction was noticed especially after EU ban on cadmium use.

Finally, lithium-ion batteries, as everywhere, have constantly been increased. Especially, export rose dramatically after 2019 with China becoming the world’s largest lithium-ion battery producer.

Production of batteries in China

According to various websites, China Battery Association (CBA) annual report query, industry reports, there are some very limited data on lithium battery, lead-acid battery, and silver oxide battery production (Fig. 3.13–3.14).

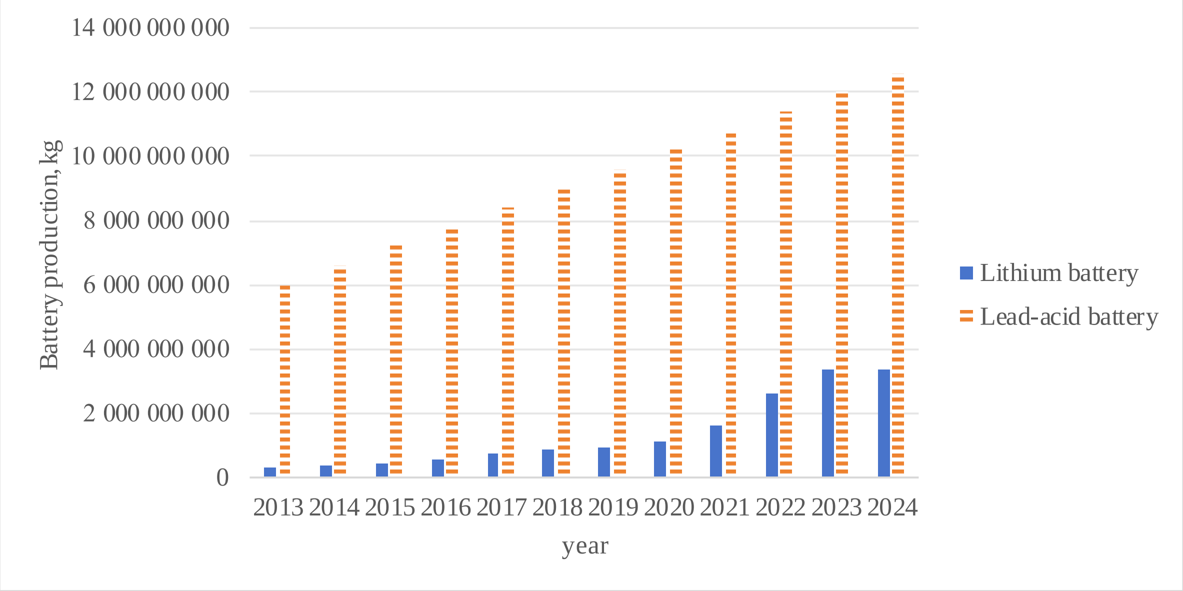

Figure 3.13 – China's lithium and lead-acid battery production

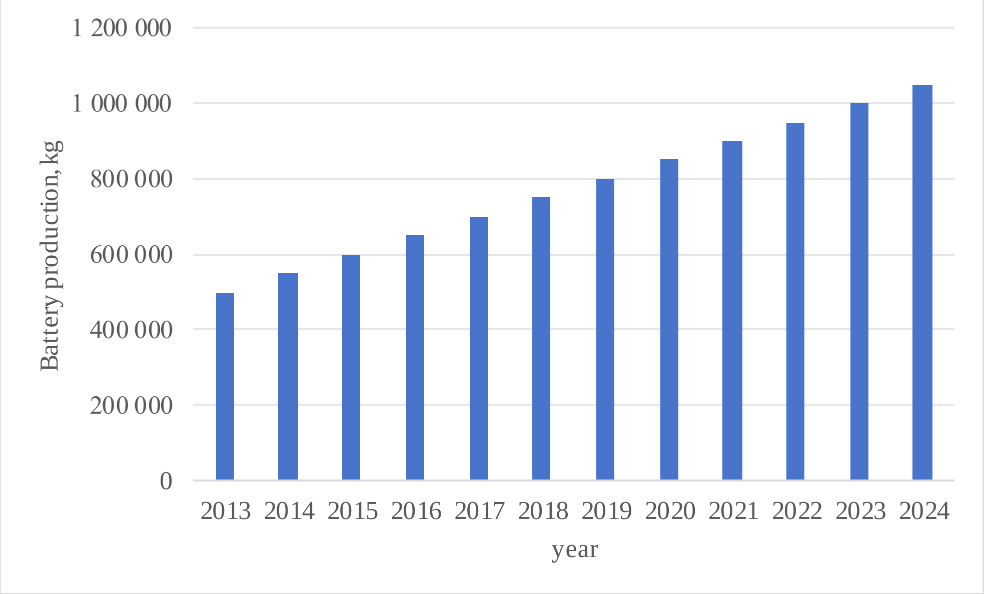

Figure 3.14 – China's silver oxide battery production

As one can see, there is constant growth of battery production in China. Lead-acid and silver oxide batteries were doubled in previous 10 years. In the same time, the domestic production of lithium batteries in China increased dramatically in past 5 years. Lithium batteries comprises both primary lithium and lithium-ion batteries.

Batteries placed on the market in China

The specific data of sales volume of some battery types in China from 2013 to 2023 are included in the Table3.14: both calculated by the Eq. 3.1 and searched (literature data).

Table 3.14. Amount of batteries placed on the Chinese market (tons)

Year	Lithium battery (lithium primary + lithium-ion)		Lead-acid battery		Silver oxide battery		Zinc-air batteries		Nickel-cadmium batteries	
	Calculated	Literature data on sales	Calculated	Literature data on sales	Calculated	Literature data on sales	Calculated	Literature data on sales	Calculated	Literature data on sales
2014	370794	150000	6051364	21000000	589	520	50000	52000		9500
2015	464032	250000	6489138	22000000	211	540	52000	54000		9000
2016	585328	350000	7181672	23000000	576	560	54000	56000		8500
2017	733663	500000	7752283	24000000	754	580	56000	58000		8000
2018	875000	750000	8346792	25000000	826	600	58000	60000		7500
2019	944928	1000000	8844298	26000000	890	620	60000	62000		7000
2020	1092308	1250000	9469973	27000000	862	640	62000	64000	6500	6500
2021	1582912	2000000	9967795	28000000	920	660	64000	66000	6000	6000
2022	2590955	3300000	10444671	29000000	990	680	66000	68000	5500	5500
2023	3345123	4500000	10967450	30000000	1013	700	68000	70000	5000	5000

Since the production of lithium-ion batteries alone is not known, we can use lithium battery (lithium primary + lithium-ion) production for the following calculations.

If no production data were available for certain battery type, the sales data found in the open sources were used as POM amount.

Estimation of average lifespan of batteries

The life of lead-acid batteries is relatively short, with a typical charge and discharge cycle of 300–500 times and a service life of about 2 years. The self-discharge rate of silver oxide batteries is relatively low, about 5–10% per year. The lifetime of such battery is usually 1.5–2 years. In this study, we use 2 years lifespan for lead-acid batteries.

Silver oxide battery has an average lifespan around 2–3 years [87]. In this study, we use 2 years lifespan for lithium batteries.

Zinc-air battery has very short lifetime – up to 1 year [88]. In this study, we use 1 year lifespan for zinc-air batteries.

The life of lithium-ion batteries is usually measured by the number of charge and discharge cycles. Generally, the lifecycle of lithium-ion batteries is 300–500 times (the capacity drops to about 80% of the initial capacity). High-quality lithium-ion batteries (such as lithium iron phosphate batteries) can have a lifecycle of more than 2,000 times. For different applications, there are different lifespans: electric car – 8–12 years, smartphone – 2–4 years, laptop – 4–6 years [89]. In this study, we use 4 years lifespan for lithium (lithium-ion) batteries.

The lifecycle of nickel-cadmium batteries is usually 500–1,000 times (the capacity drops to about 80% of the initial capacity). Under ideal conditions, high-quality nickel-chromium batteries can achieve a cycle life of more than 1,500 times. The lifecycle of nickel-cadmium batteries is usually 4–5 years [90]. In this study, we use 2 years lifespan for nickel-cadmium batteries.

Calculation of waste batteries generation

According to the Eq. 3.2–3.4, the specific trends of waste battery generation were obtained (see Fig. 3.15–3.19). For most battery types, the calculation has been done for years 2019–2023 because time period of 2014–2018 does not include batteries sold before 2014 (we have the data starting from 2014). For nickel-cadmium batteries POM has been calculated for years 2020–2023 due to the lack of data. Therefore, only forecast can be done for this battery type for the years 2026–2030 (taking into account average 5-year lifetime).

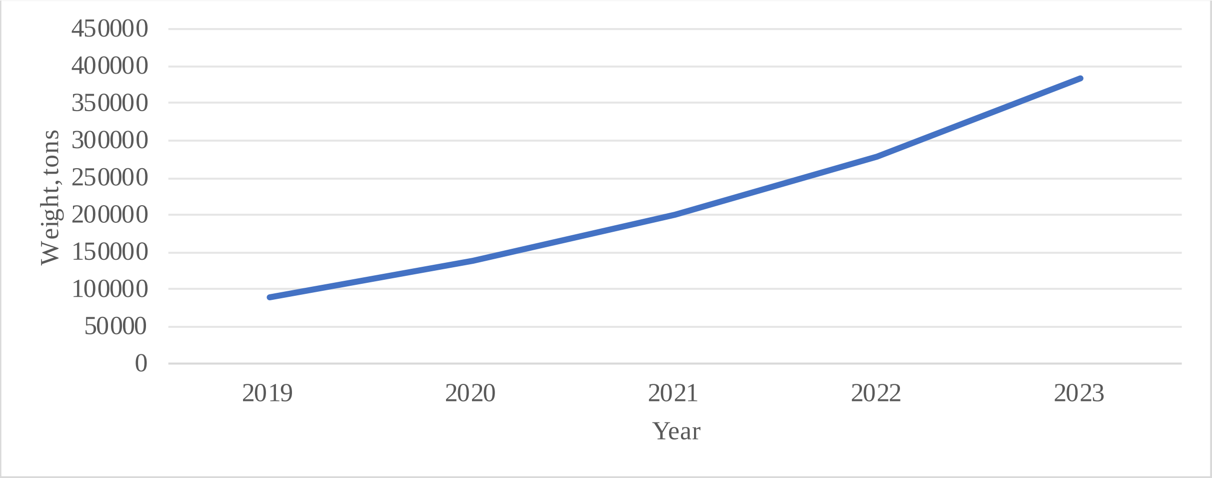

Figure 3.15 – Waste lithium battery generation

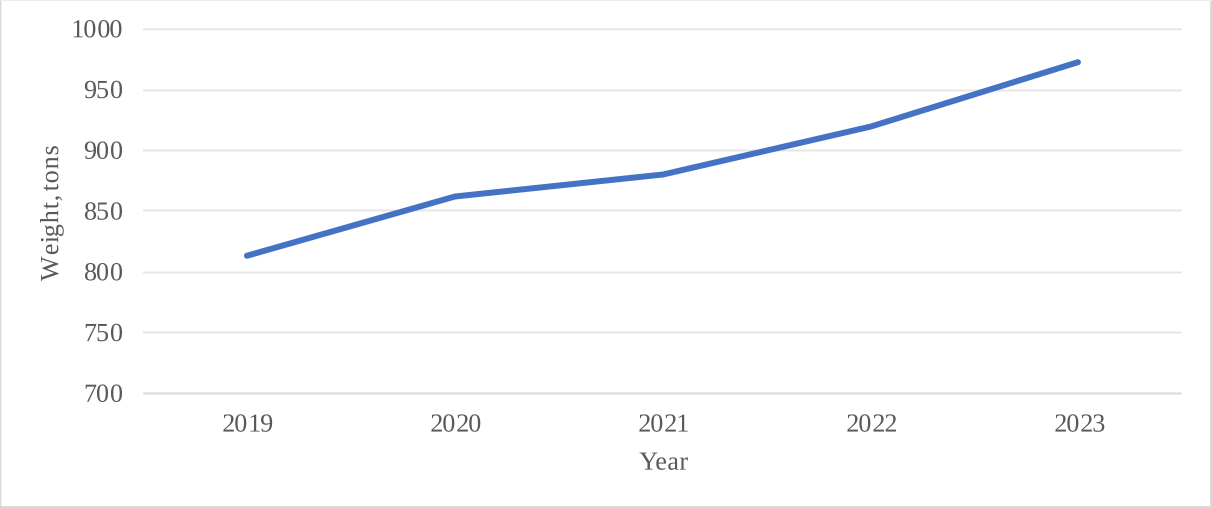

Figure 3.16 – Waste silver oxide battery generation

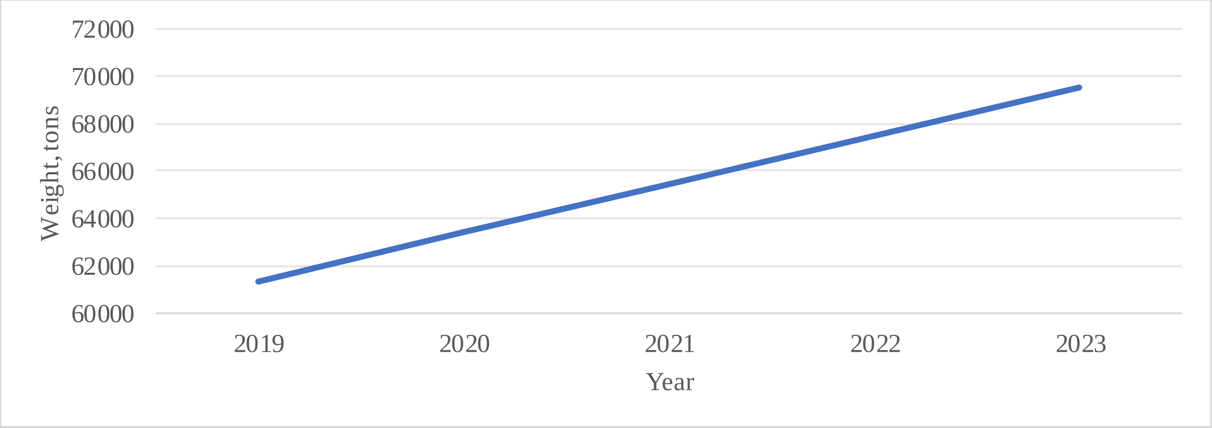

Figure 3.17 – Waste air-zinc battery generation

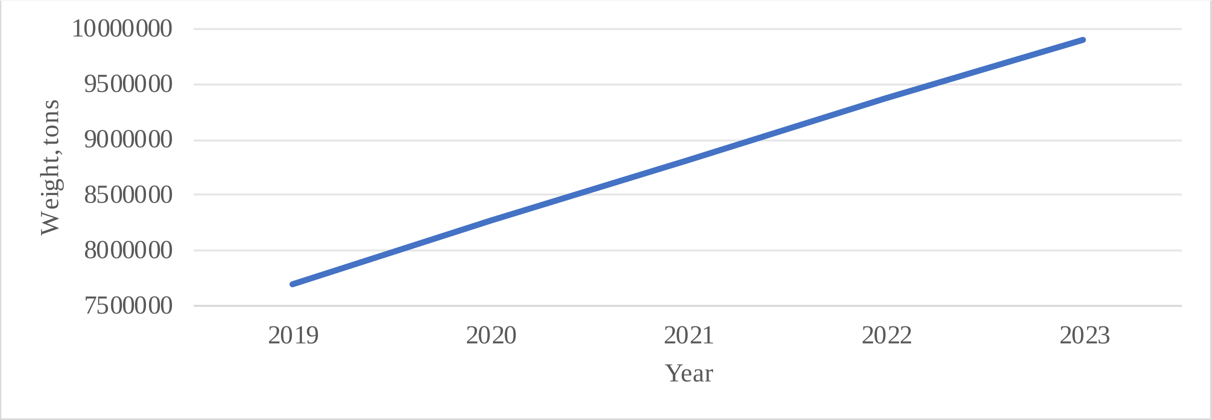

Figure 3.18 – Waste lead-acid battery generation

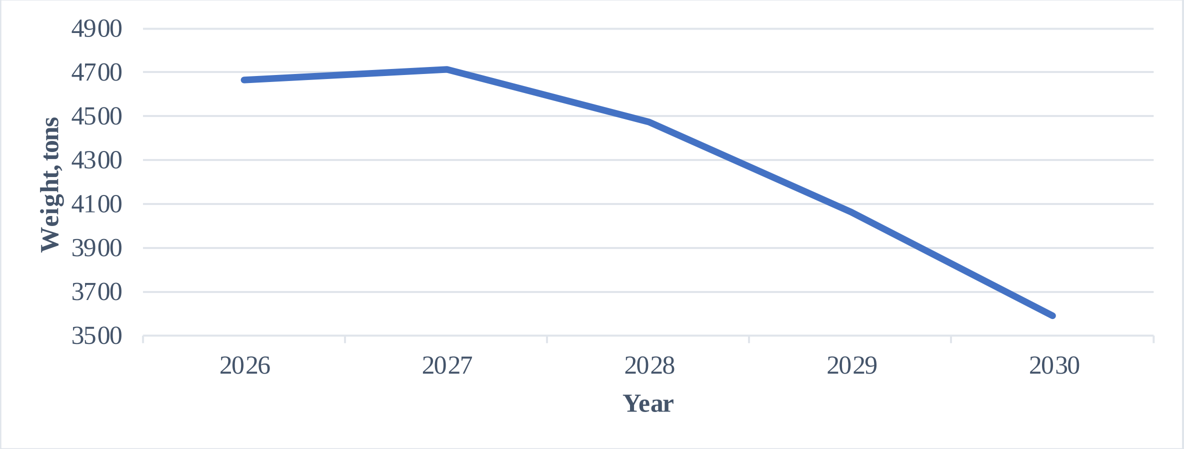

Figure 3.19 – Waste nickel-cadmium battery generation

According to Fig. 3.15–3.19, the waste batteries generation trends show the following characteristics:

Waste lithium batteries (Fig. 3.15). With the rapid popularization of new electric vehicles and consumer electronics (such as smartphones and laptops), use of lithium batteries has surged, resulting in an increase in their waste volume year by year. Especially, electric vehicles enter the waste cycle after 2020 (average lifetime 5–8 years), and the volume of waste batteries has increased significantly.

Waste silver oxide batteries (Fig. 3.16). In 2019–2021, the replacement of medical equipment (such as hearing aids and precision instruments) has accelerated, resulting in the increase of waste silver oxide batteries with possible peak in 2023.

The growth of waste zinc-air batteries (Fig. 3.17) and waste lead-acid batteries (Fig. 3.18) is similar, but future trends can be different. While zinc-air batteries are still demanded, though in limited quantities, in various equipment, the use of lead-acid batteries seems to have passed a peak value (due to electric cars expansion) meaning less waste battery generation in coming years.

Waste nickel-cadmium batteries are the only battery type demonstrating reduction according to the forecast (Fig. 3.19). This is mainly affected by environmental protection bans and nickel-cadmium battery market shrinks.

In summary, waste lithium batteries (driven by the new energy industry) and lead-acid batteries (huge stock market) are the main contributors to waste battery volume growth, covering 99% of around 10.5 million tons of waste battery generation in China.

Regarding the waste battery flow in China, the following may be summarized:

1. Trends in China's battery production. The development focus of China's battery industry is on new high-energy batteries such as nickel-hydrogen power batteries, lithium-ion batteries, and fully sealed maintenance-free lead-acid batteries. The average annual increase in primary batteries production is 200 million pcs, focusing on adjusting the product structure, increasing the proportion of alkaline zinc-manganese batteries, and accelerating the process of low-mercury and mercury-free batteries production.

2. Factors affecting the amount of waste batteries. The amount of waste batteries generated usually involves factors such as battery usage, lifetime, and recycling rate. The simplified steps for calculating the amount of waste batteries generated include determining battery usage, estimating the average battery life, and considering the recycling rate. Different types of batteries have different lifespans and characteristics.

3. Battery circulation analysis. China's battery sales data mainly comes from domestic production and net imports. From 2014 to 2023, China's imports of primary batteries generally showed a downward trend, while exports showed an upward trend, especially a significant increase in net export weight. For example, the export volume of lithium batteries has increased significantly after 2020, while the import volume of air-zinc batteries has increased significantly after 2020. Waste lithium

batteries (driven by the new energy industry) and lead-acid batteries (huge stock market) are the main contributors to waste battery volume growth, covering 99% of around 10.5 million tons of waste battery generation in China.

3.3 Study on resource potential of metals in waste batteries

Waste batteries contain large amounts of metals and other resources. As the price of minerals has soared, the recycling of waste batteries and the recovery of cobalt, nickel, and copper from battery is becoming important source of valuable metals.

According to the composition of the battery, the highest value metals in all types of waste batteries are silver, nickel and cadmium. The recovery value of lead, mercury and zinc is low [91]. At present, the amount of waste lead-acid batteries in China is the largest, and the consumption of lead in lead-acid battery production is about 300,000 tons. The amount of waste zinc-manganese batteries ranks second, the amount of waste nickel-cadmium batteries and nickel-metal hydride batteries was increasing, and the amount of waste silver oxide batteries and mercury oxide batteries was less. The collection of lead-acid batteries is relatively easy, and the collection of other types of waste batteries is difficult.

When collecting and recycling used primary batteries, the treatment cost mainly depends on whether the waste batteries are sorted.

In China, if waste batteries are not sorted, they may or may not contain mercury, cadmium and lead. Therefore, in the recycling process, these waste batteries must be sorted. In this case, recycling costs per ton of used primary batteries range from $1,000 (for standard waste batteries) to $2,500 (for contaminated hybrid batteries). 1 ton of waste batteries usually contain an average of 20,000 to 40,000 batteries.

The recycling costs of different types of battery vary. For example, the cost of processing a mercury-free primary battery is about $700/t, while the cost of mercury oxide button battery processing is up to $2,800. At present, mercury-free waste batteries generally account for 50% of the total amount of waste batteries, and the most expensive button batteries are less than 2% of the total amount of waste batteries.

As with the collection costs, there are certain differences in battery recycling costs for different countries.

After the use of a battery, some zinc powder and manganese powder in the battery become zinc chloride, manganese sesquioxide and other substances in the chemical reaction, but they are still valuable metal resources. According to China's production level, battery production consumes 250,000 tons of zinc, 240,000 tons of manganese, 4,500 tons of copper, and 60 tons of mercury per year. In addition, there is a considerable amount of zinc chloride, graphite, iron, etc.

Due to management and technical reasons, the recovery rate of used primary batteries in China has not been high, such as the recovery rate of zinc in many research work trials is generally 70% to 80%, the recovery rate of manganese is 80% to 90%, if expanded to industrial production recovery rate may be lower. At that rate, China still loses a significant amount of metal each year [92].

Nickel-metal hydride batteries contain a variety of high-value metals and are usually sold to recyclers at prices that depend on market conditions.

3.3.1 Resource value of waste nickel-cadmium batteries

For nickel-cadmium batteries, the price of recycling is the same as that of lead-acid batteries, and is related to the market price of nickel and its content in batteries. If the nickel price is high and the nickel content exceeds 12% of the total battery weight, the supplier of the used battery may be paid to send the used battery to the recycling processing plant. If the nickel content is relatively low, the processing fee may be increased to $400/t.

China is a cadmium-poor country, and its reserves of nickel are below the world average, both of which it imports. The recycling of waste nickel-cadmium batteries can make full use of resources and reduce the import of cadmium and nickel [93].

Cadmium is an important raw material in industrial production, and its addition has a significant impact on product performance. The main uses of cadmium are in nickel-cadmium batteries, cadmium-containing pigments, cadmium stabilizers, cadmium coatings, cadmium alloys, and cadmium compounds (like cadmium phosphide). In recent years, the main use of cadmium has shifted from traditional application areas such as pigments, stabilizers, and coatings nickel-cadmium batteries. The latter consumes more than 75% of the total cadmium usage. Figure 3.20 shows the flow of cadmium materials [94].

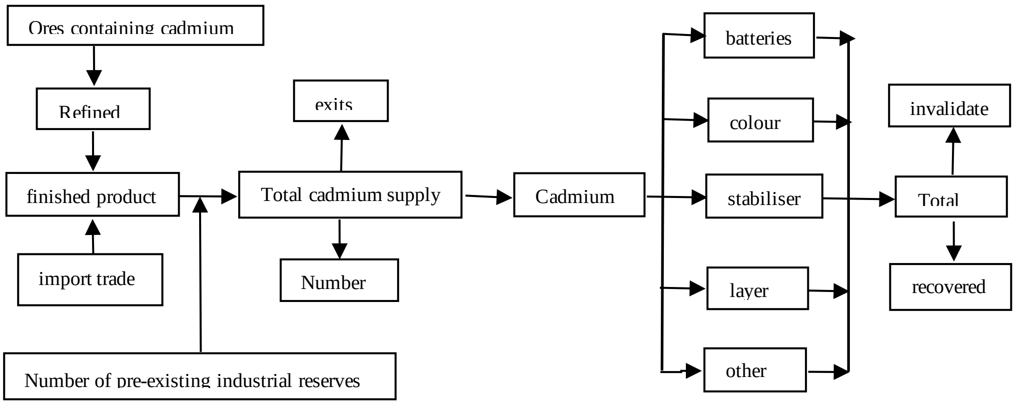

Figure 3.20 – The flow of cadmium

As can be seen from Fig. 3.20, the total cadmium supply mainly comes from refining, importing and existing industrial reserves of cadmium-containing ores. Among them, the use and waste nickel-cadmium batteries are important components of cadmium material flow. If the discarded nickel-cadmium batteries can be recycled, the refining of cadmium-containing ores will be greatly reduced. Since most of the cadmium is used in the production of nickel-cadmium batteries, if cadmium can be recovered as a pure metal and used in the production of new nickel-cadmium batteries, the closed-loop logistics cycle of cadmium will be the greatest protection for the environment and resources.

Cadmium is a rare metal, its content in a raw ore is 0.01–0.7%, the production of 1 kg of cadmium requires 10000 kg of cadmium raw ore. The cadmium content in nickel-cadmium batteries is over 20%, this is over 200 times more than in cadmium raw ore. Using waste nickel-cadmium batteries as raw materials to produce cadmium can reduce raw material consumption, reduce energy consumption, and greatly reduce waste emissions [95].

The material flow of nickel is basically similar to that of cadmium, the difference is that nickel generally cannot be recovered as a pure metal, so the recovered nickel generally cannot be used to continue the production of electrodes, but the recovered nickel can be used to produce battery casings and other nickel-containing products. The content of nickel in an ore is generally less than 1%, while it is over 25% in nickel-cadmium batteries. Thus, it can be seen that waste nickel-cadmium batteries as raw materials for nickel production also has great advantages.

Fig. 3.21 shows the logistics analysis diagram of nickel-cadmium batteries. It can be seen that if waste nickel-cadmium batteries are used as raw materials to produce new nickel-cadmium batteries, nickel ore and cadmium ore resources can be saved, and energy consumption and waste emission in the primary nickel-cadmium metal metallurgy process can be reduced [96-97].

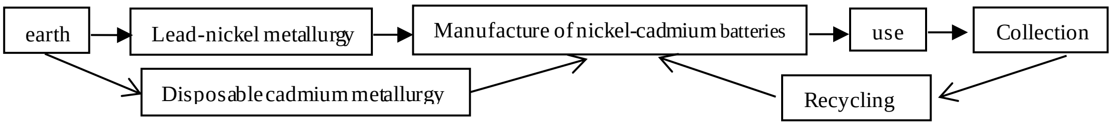

Figure 3.21 – Logistics analysis diagram of nickel-cadmium batteries

Through the life cycle analysis of small nickel-cadmium batteries, it is concluded that 65% of the energy consumption in nickel-cadmium battery production is used for battery manufacturing, and 32% is used for raw material production. When waste nickel-cadmium batteries are used as raw materials, the energy consumption in battery manufacturing will be reduced by 16%, and the energy consumption in raw material production will be reduced by 46% to 75%.

3.3.2 Resource value of waste lead-acid batteries

There are many ways to recycle waste lead-acid batteries. Most of the waste lead-acid batteries come from automobiles and other vehicles. The price of waste lead-acid batteries recycling depends on the price of lead in the metal market and the number of waste lead-acid batteries that are recycled. The treatment cost of lead-acid batteries is also related to the lead content in the battery [98]. Used waste lead-acid batteries are usually collected from consumers at the point of lead-acid batteries sale. Otherwise, waste lead-acid batteries are sent directly to recycling facilities. The cost of waste battery disposal can be included in the cost of recycled lead. Retailers and manufacturers of lead-acid batteries can also support the cost of collecting discarded lead-acid batteries at collection points [99].

In addition to the electrode plate, other parts of the lead-acid battery, such as polypropylene (or hard rubber) containers and stoppers, lead plate ends, connectors and plates (positive and negative electrodes composed of lead salts and lead oxides) and electrolytes composed of sulfuric acid solutions can be recovered [100].

Recycling the lead from waste lead-acid batteries costs 38% less than extracting it from ore, and uses one-third less energy. Therefore, the recycling of waste lead-acid batteries is of great economic value. Besides, from the environmental perspective, in addition to preventing environmental pollution, the recycling of waste lead-acid batteries also has the following effects:

(1) Reduce the amount of lead mining and extend the supply period of mineral resources.

(2) Reduce the cost of the final product. The cost of lead recycling is lower than smelting lead from ore, and the amount of waste generated is less.

(3) Save energy. The primary production of the metal is energy-intensive, while the secondary recycling of lead into commodities requires less energy.

(4) Increase the reuse opportunities for other substances in lead-acid battery products. Recycling the lead from the battery additionally recover other elements, such as tin and copper.

(5) Increase job opportunities. The collection, sorting and processing of different types of batteries, including different types of batteries within the same type, provides a large number of employment opportunities for people.

3.3.3 Resource value of waste lithium-ion batteries

Lithium-ion batteries typically consist of heavy metals, organic compounds, and plastic components in a ratio of about 5% to 20% cobalt, 5% to 10% nickel, 5% to 7% lithium, 15% organic compounds, and 7% plastic. Take cobalt as an example. As a precious metal material, cobalt is also an important strategic material and is expensive. It does not have a single deposit, but mostly occurs in copper and nickel ore with low grade. In 2006, the price of lithium cobalt oxide in China remained at around 240000 yuan/ton. By 2008, the price had soared to 600000 yuan/ton, with an increase of more than 100%. By 2023, the price of cobalt had declined somewhat, also maintaining at 275000–341000 yuan/ton, bringing specific economic pressure to the lithium ion battery industry, which requires a large number of lithium cobalt oxide materials. In 2008, China's demand for lithium cobalt oxide materials was 2400 tons, in 2016, the market demand for lithium cobalt oxide was 6500 tons, and in 2022, the market demand was even closer to 10000 tons. China is a cobalt poor country, and its own resources are far from meeting the market demand, requiring a large amount of imported cobalt [101].

In 2013, the world's demand for lithium-ion batteries will approach 4 billion units, and by 2016, the total output value of the world's lithium-ion battery market will reach 10 billion USD. Countries all over the world pay more attention to cobalt recycling in industrial production. In China, the demand of cobalt is about 600–800 tons every year, and over 60% is imported. As can be seen from Table 3.16, waste lithium-ion battery is a kind of waste with high cobalt content. A 40 g lithium-ion battery contains about 6 g of metallic cobalt, which is far greater than the cobalt content in natural minerals. According to the current production of lithium ions, after 2–3 years of lithium-ion service life, the number of waste lithium-ion batteries will reach 2–5 billion tons. If effective metal recovery can be carried out, about 600 tons of cobalt can be recovered. Therefore, centralized recycling and utilization of used lithium ion batteries can effectively reduce their damage to the environment, alleviate the pressure on environmental protection, and bring huge economic income.

Taking a common mobile phone battery weighing about 40 g as an example, it can be seen that the content of metal materials is high (Table 3.15) [102]: mainly iron and aluminum, but also more valuable cobalt and copper.

Table 3.15. Metal content in common lithium-ion phone batteries

Element name	**cobalt**	**copper**	**aluminum**	**iron**	**Lithium**
Content, %	15	14	4.7	25	0.1

3.3.4 Resource value of waste button batteries

The recycling value of the waste button battery depends on three main factors: the value of the metal contained in the waste button battery, the amount of waste resources and the collection difficulty.

At present, the shortage of some non-ferrous metal resources in China is serious, and vigorously developing non-ferrous metal reproduction has become an urgent task for sustainable development. Today, two-thirds of China's non-ferrous metal mines have entered the middle and late stage of mining. Besides, many non-ferrous metal mines are to a large extent on the verge of exhaustion or greatly shortened life because of disorderly and unreasonable mining. As the world's largest battery producer, China has a large amount of zinc, manganese, copper, nickel and other metals consumed in the production of batteries every year. The production of button batteries requires the consumption of metals such as nickel, manganese, zinc, cadmium and silver, which are very valuable resources. Due to the lack of effective management measures, a large number of waste button batteries are directly discarded as waste [103].

The world's zinc resources are limited. According to the current mining technology and the rate of exploitation, zinc resources will be exhausted in 20 to 40 years. If the mining technology is improved, the depletion time of zinc resources will only be doubled. According to the data, the annual consumption of zinc in China's dry battery production is close to 250,000 tons, which is about 15% of the total annual zinc production [104]. Although the metal value of the waste button battery is higher for silver, nickel, cadmium, followed by lead, mercury, zinc is lower, but due to the shortage of resources and the absolute amount of resources used in the production of the button battery, the recycling of various valuable metals in the waste button battery has a certain resource value.

3.3.5 Estimation of waste battery resources in China

China is the world's largest battery producer, but also a large consumer. According to the data provided by the China Battery Industry Association, China's annual output of batteries is about 18 billion, and about 10 % are exported. China consumes about 8 billion batteries per year. Button batteries are used more in small portable electronic products, and the consumption is also very considerable.

Some estimates of the total amount of metal used in zinc-manganese dry batteries are shown in Table 3.16 [91].

Table 3.16. Total amount of metals in waste zinc-manganese batteries generated in China every year

Metal	Manganese	Zinc	Copper	Iron	Metallic
Weight, tons	109200	38200	600	29600	2.48

Table 3.17 shows the estimated annual recyclable materials and recycling amount of used batteries in Shanghai (this estimated data assumes that the recovery rate of used batteries reaches 60%).

As can be seen from Table 3.17, only from the annual waste batteries in Shanghai, for silver oxide batteries (generally dominated by silver oxide button batteries), 528.4 kg of silver can be recovered. The total amount of batteries consumed in Shanghai is about 100 million per year, accounting for only 1/80 of

China's battery consumption. If the materials in China's waste button batteries are recycled, the amount of recycling is quite large.

Table 3.17. Recyclable materials and recycling amount of used batteries in Shanghai [105]

Battery type	Amount of recycled batteries, t	Mercury, kg	Cadmium, kg	Zinc, t	Tungsten, kg	Sulfur, t	Lithium, kg	Silver, kg	Iron, t
Manganese battery (including alkaline zinc-manganese button battery)	180	1800	0.72	9.38	234	26.4	0	0	2.44
Silver oxide battery (including button type)	4.5	90	0	0	41.6	323.8	0	528.4	0
Mercuric oxide battery (including button type)	1.5	525	0	0.06	small amount	0	0	0	Small amount
Zinc-air button battery	1.5	30	0	0.46	45.4	small amount	0	0	0
Lithium battery (lithium button battery)	3.0	0	0	0	52.2	0.05	80.8	Small amount	0.28
Total	190.5	2445	0.72	9.9	373.2	350.25	80.8	528.4	2.72

3.4 Waste battery generation and collection in developing countries: The case study of Ukraine and China

As an indispensable energy supply method in modern families, batteries have been used in all aspects of daily life [106]. From traditional remote controls and electronic toys to emerging smart home devices, all kinds of electronic products rely on batteries to provide continuous and stable power support [107]. With the rapid development of science and technology and the improvement of people's living standards, the types and number of electronic devices in the home have shown an explosive growth trend, which directly leads to the continuous increase in the annual consumption of household batteries.

What is more worthy of attention is the potential harm caused by a large number of discarded batteries [108]. With the continuous enhancement of environmental awareness, the annual consumption of household batteries and their environmental impact are gradually becoming an important issue worthy of attention [109]. Waste management system in developing countries (like China or Ukraine) usually lacks the effectiveness and waste batteries mainly end up in municipal landfills along with other waste. When released into the environment, waste batteries pose an environmental threat due to contamination with heavy metals and other toxic substances [110]. This creates environmental risks and leads to the loss of potential resources (especially for lithium-ion batteries, which contain 5–20% cobalt, 5–10% nickel and 5–7% lithium [111]). To reduce the environmental impact and manage waste batteries more effectively, it is necessary to know waste battery generation amount. Both in China and Ukraine, statistical data on waste generation, and especially waste batteries, are quite limited and often inaccurate. According to previous research [112], about 75–80% of batteries in Ukraine are not accounted for in waste streams (up to 99% for household batteries, i.e. batteries in household waste are practically not included in official statistics). Besides, batteries in waste electrical and electronic equipment remain unaccounted for [113].

Data on waste battery generation in different countries often vary significantly. This is due to the availability/lack of waste battery collection schemes and relevant statistics. For example, the content of waste batteries in household waste in Denmark is 0.02–0.06%, which corresponds to an average of 208 g (9 pcs.) of batteries per year per household [114]. This constitutes 39% of all waste battery generated. Thus, the total amount of waste batteries can be estimated at 0.1% of household waste. There is an access to special waste collection points in each Danish municipality. Therefore, most waste batteries are collected separately, with relatively low amount in residual household waste. This provides a comprehensive statistic on waste battery generation. A study conducted in Germany [115] also showed an average of 0.04% of waste batteries in household waste. In Poland, as of 2004, only 6.5% of batteries were collected separately (12.2 g/year per person)

[116]. Accordingly, about 190 g/year of batteries remained in mixed waste. However, as of 2018, the collection rate had increased to 80% [117], which is one of the highest rates in the EU. Waste battery content in household waste in China is reported to be significantly higher (250 g/year per person) [118].

This study aims to estimate the number and weight of waste household batteries in developing countries (for case studies of China and Ukraine) by comparing the data from various sources: experimental collection of waste batteries in university, analysis of batteries in household appliances, and open-access statistics.

In-depth understanding of the use of household batteries has multiple practical significance. First, through scientific energy management, families can optimize battery efficiency and reduce unnecessary electronic waste [119]. More importantly, promoting the use of environmentally friendly batteries and the standardized recycling of waste batteries will have a positive role in building a resource-saving and environmentally friendly society [120,121].

Methodology

As stated above, three sources of waste battery generation data were analyzed: experimental collection of waste batteries in university, analysis of batteries in household appliances, and open-access statistics.

Experimental collection of waste batteries in university

For the experimental setup, a special container for waste batteries was installed in one of the buildings of Vinnytsia National Technical University, Ukraine (VNTU). In the study, 80 people working/studying in the specified building were involved (60 students, 20 teaching and engineering staff) during 257 days (from 01.02.2023 to 05.10.2023). It is evident that waste batteries were generated not only by these people, but also by their family members/roommates. Approximately half of the students (about 30 people) temporarily live in the dormitory, so they represent only themselves, and not the whole family. It can be assumed that the remaining participants – about 50 people (30 students and 20 teaching/engineering staff) – brought waste batteries generated in their families. With average 2.6 people in one

Ukrainian family, the estimated number of participants was 160 (50*2.6 + 30). There is a possibility that other visitors could have brought used batteries. However, this was not taken into account since it was impossible to control that. All participants were instructed to bring all used batteries generated in everyday life to the container. After completing the battery collection, they were sorted by type, and the number and weight were calculated for each battery type. The average yearly number (weight) of batteries Nc (Wc) per person can be calculated using the equations:

$$W_c = W \cdot 365 / (n \cdot t), \tag{3.5}$$

$$N_c = N \cdot 365 / (n \cdot t), \tag{3.6}$$

where W is the weight of batteries collected, grams; N is the number of batteries collected, pcs; n is the number of people involved in battery collection; t is the duration of battery collection, days.

Batteries in household appliances

Household appliances with batteries were analyzed by the following data: the type and number of batteries, frequency of battery replacement. The study involved 8 PhD student families: 4 families from China (13 people) and 4 families from Ukraine (10 people), the total number of people was 23. Due to objective reasons, there was no possibility to involve more participants. The data from families were averaged for each country and the number of waste batteries per person per year was determined. The following methodology was used for estimating the number of waste batteries in household appliances:

a) Data collection and organization:

Device list: List common battery-powered appliances in the household (such as remote controls, wireless keyboards, smart watches, etc.).

Number of devices: Count the number of each device in each household.

Battery type and quantity: Identify the type and number of batteries used in each device (e.g., two AAA alkaline batteries, one lithium-ion rechargeable battery, etc.).

Annual replacement times: Count the number of times the battery needs to be replaced each year (e.g., 3 times a year, once per 2 years, etc).

b) Calculation of the annual number of waste batteries:

We assume that replacing a battery is equivalent to generating a waste battery. Based on the data collected, we can calculate annual number of waste batteries N_h for each device:

$$N_h = \text{number of appliances} \times \text{batteries quantity in the appliance} \times \text{annual battery replacement times} \tag{3.7}$$

c) Classification:

Summarize the annual number of waste batteries for each household by battery type (such as alkaline batteries, lithium-ion batteries, etc.).

d) Calculation for the average household:

For the annual number of waste batteries of the same device or battery type, calculate the average value of several households.

e) Estimation of waste battery weight in one household:

Calculate the total weight of waste batteries per one year based on the average weight of the battery type:

$$W_h = \Sigma\, n_i \cdot w_i \tag{3.8}$$

where n_i is the number of batteries of i type, w_i is the weight of a single battery of i type.

Open-access statistics and other studies

Open access data on the number of waste batteries collected in special containers of retail chains, institutions, public organizations, etc. were analyzed. Besides, where available, the official statistics on waste batteries generation and collection was accessed. Also, other studies were analyzed to compare waste battery generation.

Waste battery collection

Amount of waste batteries collected in China and Ukraine was analyzed based on literature review, internet search, commercial data, etc. Then, collection rate is calculated by the equation:

$$R = W_c / W_h, \tag{3.9}$$

where W_c is amount of waste batteries collected.

Results

1. Experimental collection of waste batteries in university

As a result of waste battery collection in VNTU (around 160 participants, 257 days of collection), 1052 batteries with a total weight of 16.434 kg were collected (Table 3.18).

Table 3.18. Characteristics of waste batteries

Group	**Battery type**	**Number, pcs.**	**Weight, g**	**Average weight of one battery, g**	**Average number of batteries per 1 person, pcs/year**	**Average annual weight of waste batteries per 1 person, g/year**
Zinc / dry	R6, size AA	262	3728.5	14.231	2.42	34.436
	R03, size AAA	192	1365.1	7.110	1.77	12.608
	R14, size C	13	604.5	46.500	0.12	5.583
	R20, size D	9	957	106.333	0.08	8.839
	6F22	15	557	37.133	0.14	5.144
Alkaline	LR6, size AA	336	7017.5	20.885	3.10	64.812
	LR03, size AAA	133	1512.8	11.374	1.23	13.972
	A27 (MN27)	1	4.4	4.400	0.01	0.041
	A23 (MN21/23)	3	24.7	8.233	0.03	0.228
Rechargeable	HR6, Ni-MH size AA	10	284.6	28.460	0.09	2.629
	KR6, Ni-Cd size AA	4	71.4	17.850	0.04	0.659
	HR03, Ni-MH size AAA	9	73	8.111	0.08	0.674
	Li-ion	6	144.7	24.117	0.06	1.336
Button	Silver-oxide, 389 type	1	1.26	1.260	0.01	0.012
	Alkaline, AG13 (LR44)	12	22.1	1.842	0.11	0.204
	Alkaline, AG4 (LR626)	2	0.7	0.350	0.02	0.006
	Alkaline, AG10 (LR1130)	10	11.5	1.150	0.09	0.106
	Alkaline, AG3 (L736/LR41)	8	4.6	0.575	0.07	0.042
	Alkaline, G12a (LR43)	1	1.5	1.500	0.01	0.014
	AG1 (LR621), button	8	2.17	0.271	0.07	0.020
	CR2016/2032, Lithium button	17	45.3	2.665	0.16	0.418
Total		**1052**	**16434.33**		**9.72**	**151.785**

According to the Table 3.18, the most commonly used are alkaline batteries of AA size, as well as zinc-carbon batteries of AA and AAA sizes. The average person uses about 10 batteries in 1 year (4.5 zinc-carbon, 4.4 alkaline, 0.3 rechargeable and 0.5 button) with a total weight of about 150 g (Fig. 3.22). Therefore, over 95% of household batteries are dry batteries (zinc-carbon and alkaline). According to this study, the share of lithium-ion batteries, despite their widespread use, remains quite insignificant – about 1% by weight, primarily due to their comparatively significant lifetime.

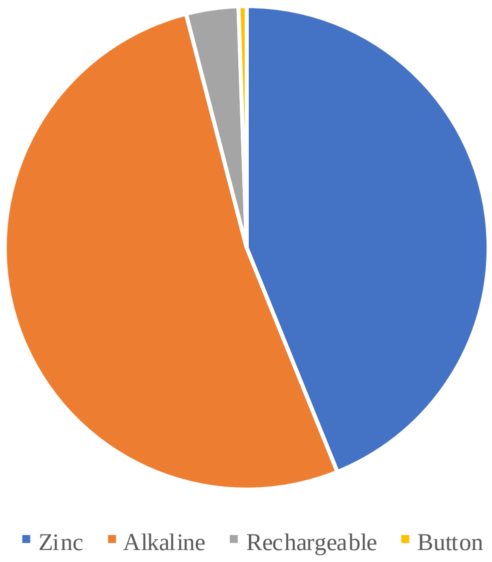

Figure 3.22 – Waste batteries collected by weight

It is worth noting that the number of rechargeable batteries may be underestimated in this study, since the duration of the study (257 days or 0.7 year) is much shorter than batteries lifetime (usually 2–4 years). For example, almost every person uses a mobile phone and produces at least 1 lithium-ion battery in 4–5 years. This corresponds to an annual amount of 0.2–0.25 batteries, although in this study the amount of lithium-ion batteries is estimated at only 0.06 pcs/year per person.

2. Batteries in household appliances

The characteristics of waste batteries in household appliances/devices (quantity, type, and frequency of replacement) were determined for 4 Ukrainian and 4 Chinese families (see Tables 3.19–3.20).

Table 3.19. Waste batteries in Chinese families

Device	**Battery type**	**Number of batteries in 1 year**				
		Family 1	**Family 2**	**Family 3**	**Family 4**	**Average**
TV remote control	Alkaline / Zinc, AAA	6	12	6	6	7.5
Air conditioner	Alkaline / Zinc, AA	4	–	2	4	2.5
Wireless mouse	Alkaline / Zinc, AAA	8	8	4	–	5
Wireless keyboard	Alkaline / Zinc, AA	8	8	–	–	4
Wireless doorbell	Lithium, button	1	1	1	1	1
Wireless headphones	Lithium, button	8	32	8	8	14
Calculator	Lithium, button	0.5	1	–	1	0.625
Flashlight	Alkaline / Zinc, AAA	8	8	4	4	6
Laptop	Rechargeable, Li-ion	2	2	1	1	1.5
Tablet	Rechargeable, Li-ion	1	1	2	1	1.25
Wireless presenter (PPT page turner)	Lithium, button	4	–	2	–	1.5
Smartwatches	Lithium, button	2	5	1	0.5	2.25
Bluetooth speaker	Rechargeable, Li-ion	4	2	–	2	2
Portable fan	Rechargeable, Li-ion	12	16	4	16	12
Total						61.125

Table 3.20. Waste batteries in Ukrainian families

Device	**Battery type**	**Number of batteries in 1 year**				
		Family 1	**Family 2**	**Family 3**	**Family 4**	**Average**
Smartphone	Rechargeable, Li-ion	0.5	0.6	0.5	0.5	0.525
Alkometer test	Alkaline / Zinc, AAA	–	–	0.6	–	0.15
Laser rangefinder	Alkaline, button, LR44	–	–	0.6	–	0.15
	Alkaline, LR23	–	–	0.3	–	0.075
Digital thermometer	Lithium, button, CR1632	–	–	1	0.2	0.3
	Alkaline / Zinc, AAA	–	–	2	–	0.5
Car keys	Lithium, button, CR1632	–	–	0.1	–	0.025
Laptop	Rechargeable, Li-ion	0.2	8	0.2	–	0.3
Water quality tester	Alkaline, button, LR44	–	–	0.4	–	0.1
Digital multimeter	Zinc, 6F22	–	–	1	–	0.25
Digital caliper	Alkaline, button, LR44	–	–	2	–	0.5
Toy car	Rechargeable, lead-acid, 6-FM-7	–	–	0.2	–	0.05
Toy car remote control	Alkaline / Zinc, AAA	–	0.3	4	0.2	1.125

Continue of the Table 3.20

Powerbank	Rechargeable, Li-ion	–	1.5	0.6	–	0.525
Petrol generator	Rechargeable, lead-acid, 6-FM-7	–	–	0.4	–	0.1
Electrical instrument	Rechargeable, Li-ion	–	–	0.4	0.2	0.15
Digital thermohygrometer	Alkaline / Zinc, AAA	–	–	2	–	0.5
Toy	Alkaline, button, LR41	24	–	1.5	–	6.375
	Alkaline / Zinc, AAA	–	32	1.2	–	8.3
	Alkaline / Zinc, AA	–	46	–	–	11.5
Watches	Alkaline / Zinc, AA	1.4	0	6	1	2.1
TV control	Alkaline / Zinc, AAA	0.4	4	4	2	2.6
Flashlight	Alkaline / Zinc, AA	4.6	5	8	–	4.4
Calculator	Lithium, button		1	–	1	0.5
PC mouse	Alkaline / Zinc, AA	2	4	–	2	2
Wireless keyboard	Alkaline / Zinc, AA	–	4	–	4	2
Wireless doorbell	Lithium, button	–	0.6	–	1	0.4
Camera	Alkaline / Zinc, AA	–	–	–	12	3
Remote control, air conditioner	Alkaline / Zinc, AAA	–	2	–	–	0.5
Remote control, chandelier	Alkaline / Zinc, AAA	–	2	–	–	0.5
Electronic scales	Alkaline / Zinc, AAA	–	1	–	–	0.25
Tablet	Rechargeable, Li-ion	–	0.25	–	–	0.0625
Bluetooth Wireless Speaker	Rechargeable, Li-ion	–	0.6	–	–	0.15
Vacuum cleaner	Rechargeable, Li-ion	0.25	–	–	–	0.0625
Air humidifier	Rechargeable, Li-ion	0.2	–	–	–	0.05
Fluff remover	Rechargeable, Li-ion	0.1	–	–	–	0.025
Cordless high-pressure washer	Rechargeable, Li-ion	0.1	–	–	–	0.025
Scales	Alkaline, button, LR44	0.6	–	–	–	0.15
Laser point	Alkaline, button, LR44	6	–	–	–	1.5
Trimmer	Alkaline / Zinc, AA	0.5	–	–	–	0.125
Total						51.98

Since alkaline and zinc batteries are interchangeable, they both can be used in devices requiring AA or AAA size batteries. It is not possible to identify which type is used (it varies, sometimes we buy alkaline, next time – zinc battery). Therefore, we were able estimate only total amount of dry batteries (including both alkaline and zinc). We assume that battery replacement is equated to the generation of waste battery.

3. Comparison of battery quantity

Total quantity

The average annual battery usage by Chinese families is about 20% higher comparing to Ukrainian families (61 and 52 batteries, respectively, see Table 3.21).

Table 3.21. Average number and weight of batteries in families by battery type

Type of battery	Average number of batteries in one family, pcs/year		Average weight of batteries in one family, g/year	
	China	**Ukraine**	**China**	**Ukraine**
Rechargeable Li-ion	16.75	1.95	404	47
Rechargeable lead-acid	0	0.15	0.00	315
Alkaline / zinc	25	39.875	335	534
Button	19.375	10	35	18
Total	61.125	51.975	774	914

This difference may be due to the higher penetration rate of electronic devices (such as toys, remote controls, and smart home devices) in Chinese households, as well as higher amount of people in Chinese families: in this study, average Chinese family has 3.25 people and average Ukrainian family has 2.5 people. The latter is clearly seen if calculating batteries quantity per 1 person–there are around 20 batteries per year used by one person both in China and Ukraine (Figs. 3.23–3.24) with slightly higher amount in Ukraine.

Battery type

The similar pattern for both countries includes, as expected, the prevalence of dry batteries (alkaline and zinc). While it is a total domination in Ukraine (about 75% of total battery amount), their prevalence in China is not so evident. In fact, average use of primary alkaline / zinc batteries in Ukraine is twice more. On the contrary, rechargeable Li-ion batteries are in more widespread use in China (yearly 5 li-ion batteries per 1 person, while average Ukrainian uses only 1 such battery). This is due to the use of more smart devices by Chinese families.

Both in China and Ukraine, dry batteries are followed by button batteries that are used more intensively in China. This may be related to the higher demand for small devices such as children toys, electronic scales, smart watches, etc.

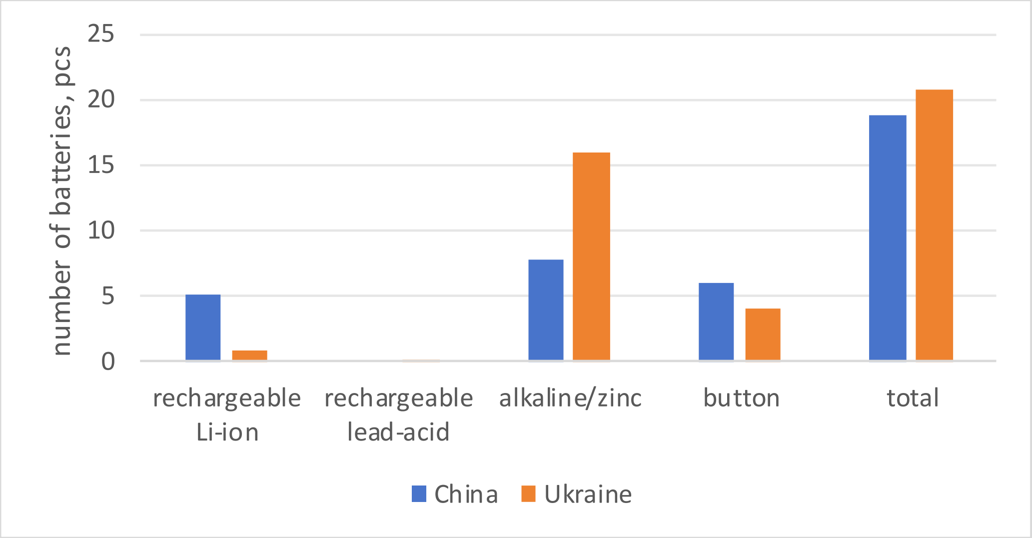

Figure 3.23 – Number of batteries used by one person in 1 year

Another main difference between China and Ukraine is rechargeable lead-acid batteries that were not submitted by Chinese families in this study. In fact, only one Ukrainian family reported about this battery type usage in household appliances. Therefore, it is possible that conclusion on lead-acid batteries amount can be incorrect, and more research is needed.

4. Battery weight comparison

The average annual total battery weight of Chinese households (774 grams) is almost 20% lower that of Ukrainian households (914 grams), mainly due to the presence of lead-acid batteries in one Ukrainian family (as shown above). If exclude lead-acid batteries, per person battery use is quite similar in China and Ukraine: 238 g and 240 g, respectively, while lead-acid batteries substantially increase total battery use in Ukraine (up to 365 g/year per 1 person).

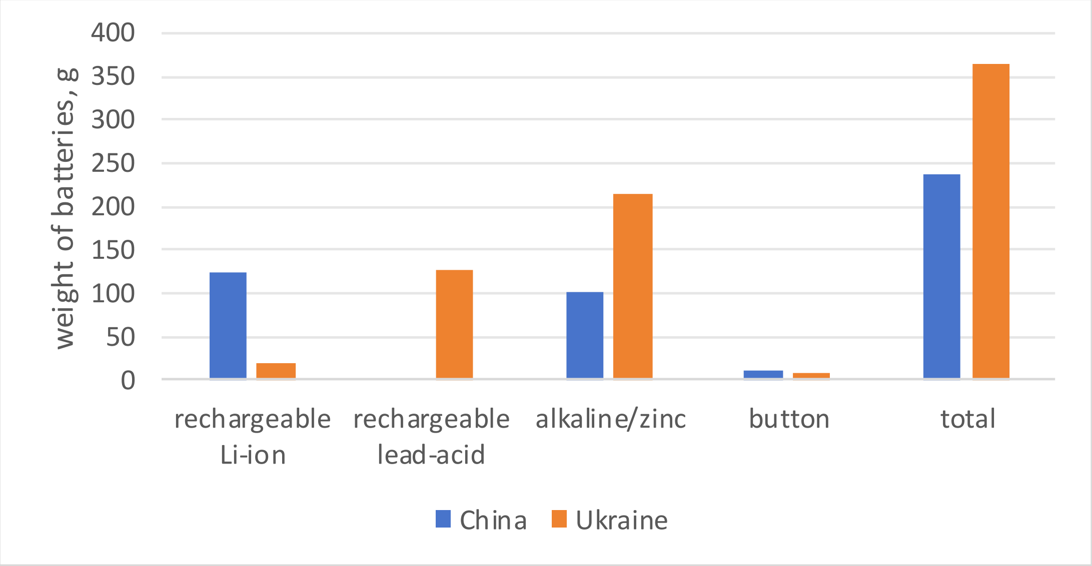

Figure 3.24 – Weight of batteries used by one person in 1 year

While alkaline/zinc and button batteries are most widely used in Chinese households, but, in terms of weight, rechargeable Li-ion batteries contribute the most (over 50% of total battery weight). Although the number of button batteries is large, they are very light, and the total weight contribution is quite low (about 48.4 grams).

The similar pattern is noted for Ukraine. The differences include: a) low weight of Li-ion batteries (due to lower quantity of such batteries comparing to Chinese families); b) the domination of alkaline/zinc batteries, still having the largest weight among all the batteries, is not so evident due to the high contribution of heavy lead-acid batteries.

Ukrainian families may be influenced by traditional consumption concepts and prefer to buy low-priced primary batteries, but are sensitive to the initial cost of rechargeable batteries. Chinese families may give priority to rechargeable lithium-ion batteries and long-term economic considerations.

There are also the differences in the electronic product market. As a global electronic product manufacturing center, China has a high penetration rate of small electronic devices (such as smart toys and IoT devices), which drives the demand for Li-ion and button batteries. Chinese people may pay more attention to durability, and rechargeable devices (such as power tools and high-end home appliances) account for a higher proportion.

In comparison to the experimental collection of waste batteries in Ukrainian university, the total number of waste batteries from household appliances/devices is twice higher (besides, the total weight of batteries–about 1.3 kg/year per 1 person–is an order of magnitude more). This can be explained, on the one hand, by the underestimated amount of collected batteries (it is likely that not all spent batteries were brought to the container). On the other hand, overestimation of battery quantity in appliances/devices is also possible. For example, due to the limited number of participants. Also, the participants are young people (aged 30–40), who, as a rule, use more devices than other families). Additionally, the significantly higher weight of batteries in household appliances/devices in Ukraine can be explained by the presence of heavy lead-acid batteries, which were not collected in a special container for obvious reason.

In terms of battery type, the share of alkaline and zinc batteries found in household devices is slightly lower comparing to the results of battery collection (75% vs 95%), although there are significantly more button batteries (up to 20%). For other battery types, both data sources are correlated, with the exception of lead-acid batteries (see explanation above).

5. Official statistics and previous studies

In our previous study [122], total waste battery generation in China was estimated at over 10 million tons per year (estimation by trade data). Excluding lead-acid batteries that are mainly used by cars, but not in household devices, the approximate yearly generation of waste batteries in China is around 0.6 million tons or 400 g/person. Similarly, another study [123] estimates yearly waste battery generation at 380 g/person. Comparing to the data we have obtained in this study, this is 1.5 times more, but, in general, the data are consistent since some part of batteries are used outside households (offices, shops, etc.).

Regarding Ukraine, according to official statistics [124], there are 4–4.5 thousand tons/year of waste batteries generated. This is about 100 g/year per person. Although previous studies show official statistics probably underestimate the amount of waste batteries (it amounts to 6–7 thousand tons/year or 150–170 g/year per person, without lead-acid batteries, based on an analysis of battery production, import and export), these data are consistent with this study's result (Fig. 3.25).

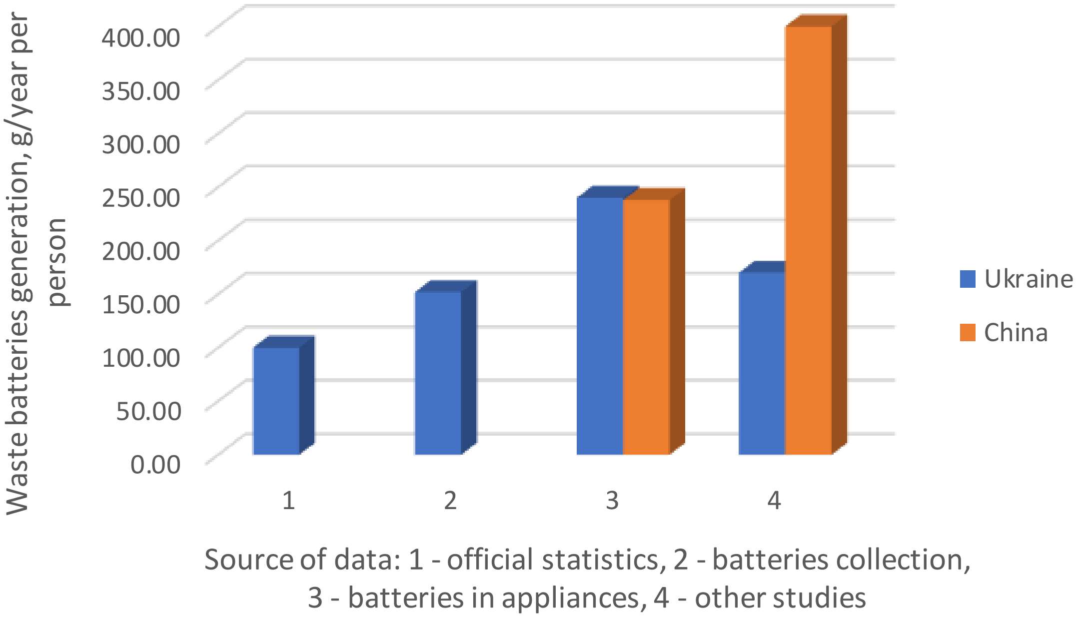

Figure 3.25 – Waste batteries generation by various data sources

6. Waste battery collection

There is no waste battery collection system established in China and Ukraine. At the same time, there are some public places (shopping malls, communities, schools and other), where waste batteries are collected by private companies and non-governmental organizations. They cover very small share of total waste batteries.

Based on the data from battery collection points in China, there are average 1500 tons of waste batteries collected (Table 3.22, data as of 2023).

As waste battery collection points are located only in cities, it is correct to estimate collection rate in cities, but not rural areas. Estimated urban population in China is 930 million people. 1500 tons of waste batteries collected correspond to 1.6 grams/year per persons. In this study, we estimated waste battery generation in China at 238 g/year per person. Therefore, according to the Eq. 5, waste battery collection rate can be estimated at 0.7% that is very few and means over 99% of waste batteries are lost along with other household waste.

Table 3.22. China's public places battery collection

Place type	**Covered cities**	**Annual collection weight, tons**
Shopping mall/supermarket	Beijing, Shanghai, Shenzhen, etc.	50–100
Community recycling station	Large and medium-sized cities nationwide	over 1000
School	Primary and secondary schools in key cities	200–300
Subway/bus station	Shenzhen and Chengdu pilot areas	20–30
Government service centre	Yangtze River Delta, Pearl River Delta	10–20

In Ukraine, only 100–120 tons of batteries are collected yearly [125]. Taking into account 28 million people of urban population, this is 3.5–4 grams/year per person. By the Eq. 3.5, waste battery collection rate in Ukraine is around 1.5%, though twice that of China, but still very low.

Limitations

There are many differences in battery usage between village and city households, which are mainly affected by factors such as the penetration rate of electrical equipment, lifestyle, infrastructure and economic level. The following are the key points of the comparative analysis:

1. Differences in battery types and uses

City households: more batteries are used for small electronic devices (such as remote controls, smart door locks, electronic scales, children's toys), digital products (wireless headphones, keyboards and mice) and emergency equipment (flashlights, backup power supplies). Primary dry batteries are the main ones, and some households use rechargeable batteries or button batteries.

Village households: focus on basic electrical appliances (flashlights, radios, simple remote controls), agricultural equipment (such as insect killer lamps, thermometers and hygrometers) and children's toys. Cheap dry batteries are the main ones, and rechargeable batteries are used less (due to high initial cost and inconvenient charging).

2. Usage comparison

City households: Battery consumption is higher due to wider use of electronic devices. For example, an urban household may use over 10 remote controls (air conditioners, TVs, stereos, etc.) at the same time. However, some devices are turning to plug-in or built-in lithium batteries (such as mobile phones and laptops), which may reduce the demand for primary batteries.

Village households: battery usage of a single household is low, but the total amount cannot be ignored (due to the large population). Some remote areas rely on battery power supply (such as solar cell energy storage in areas without stable power grids). Agricultural equipment may increase battery demand seasonally (such as the use of appliances during the autumn harvesting).

This study uses China and Ukraine as cases, and estimates and compares the generation and recycling status of household waste batteries in developing countries through experimental collection, household equipment analysis and public data. The following main conclusions are drawn.

Waste batteries are used frequently and in concentrated types: ordinary residents use an average of about 10-20 batteries per year, of which more than 90% are dry batteries (alkaline and zinc-carbon batteries); lithium-ion batteries are few in number but account for a large proportion by weight.

There are obvious differences between countries: China's household battery use is slightly higher than Ukraine's, especially lithium-ion batteries, which is more frequent, reflecting a higher penetration rate of electronic devices; while Ukraine relies more on disposable dry batteries and uses lead-acid batteries in some households.

The recycling rate is extremely low: Although both countries have a small number of recycling points, the waste battery recycling system is not yet sound. The recycling rate of urban residents in China is only 0.7%, and that in Ukraine is 1.5%. The vast majority of waste batteries are still mixed with domestic waste, bringing risks of heavy metal pollution and resource waste.

Data statistics are missing and need further research: Existing official statistics often underestimate the actual amount of waste batteries generated, making it difficult to accurately formulate recycling policies. In particular, there is a lack of effective data support for battery use in rural areas and non-family places.

In summary, to effectively manage waste batteries, it is necessary to establish a comprehensive and accurate statistical system, strengthen public environmental awareness, and promote the construction of an efficient and convenient classification and recycling network, so as to reduce environmental risks and achieve resource recycling.

3.5 Conclusion to the Chapter 3

The study adopts a quantitative analysis method, combined with China's battery production, sales, import and export data (2014–2023), and obtains data through the United Nations Commodity Trade Database and the China Battery Association report. The Weibull life distribution model was used to estimate the waste battery generation in China. The calculation is also based on the average lifetime and recycling rate of batteries. China's imports of batteries generally showed a downward trend, while exports showed an upward trend, especially lithium batteries (both primary and lithium-ion rechargeable). With a constant increase in batteries production, amount of batteries on Chinese market has grown during last 10 years, although some battery types (lead-acid, nickel-cadmium) demonstrate reduction due to the replacement with other batteries.

According to our calculations, waste lithium batteries (driven by the new energy industry) and lead-acid batteries (huge stock market) are the main contributors to waste battery volume growth, covering 99% of around 10.5 million tons of waste battery generation in China. Further research prospects are to introduce more variables (such as technological progress and consumer habits) to improve the waste battery generation prediction model through dynamic model optimization.

This study identified that Chinese households use an average of approximately 61 batteries per year, about 20 per person, with lithium-ion batteries being the most prevalent. Ukrainian households use an average of approximately 52 batteries per year, about 20 per person, with dry-cell batteries being the dominant type. Recycling rates are extremely low.

This chapter also systematically assesses the resource recycling potential of waste batteries, focusing on the generation volume, circulation trends, and metal resource value of waste batteries. It also compares the differences in waste battery management, recycling rates, policies, and technologies among different countries using China, Japan, the United States, the European Union, and Ukraine as case studies. China is the world's largest producer and consumer of batteries, consuming approximately 7-8 billion batteries annually, but its recycling rate is less than 2%.

China's annual waste batteries contain large amounts of metals such as zinc, manganese, copper, nickel, cobalt, silver, and lithium. Increasing recycling rates can significantly reduce dependence on primary mineral resources. The metal resource potential of waste batteries is assessed: nickel-cadmium batteries contain over 20% cadmium, more than 200 times that of ore; recycling can significantly reduce energy consumption and pollution. Recycling lead from lead-acid batteries saves 38% more energy and is less expensive than extracting lead from ore. Lithium-ion batteries contain 5-20% cobalt, 5-10% nickel, and 5-7% lithium, making them highly valuable for recycling. Button batteries contain silver, nickel, zinc, etc., offering significant recycling potential but are difficult to collect.

The generation of waste batteries is large and growing rapidly, especially lithium-ion batteries with the widespread adoption of electric vehicles and energy storage systems. Recycling rates are generally low, and developing countries like China and Ukraine have inadequate recycling systems and weak policy enforcement.

The potential for resource recycling is enormous. Waste batteries contain a large amount of valuable metals, and recycling can alleviate resource shortages, reduce energy consumption, and decrease environmental pollution. However, data collection is incomplete, particularly regarding battery usage in rural areas and non-household locations. It is necessary to strengthen public awareness, improve the recycling network, and formulate effective policies to achieve the resource-based and harmless management of waste batteries.

CHAPTER 4 WASTE BATTERIES RECYCLING TECHNOLOGIES

4.1 Analysis of waste battery recycling

4.1.1 Current situation on waste batteries recycling in developed countries

The recycling of waste batteries started in Europe. In 1991, the European Union issued a decree on battery recycling, requiring EU countries to ban the sale of batteries with high mercury content and to classify and recycle cadmium and lead batteries. Germany, Denmark, the Netherlands and other countries passed legislation in the early 1990s to emphasize the recycling of waste batteries.

Based on the sustainable development strategy, the Netherlands officially promulgated legislation in 1993, emphasizing that incineration and landfilling are not suitable methods for waste batteries treatment, and stipulated the corresponding responsibilities of battery producers for the recycling and disposal of waste batteries, and required the establishment of a corresponding disposal system.

Denmark is one of the first countries in Europe to establish the collection of waste batteries. It began to collect used nickel-cadmium batteries in 1996 [126]. Similar to Denmark, Germany also passed regulations on the collection and treatment of waste batteries on October 1, 1998. By supervising battery manufacturers and adopting a monetary pressure system, it achieved effective recycling of waste batteries [127].

The United States is the country with the most detailed regulations on the management of waste batteries. It has not only established a complete waste battery recycling system, but also established a number of waste battery processing plants, and continuously carried out publicity and education for the public to consciously support and cooperate with the use of waste batteries [128]. There are many waste battery recycling companies in the United States, and many local waste removal companies are also engaged in battery recycling business. The largest battery recycling company in the United States is RBRC (Rechargeable Battery Recycling

Company), a non-profit environmental protection organization sponsored by more than 300 manufacturers of nickel-cadmium batteries across the country.

Japan began collection of waste batteries in 1993, setting up specially marked collection bins in major shopping malls and public places, and relying on the sponsorship of battery manufacturers to implement recycling [129].

South Korea has passed legislation to establish a waste recycling responsibility system [130]. The responsibility system stipulates that some waste consumer products with recycling value, particularly waste batteries, should be handed over to manufacturers for recycling and reuse. To ensure the waste responsibility system can be implemented, South Korea has established a number of cooperatives specializing in waste collection and treatment. Manufacturers entrust the task of recycling and sorting to cooperatives, which regularly collect these items, sort them, and transport to manufacturers to form a logistics system of a certain scale. In addition, waste sorting equipment is installed in residential areas, both in urban and rural areas, to facilitate recycling and sorting by cooperatives.

4.1.2 Current situation on waste battery recycling in China

According to China's national conditions, all factors of social resources are conducive to recycling, whether it is legislation or logistics resources, they can be cut in at any time, but there is a lack of an integrated system. Although China's waste battery processing industry has a certain technological gap developed countries, it can operate normally. The current problem is more about the source of raw materials.

In view of the existing gaps, this study proposes that waste battery recycling should be used as a complete system, connecting the three elements of users, enterprises, and factories, and being user-oriented, integrating available logistics resources, drawing on foreign recycling experience, and designing a waste battery recycling system based on China's national conditions.

The waste battery recycling system is meaningful for solving the problem of waste battery residues in China, and it also has certain reference value for the recycling of other related pollutants. In this ever-changing information age, electronic products will become more common and the demand for batteries will continue to increase. The development of various new batteries does not mean that the recycling of waste batteries is meaningless. Although the environmental harm of useless batteries is negligible at present. However, the resource efficiency cannot be ignored, so the research on the waste battery recycling system based on national conditions is also full of reference significance for the future [131].

The core operation of China's current battery recycling system involves the responsible parties collecting batteries through a multi-party network of third-party collection points. This process is uniformly managed according to Chinese management standards. Batteries with good performance are tested and then used in energy storage, low-speed vehicles, and communication base stations, achieving degraded use. Batteries that cannot be reused are intelligently dismantled and subjected to hydrometallurgical/pyrometallurgical processes to extract key metals such as lithium, cobalt, and nickel. Finally, the materials are returned to battery manufacturing, forming a closed-loop cycle.

4.2 Analysis of waste battery processing methods

Most batteries are mixed with household waste and landfilled or incinerated. The following describes the waste batteries processing from the perspectives of landfill and incineration [132].

4.2.1 Analysis of industrial processing methods for waste batteries

There are three common methods for waste batteries management: solidification and deep burial, storage in abandoned mines, and recycling [133].

Common industrial treatment methods for waste batteries are shown in the Table 4.1 [134].

Table 4.1. Industrial processing methods for waste batteries

1. Physical processing	Crushing and sorting: Metals, plastics and other materials are separated through mechanical crushing and screening.
	Magnetic separation: Separation of iron materials by magnetic difference.
	Gravity sorting: Separation of different components according to density difference.
2. Chemical processing	Acid leaching: Dissolving metals with acidic solution and then recovering them through precipitation, extraction and other methods.
	Alkaline leaching: Treatment with alkaline solution to recover specific metals.
	Electrolysis: Recovering high-purity metals through electrolysis.
3. Thermal processing	Incineration: High-temperature incineration removes organic matter and recovers metals.
	Pyrolysis: Heating under oxygen-free conditions to decompose organic matter and recover metals.
4. Biological processing	Bioleaching: Dissolve metals with microorganisms, suitable for low-grade batteries.
	Biosorption: Use microorganisms or biological materials to absorb metal ions.
5. Direct recovery	Repair and reuse: Repair some batteries and reuse them.
	Cascade utilization: Use batteries with reduced performance for low-demand scenarios such as energy storage.
6.Hydrometallurgy	Solvent extraction: Selectively extract metal ions with organic solvents.
	Chemical precipitation: Recover metals through chemical reaction precipitation.
7.Pyrometallurgy	High temperature smelting: separation of metal and non-metal components at high temperatures.
	Reduction smelting: recovery of metals through reduction reactions.

4.2.2 Recycling methods for certain battery types

1. Lead-acid batteries

Currently, only a few enterprises in China use new technologies for pre-treatment and sorting of waste lead-acid battery to recover lead without pollution. Most companies still use manual sorting and earthen furnace smelting. A large number of harmful substances such as lead vapor are generated during the smelting process, which severely pollutes the environment [135].

2. Primary dry batteries

Primary dry batteries are cylindrical, and the outer cylinder is made of zinc. This zinc cylinder is the negative electrode of the battery; the carbon rod in the centre of the cylinder is the positive electrode; the inside of the cylinder contains manganese dioxide, ammonium chloride and zinc chloride. There are two main methods for recycling: extracting ammonium chloride and zinc [136].

3. Lithium-ion batteries

Lithium-ion battery recycling technology aims to efficiently recover valuable metals (such as lithium, cobalt, nickel, manganese, etc.) and other materials from lithium-ion batteries while reducing environmental pollution [137].

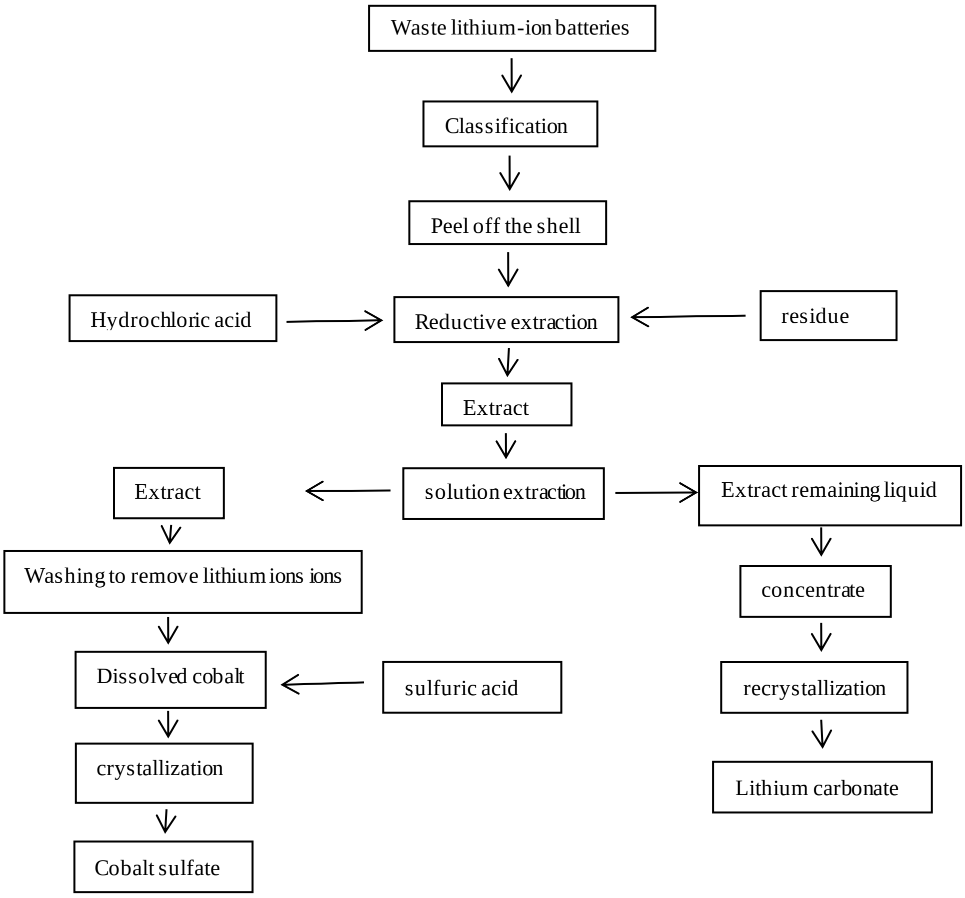

Figure 4.1 – A typical lithium-ion battery recycling process flow chart

The following are common lithium-ion battery recycling technologies:

a) High temperature treatment. The organic matter is decomposed by high temperature heating to enrich metals. At high temperatures (usually above 1000°C), organic matter burns and volatilizes, and metal oxides are reduced to metals or alloys.

b) Chemical leaching. Chemical solvents are used to selectively dissolve metals, and then recover them through precipitation, extraction, etc.

c) Biometallurgy. Microorganisms or their metabolites are used to dissolve metals. Microorganisms leach metals from electrode materials through oxidation, reduction, etc.

d) Direct recovery method. Electrode materials are repaired through physical or chemical methods so that they can be reused in battery manufacturing. Positive electrode materials (such as lithium cobalt oxide) are separated and recovered from waste batteries.

e) Electrochemical recovery. Metals are recovered from solutions through electrolysis. Metal ions are electrolytically deposited in the leaching solution into pure metal.

f) Combined recovery process. Combining multiple technologies is used to improve recovery efficiency and metal recovery rate.

A typical lithium-ion battery recycling process flow chart in Fig. 4.1.

4.2.3 Waste batteries recycling in Europe

European countries are effective in collecting and recycling batteries, but they also face the problem of not being able to make a profit. Therefore, it is impossible to make a profit by simply recovering the metals from waste batteries. At present, Germany has a processing fee gap of at least 1,000 euros for every ton of waste batteries it processes. Europe has not solved this difference through government subsidies. The European Portable Battery Association believes that the method of collecting deposits is not advisable because many batteries have a long lifecycle. Currently, the development and utilization of recycling technologies for various types of batteries are spread mainly in Europe. The technical parameters of waste battery recycling methods are summarized in the Table 4.2 [138].

Table 4.2. Recycling methods and technical parameters of various types of batteries

Battery type	**Technical classification**	**Typical process name**	**Technical parameters**
Primary battery	Heat treatment	AFE (Valdi), France (electric arc furnace)	Production capacity: > 4000t/a Valuable final products: manganese iron and zinc/zinc oxide Processing fee: >700-750 euros/t
		CITRON, France (oxidation-reduction)	Production capacity: > 100000 t/a Valuable final products: iron, manganese oxide, and zinc/zinc oxide Processing fee: >800 euros/t

Continue of the Table 4.2

		DUCLOS Environment, France (heat treatment)	Production capacity: 500 t/a Valuable final products: metal waste and mercury Processing fee: 1000 euros per ton
	Physical and chemical equipment	EURODIEUZE INDUSTRIE, France (crushing, precipitation, filtration)	Production capacity: > 2000 t/a Valuable final products: zinc, manganese, polymeric acid salts Processing fee: >1000 euros/t
		RECUPYL, France (crushing, dissolution, precipitation, filtration)	Production capacity: > 4000 t/a Valuable final products: manganese iron and zinc/zinc oxide Processing fee: >700~750 euros/t
		ZIMAVAL TECHNOLOGY, France (crushing, dissolution, precipitation, filtration, electrolysis)	Production capacity: > 4000 t/a Valuable final products: iron, manganese salts, and zinc Processing fee: >800 euros/t
		REVATEC SA and ERACHEM, Belgium (crushing, dissolution, precipitation, filtration)	Production capacity: > 4000 t/a Valuable final products: iron and zinc, manganese salts Processing fee: >700-750 euros/t
		PROCESS, Spain (crushing, dissolution, precipitation, filtration)	Production capacity: > 2000 t/a Valuable final products: Zinc sulfate solution, iron and manganese salts Processing fee: > 1200 euros/t
Button cell	Heat treatment	INDAVER, Belgium (heat treatment)	Production capacity: > 200 t/a Valuable end products: metal waste and mercury Processing fee: 2000 euros/t
		MBM, France (heat treatment)	Production capacity: > 40 t/a Available end products: metal waste and mercury Processing fee: >2000-2500 euros/t
Nickel battery (Ni-Cd, Ni-MH)	Heat treatment	SNAM, France (crushing, heat treatment, cadmium distillation)	Production capacity: > 7000 t/a Valuable end products: iron nickel and cadmium Processing fees: subject to change
		NIREC, Germany (Thermal Process)	Production capacity: > 1000 t/a Valuable end products: iron nickel Processing fees: subject to change
		ACCUREC, Germany (crushing, heat treatment)	Production capacity: > 2000 t/a Valuable end products: iron nickel and cadmium Processing fees: subject to change
Lithium-ion battery	Heat treatment	TOXCO, United States (Low Temperature Crushing, Chemical Processes)	Production capacity: > 1000 t/a Valuable end products: plastics, metals, lithium salts Processing fees: subject to change

4.3 Status of waste battery recycling in China

At present, China's waste battery recycling is still very scarce, and the huge battery production and consumption form a huge contrast with the recycling rate.

China's attempts to recycle waste batteries began in 1990. China also followed Japan and the United States to encourage companies to establish their own recycling systems. However, these systems are not perfect and the effect is not significant. Many researchers have also proposed a producer responsibility system, but due to the imperfect market system, it has not been well implemented. At present, the battery recycling work of non-governmental organizations in China lacks circular and industrialized operations, which is significantly different from that of European and American countries and cannot become the main force for recycling [139].

It is necessary to unify the planning of battery production labels, ingredients and treatment standards, and clarify the division of responsibilities between battery manufacturers and sellers. Strict waste regulations and waste battery separation and treatment should be implemented [140].

Hong Kong, China has a complete private waste battery collection system and organizes transportation to overseas for recycling. Due to the small area of Hong Kong, waste batteries are also directly transported to other regions for unified treatment through waste sorting.

Effective recycling and reuse of waste batteries under circular economy principles are of great practical significance. Table 4.3 shows the quantity and growth rate of waste battery recycling in China from 2016 to 2023 [141].

Table 4.3. Growth rate of waste battery recycling in China from 2016 to 2023

	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Quantity recovered (thousand tons)	93	95	100	120	176	189	236	274
Growth rate (%)		2.2	5.3	20	46.7	7.4	24.9	16.1

4.3.1 Analysis of certain battery types recycling in China

The following is the relevant situation of battery collection in China from 2013 to 2024 (Table 4.4).

Table 4.4. Data on waste battery recycling in China

Battery recycling in China (weight, tons)					
Year	**Lithium-ion battery**	**Lead-acid battery**	**Mercury oxide battery**	**Silver-oxide battery**	**Nickel-cadmium battery**
2013	10000	1500000	100	80	10000
2018	70000	3000000	80	180	15000
2020	200000	3500000	50	200	20000
2022	300000	4000000	30	250	22000
2024	500000	4500000	10	300	25000

From 2013 to 2024, China's lithium-ion battery recycling rate showed a gradual upward trend. The following are the main changes in each stage.

From 2013 to 2017, the lithium-ion battery recycling industry was just starting, policies and technologies were not yet perfect, and the recycling system was not appropriate. The recycling rate was low, about 5–10%. From 2018 to 2020, the government issued a number of policies to promote the construction of the recycling system, and enterprises began to lay out. The recycling rate increased to 10–20%.

From 2021 to 2023, technological progress and large-scale production reduced recycling costs, market demand increased, and more companies entered this field. The recycling rate further increased to 20–30%. Later on, policies, technologies and markets will further mature, the recycling network will be more complete, and the recycling rate will continue to rise. The recycling rate is expected to reach 30–40%.

From 2013 to 2024, China's nickel-cadmium battery recycling rate also showed a gradual upward trend, but because the application of nickel-cadmium batteries is gradually replaced by new batteries such as lithium-ion batteries, the changes in its recycling rate are different from those of lithium-ion batteries. The following are the main changes in each stage.

From 2013 to 2017, nickel-cadmium batteries were mainly used in power tools, emergency lighting and other fields, and the market size was relatively stable. The recycling system was initially established, but the recycling rate was low, mainly relying on small recycling companies and informal channels. The recycling rate was about 10–15%. From 2018 to 2020, environmental protection policies became stricter, especially the introduction of regulations such as the "Technical Policy for the Prevention and Control of Waste Battery Pollution", which promoted the standardized recycling of nickel-cadmium batteries. At the same time, the cadmium pollution problem of nickel-cadmium batteries received more attention, prompting companies to strengthen recycling. The recycling rate increased to 15–25%.

From 2021 to 2023, with the popularization of lithium-ion batteries, the market share of nickel-cadmium batteries was gradually downward, and the demand for recycling was relatively reduced. However, due to the increase in environmental protection requirements, the efficiency of formal recycling channels has improved. The recycling rate remained at 20–30%, but the market size was reduced. In coming years, the application of nickel-cadmium batteries will further decrease, but the remaining market will still need recycling and processing.

The progress of environmental protection policies and recycling technology will support the stability of the recycling rate. The recycling rate is expected to remain at 25–35%. The recycling rate data of these two batteries are compared in the Table 4.5.

Table. 4.5. Lithium-ion battery and nickel-cadmium battery recycling rate in China

Year	**Lithium-ion battery**	**Nickel-cadmium battery**
2013-2017	5%-10%	10%-15%
2018-2020	10%-20%	15%-25%
2021-2023	20%-30%	20%-30%
2024	30%-40%	25%-35%

With the strengthening of China's environmental protection regulations, the recycling technology is advanced and public environmental awareness is raised. From 2013 to 2024, the recycling rate of lead-zinc batteries in China showed a steady upward trend. The recycling rate of mercury-oxide batteries (usually referring to mercury-containing batteries) in China is relatively low, but due to its greater environmental hazards, the recycling rate has increased in recent years under the promotion of policies and technologies. The recycling rate of silver oxide batteries (usually referring to button batteries, such as silver-zinc batteries) in China is relatively low, but because it contains precious metal silver and has a certain recycling value, the recycling rate shows a slow growth trend. The recycling rate of lead-acid batteries in China has been at a high level and has shown a steady upward trend. This is mainly due to the widespread use of lead-acid batteries, mature recycling technology and strong policy support. The recycling rate data are shown in Fig. 4.2.

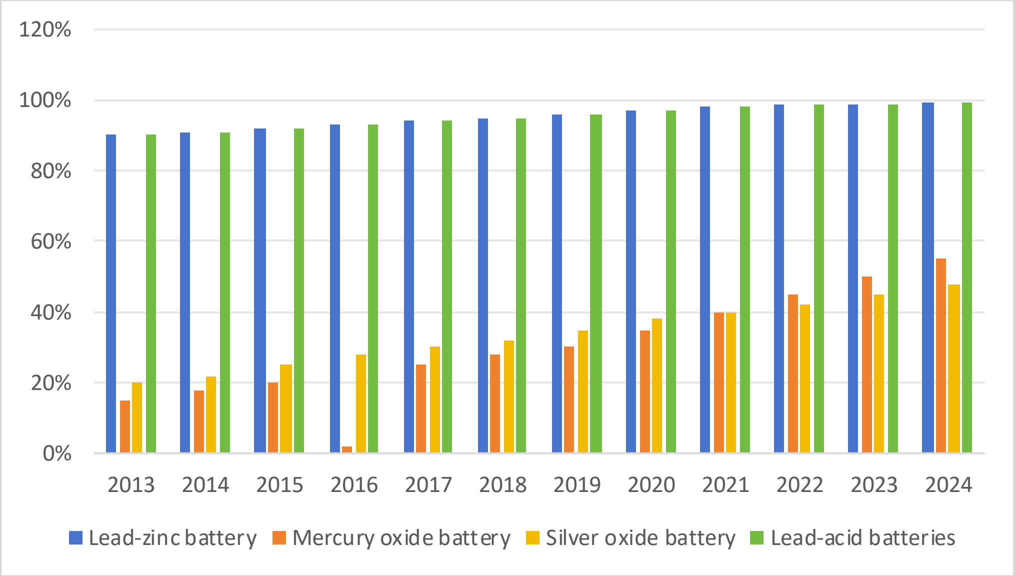

Figure 4.2 – Battery recycling rates in China

4.3.2 Collection and recycling rates

Based on own findings and taking 2023 as an example, the collection rate and recycling rate of waste batteries are calculated and the data is compared and analyzed.

The collection rate Rc is calculated by the Equation:

$$Rc = 100\% * Collection / Generation \qquad (4.1)$$

where *Collection* is amount of waste batteries collected (can be found in the Chapter 3.4); *Generation* is amount of waste batteries generated (can be found in the Chapters 3.2 and 3.4). Then:

$$Rc = 100\% * 755{,}503 \text{ tons} \div 10361500 \text{ tons} = 7.29\ \%$$

The recycling rate *Rr* is calculated by the Equation:

$$Rr = 100\% * Recycling / Generation \qquad (4.2)$$

where *Recycling* is amount of waste batteries recycled (the data are retrieved from the Table 4.3); *Generation* is amount of waste batteries generated (can be found in the Chapters 3.2 and 3.4). Then:

$$Rr = 100\% * 274000 \text{ tons} \div 10361500 \text{ tons} = 2.64\ \%$$

The reasons why the actual recycling rate of used batteries is lower than the theoretical predicted value involve many factors such as technology, statistics, management and society.

The data shows that the recycling rate is lower than the collection rate, which means that even the batteries that are collected are not being fully recycled. There are serious inefficiencies in both the collection and recycling systems for waste batteries. While the collection efforts are weak (7.29%), the recycling rate has dropped significantly (2.64%), indicating that comprehensive improvements are needed across the entire waste management chain. Closing these gaps is critical to reducing environmental harm and recovering valuable materials from waste batteries.

The overall recycling rate of used batteries in the EU is about 45–55% on average, the recycling rate of used batteries in the United States is <30% for consumer batteries, about 10–15% for power batteries, about 45% for South Korea, about 10–15% for Australia, <10% for India, and 2.64% for China.

Through comparative analysis, the reason for the large difference in the recycling rate of used batteries in various countries around the world is the difference in policies and regulations, and the different recycling systems and economic incentives. At the same time, it is constrained by technical and market factors.

4.4 Technologies of resource recovery from batteries: case study of lithium-ion battery

The main methods for waste lithium-ion batteries recycling include physical methods, dry metallurgical technology and hydrometallurgical technology. In recent years, methods such as biodissolution and ion exchange have also received widespread attention. The hydrometallurgy recycling technology mainly includes three parts: the pretreatment process of waste lithium batteries, leaching of valuable metal ions from the positive electrode material, and the recovery of valuable metal ions from the leachate. After the pretreatment of waste lithium-ion batteries and the recovery of valuable metal ions from the positive electrode material, a solution containing metal ions such as Co^{2+}, Mn^{2+}, and Li^+ is obtained. Finally, the valuable metals in the solution are recovered by precipitation, organic extraction, high-temperature direct method, etc. [142].

4.4.1 Recovery of valuable metal ions

In recent years, the main methods used include organic extraction, ion exchange, precipitation, electrodeposition and other recovery processes.

Organic extraction method

The organic extraction method is to select a suitable solvent or a mixture of several organic solvents so that these solvents can form a complex with the metal ions to be recovered. The metal ions in the complex can be easily transferred from the complex to another organic solvent, thereby achieving the separation and purification of the metal ions [143]. The organic extraction method is simple to operate, has a high metal resource recovery rate, and has a high purity of the product obtained. However, organic solvents are expensive, and they have certain hazards to the environment and human body.

Ion exchange method

The ion exchange method is to selectively remove impurities in the solution, use ion exchange resin to selectively adsorb the valuable metals in the solution, and then select a suitable eluent to elute the metal ions, so that the valuable metal ions are enriched in the solution, and finally obtain the metal product through precipitation, organic solvent extraction and other methods [144].

Precipitation method

The precipitation method is to use a precipitant to precipitate the metal ions to be recovered in the form of a precipitate. After the precipitate is recycled, reusable materials can be obtained [145]. The precipitation method can effectively precipitate the metal ions from the solution, but a large amount of reagents will be consumed during the operation, and the precipitated metal exists in the form of a composite material, which is difficult to further separate and utilize.

Electrodeposition method

The electrodeposition method is to dissolve the positive electrode material of the waste lithium-ion battery in an acidic solution and selectively remove impurity ions such as Fe^{3+} and Al^{3+} from the solution through organic solvent extraction. A certain current is passed through the electrolytic cell to precipitate metal ions (Mn^{2+}, Co^{2+}, and Cu^{2+}) at the cathode in the form of metal elements or alloys [145].

However, during the electroplating process, the reduction potentials of Co and Ni are very close, and co-precipitation is easy to occur, resulting in the formation of cobalt-nickel alloy when the positive electrode material of the lithium battery electrolyte is $LiNi_xCo_yMn_{1-x-y}O_2$. Besides, this method has high requirements for the treatment of electrolyte impurities and consumes a lot of energy, which is not conducive to industrial production.

Salting-out method

The salting-out method is used to recover cobalt and aluminum salts from the positive electrode leachate of lithium-ion batteries. The specific method is: the pretreated $LiCoO_2$ positive electrode material is leached with 3 mol/L HCl under the conditions of solid-liquid ratio of 10 g/L, temperature of 60ºC, and continuous stirring for 60 min, and then filtered to obtain a filtrate containing Co^{2+}. Then, saturated $(NH_4)_2SO_4$ aqueous solution and anhydrous ethanol are added to the filtrate to salt out the Co^{2+} from the solution in the form of $(NH_4)_2Co(SO_4)_2$. When the volume ratio of saturated $(NH_4)_2SO_4$ aqueous solution, leachate and anhydrous ethanol is controlled to be 1:2:3, the precipitation rate of Co^{2+} can reach over 92%.

The salting-out method for recovering valuable metals from lithium-ion battery leachate is simple to operate, efficient, and relatively economical and environmentally friendly, but the salting-out process is often accompanied by the precipitation of other metal salts in the solution [146].

Low-temperature heat treatment method

A simple low-temperature heat treatment method can be used to recycle lithium cobalt oxide battery. The method was checked in [147]. The specific steps were: after discharging and disassembling the waste lithium-ion battery, NaOH was added, the aluminum foil was removed, and after drying, heat treatment was performed at 200ºC, 300ºC, and 400ºC. After testing, the electrochemical performance of the $LiCoO_2$ material was improved. The maximum discharge capacity of the recycled $LiCoO_2$ material was 188 mA/g, and the capacity remained stable after 100 cycles.

4.4.2 Metal recovering from electrode materials

Since lithium-ion batteries are made of multiple materials and have a fine structure, are small in size, and highly dispersed in various materials, it is difficult to separate cobalt-containing substances by mechanical methods, and the battery cells can only be processed as a whole. Many countries use the pyrometallurgy to recycle lithium-ion batteries. After the collection of waste batteries, they are discharged, the shell is peeled off, and its metal materials are recycled. The battery core is mixed with coke and limestone and put it into a furnace for reduction roasting [148]. The alloy formed after the treatment contains metals such as copper, cobalt, and nickel. The main components of the positive electrode materials of lithium-ion battery are Co_2O_3, NiO, Al_2O_3, and Al. Among them, NiO, Al_2O_3, and Al are easily soluble in medium and strong acids, while Co_2O_3 is only soluble in dilute hydrochloric acid. The test results show that when the temperature is 80ºC, the leaching effect is the best when 20% dilute hydrochloric acid is used as the leaching solution [149]. The recycling process is shown in Fig. 4.3. This process combines the complexation method with the ion exchange method to achieve the separation and recovery of multiple metal elements from the positive electrode materials of lithium-ion battery.

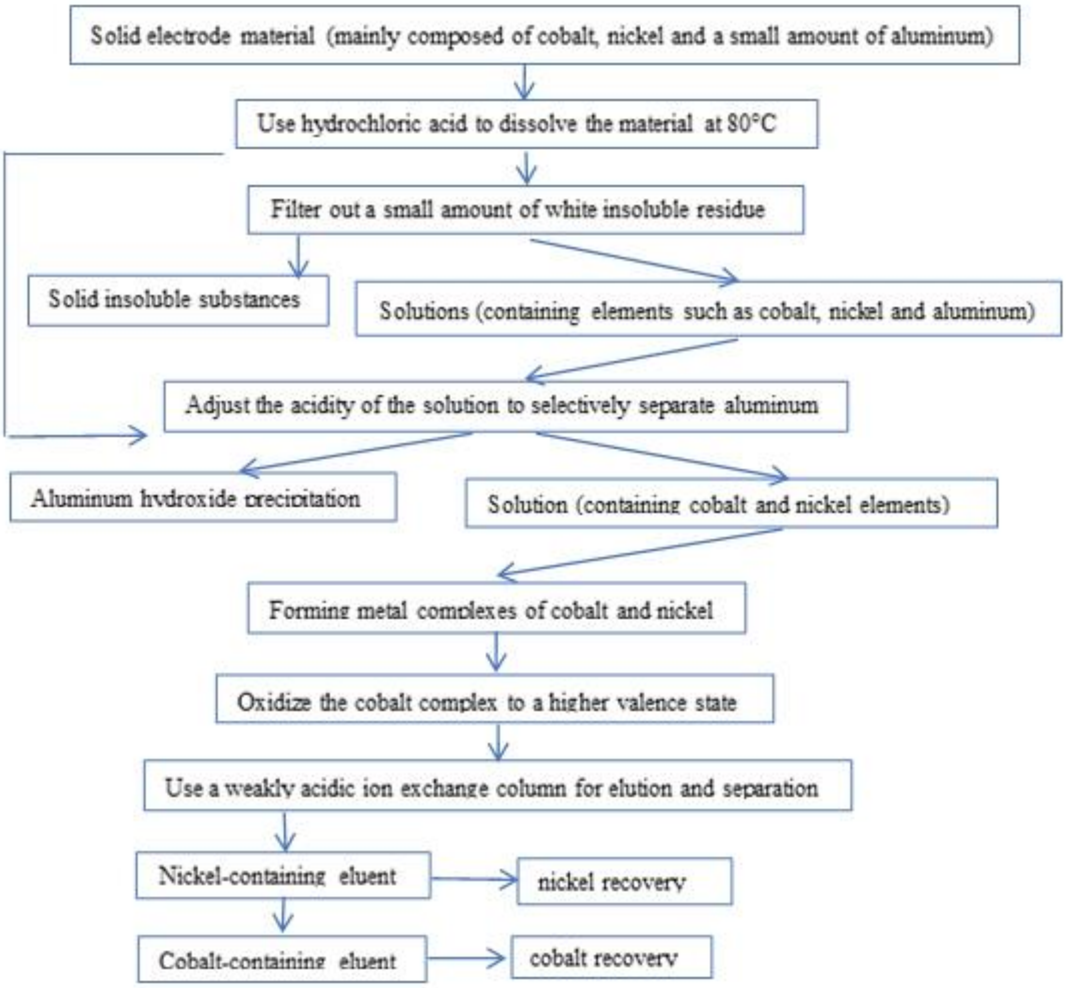

Figure 4.3 – Metal recovery process in lithium-ion battery electrode materials

This flow chart shows the process of separating and recovering cobalt and nickel from solid electrode materials. Each step clearly shows the changes in the material and the separation process.

Waste lithium-ion batteries are disassembled and separated into plastic shells, copper-iron connectors, graphite negative electrodes and positive electrodes. The process of alkaline leaching–acid dissolution–purification–cobalt precipitation is used to recover aluminum and cobalt from the positive electrode of waste lithium-ion battery. Specifically, the positive electrode is first leached with 10% NaOH solution at 90℃ so that all cobalt is retained in the alkaline leaching residue, and the leaching rate of aluminum can reach 94.84% [149]. The aluminum in the alkaline leaching solution is neutralized to pH 7 with H_2SO_4 to recover aluminum hydroxide.

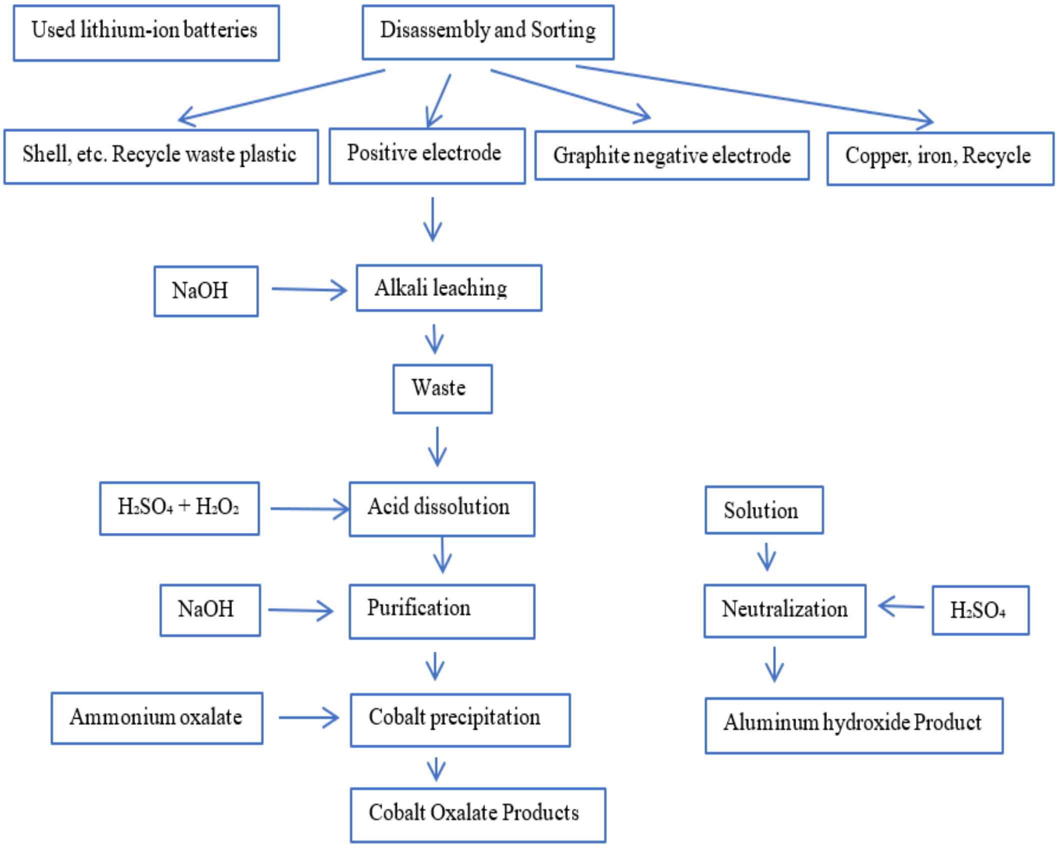

Figure 4.4 – Process flow for recycling aluminium and cobalt from lithium-ion battery cathode

The alkaline leaching residue is leached in a sulfuric acid and hydrogen peroxide system, and the leaching rate of cobalt obtained can reach 99.3%. Then, the pH of the acid-dissolved solution is adjusted to 5.0 with NaOH, and it is purified and impurities are removed. The loss of cobalt is about 1%, and 87.81% of the aluminum in the solution is removed. Manganese oxalate solution is added to the purified solution to precipitate cobalt. After drying and sieving the filter cake, a cobalt oxalate product ($CoC_2O_4 \cdot 2H_2O$) is obtained. The cobalt precipitation rate is 97.52%, and the cobalt recovery rate of the entire process is 94.23%. The process flow is shown in Fig. 4.4.

4.4.3 Flotation method for lithium cobalt oxide recovery

Flotation can be used to recover lithium cobalt oxide from ultra-thin square waste lithium-ion batteries.

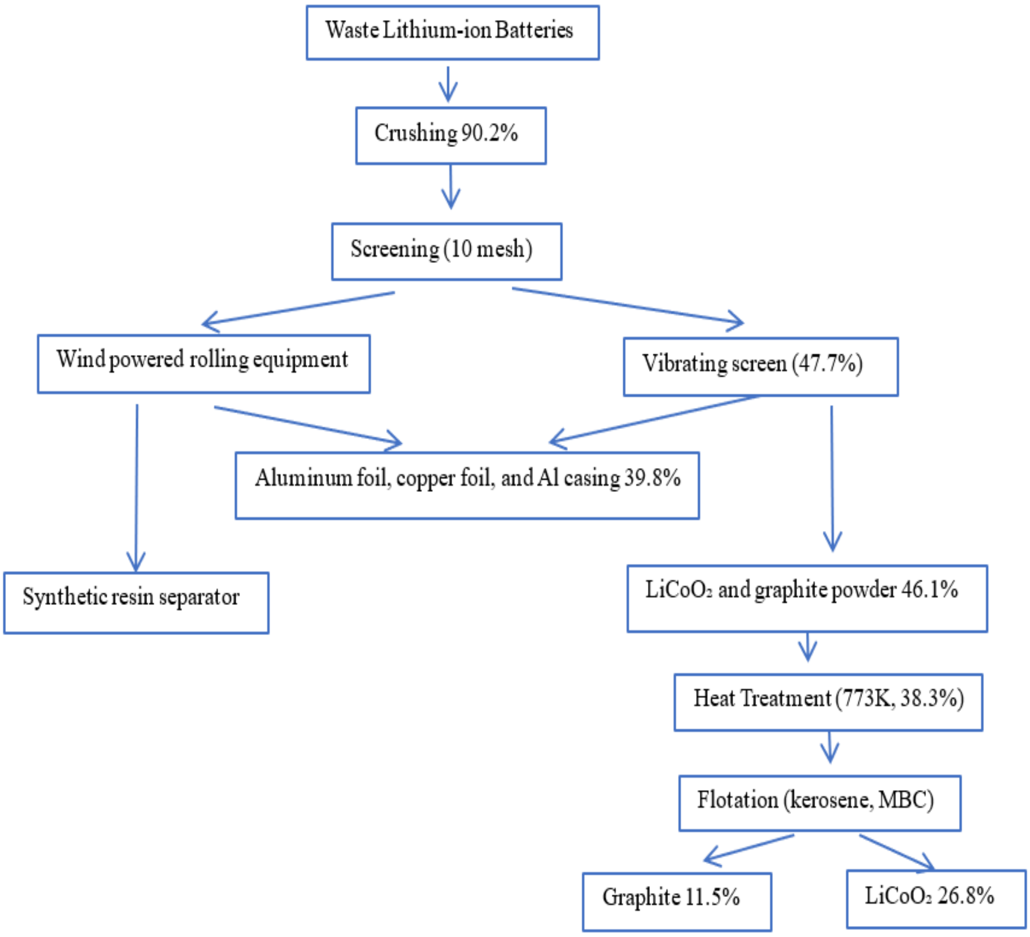

Figure 4.5 – Waste lithium-ion battery recycling process

First, the waste lithium-ion batteries are crushed by a vertical high-speed rotary crusher for 30 seconds, the crushed products are sieved with a 10-mesh sieve, and the sieved materials are sorted by a pneumatic sifter to separate the resin material and metal material (aluminum foil, copper foil, aluminum metal shell fragments, etc.) used as partitions. The sieved materials are sieved with a 65-mesh vibrating screen to separate the metal material and mixed powder (mixed powder containing lithium cobalt oxide and graphite). Then, the separated black mixed powder is heat treated at 773^{0}K for 2 hours to modify the surface of the lithium cobalt oxide particles and graphite. Then, the lithium cobalt oxide is separated from the graphite by flotation. The combined process flow of the flotation method shown in Fig. 4.5 [150] can be used to recover lithium cobalt oxide from waste lithium-ion batteries.

4.5 Environmental impact analysis of waste lithium-ion battery cathode recycling

Because of high energy density, high operating voltage, long cycle life, and high safety [151], lithium-ion batteries (Li-ion batteries) are widely used in 3C products [152], electric vehicles [153], stationary energy storage wells and other fields [154]. Due to the rapid development of electronical industry and new energy automobile industry, a large number of used batteries will be produced after the decommissioning of electrical vehicles [155]. Therefore, the disposal plan for decommissioning batteries has gradually become the focus of research in the Li-ion battery industry. After the power battery is retired, there are different ways to place it according to its capacity retention rate. Waste Li-ion batteries with a capacity retention rate of about 80% are generally converted to energy storage batteries for echelon utilization, and those with the capacity retention rate of 45–60% can be used for auxiliary frequency modulation of thermal power generation. Waste batteries with a capacity retention rate of 30%-45% can be used as backup power supply for communication equipment in the power system. When the capacity retention rate of batteries is lower than 30%, they need to be dismantled and recycled [156-158].

Cathode materials of Li-ion battery usually contain cobalt, nickel and manganese with certain biological toxicity, polluting the soil and water if battery is discarded [159]. In many cases, the organic solvent in the electrolyte is directly put into the environment without treatment causing a pollution. For example, lithium hexafluorophosphate, when mixed with water, generates hydrofluoric acid that is of great harm to the environment [160-161]. From the perspective of resource recovery, China's (main Li-ion batteries producer) cobalt reserves are 80,000 tons, accounting for about 1.1% of the world's total cobalt resources. Due to the large cobalt ore gap, China needs to import a large amount of cobalt every year [162]. China's lithium reserves are 8.1 million tons, accounting for 6.3% of the global total reserves, but due to poor mining conditions and high development costs, the external dependence of lithium resources is as high as 67% [163]. Recycling cobalt, lithium and other resources from used Li-ion batteries can effectively alleviate the pressure of cobalt and lithium resources import [164].

With the large-scale decommissioning of power batteries in the future, the valuable metals obtained through recycling can meet more than half of the raw material demand for lithium-ion battery materials [165]. Therefore, recycling Li-ion batteries can reduce the amount of minerals mined, and reduce the harm of mining to the environment while protecting raw mineral resources.

The efficient recycling of waste Li-ion batteries transforms waste to resources, which is conducive to the formation of a dynamic and sustainable cycle in the manufacturing, use and recycling of Li-ion battery industry [166], and can reduce the harm to the environment, with multiple benefits such as resources, economy and environment. Therefore, it is of great significance to study the recycling technology of waste Li-ion batteries.

In the same time, recycling processes can be harmful to the environment as well. Therefore, when trying to get resources from waste, it is important to choose appropriate method with minimal impact to the environment [167-168]. The goal of this study is to analyze waste lithium-ion batteries recycling process, with a focus on cathode materials, and its environmental impact.

4.5.1 Methodology

In this study, composition of lithium-ion battery was analyzed in order to estimate which components are potentially dangerous to environment. Based on chemicals properties, known natural regularities, and literature review, potential environmental impact pathways were identified. The environmental assessment of waste lithium-ion battery recycling process has been done for the case study of positive electrode material. Each stage of positive electrode material recycling process was analyzed in details. Then, sources of air, water, noise pollution, and solid waste were analyzed. Besides, toxic chemicals and other potential pollutants that might be generated in recycling process were identified.

4.5.2 Composition of lithium-ion batteries

Li-ion batteries are known to be composed of positive electrode, negative electrode, separator layer, binder, electrolyte, and organic solvents. The positive electrode is the component with the highest volume and cost in Li-ion batteries, and it is also the main research object for the development in the battery industry. Li-ion batteries are classified according to the types of positive electrode materials mainly including lithium cobalt oxide (LCO battery), lithium manganese oxide (LMO battery), lithium iron phosphate (LFP battery), lithium nickel cobalt manganese oxide (NCM battery), and lithium nickel cobalt aluminium oxide (NCA battery). Among them, ternary materials (NCM and NCA batteries) have become the main choices for new energy passenger vehicle power batteries due to their high energy density advantages [169].

The composition, environmental impact characteristics, and potential environmental impact pathways of Li-ion batteries are summarized in the Table 4.6.

As can be seen from the Table 4.6, serious environmental pollution can be caused by the cathode material (mainly metals): air, water and soil are pollutants recipients.

Table 4.6. Composition of Li-ion batteries, their environmental impact characteristics and potential environmental impact pathways

Major component	**Chemicals**	**Environmental impact characteristics**	**Potential environmental impact pathways**
Positive electrode	lithium cobalt oxide (LCO battery), lithium manganese oxide (LMO battery), lithium iron phosphate (LFP battery), lithium nickel cobalt manganese oxide (NCM battery), lithium nickel cobalt aluminium oxide (NCA battery)	Due to pH changes, heavy metal ions are released to the external environment	Surface water, groundwater, Soil
Negative electrode	graphite	Combustion generates CO and CO_2 emission; carbon powder dust can explode when exposed to open flames	Air
Separator layer	polyethylene, polypropylene	Combustion generates CO and CO_2	Air
Binder	polyvinylidene fluoride, polytetrafluoroethylene	Decompose at high temperature generating HF gas	Air
Electrolyte	lithium hexafluorophosphate	Highly corrosive, decomposes into HF when exposed to water, reacts with strong oxidants, and generates P_2O_5 during combustion	Air
Organic solvents	ethyl carbonate propylene carbonate, dimethyl carbonate, diethyl carbonate	React with acids, bases, strong oxidants, and reducing agents, hydrolysis generates acids and alcohols, and combustion can generate CO and CO_2	Air, Surface water, Groundwater, Soil

Heavy metals like nickel, cobalt and manganese pollute and change the pH of the environment. Another source of water / soil pollution is organic solvent as it actively reacts with oxidants and reducing agents in the environment. Other parts of waste battery mainly impact an air during the combustion or thermal decomposition generating toxic lithium, cobalt oxides, other gases.

In the waste Li-ion battery, positive electrode material (containing metals) is the most valuable for recycling. That is why this paper mainly discusses the pretreatment and recycling technology of positive electrode material recovery.

4.5.3 Positive electrode material recycling process

Today, the recycling methods for waste Li-ion batteries mainly include cascading recycling and dismantling recycling. Cascading recycling refers to the use of batteries that have been phased out from electric vehicles with high energy demands in energy storage systems or electric tools with low energy demands. When the battery performance cannot be met even in cases of low energy demands, dismantling recycling is adopted [170]. Since the cathode material is the most cost-effective component of Li-ion battery, the recycling mainly involves the recovery of metals such as nickel, cobalt, manganese, and lithium from the cathode material.

Waste Li-ion batteries are usually recycled in two ways: pyrometallurgical process and wet process. The pyrometallurgical process occurs in an ultra-high temperature environment, where the negative electrode, electrolyte, plastic, and separator in the battery are burned and decomposed. The metal elements of positive electrode are recycled in the form of alloys or oxides [171]. Although pyrometallurgical process has high compatibility with battery types and does not require classification and treatment of waste batteries, many materials cannot be recovered due to the high energy consumption, and the recovery of lithium elements still needs to be further combined with wet processes. The wet recovery process of waste Li-ion batteries mainly includes discharge pretreatment, disassembly and crushing, separation of positive electrode materials, and metal element recovery.

Discharge pretreatment

There may still be residual electricity in waste Li-ion batteries. To avoid potential hazards such as explosions or spontaneous combustion during the dismantling process, it is necessary to discharge the batteries before dismantling [172]. Generally, waste batteries are placed in an electrolyte solution (usually carbonate electrolytes (K_2CO_3 and Na_2CO_3) or sulphate electrolytes ($FeSO_4$, $MnSO_4$) [173]) and the remaining electricity is discharged.

Dismantling and crushing

After deep discharge pretreatment, waste Li-ion batteries are disassembled, crushed, and screened to achieve preliminary separation of electrode materials from separator, metal case, aluminum foil, and other materials. At the same time, combined with magnetic separation, ultrasound, flotation and other technologies, further separation is achieved.

Separation of positive electrode materials

In the manufacturing process of Li-ion batteries, the active material of the positive electrode is combined with the solvent through an organic solvent binder. After disassembly, fragmentation, and separation, the positive electrode material is mixed with binder polyvinylidene fluoride (PVDF) and conductive agent. The presence of PVDF and conductive agent can affect the leaching efficiency of metal elements from the positive electrode material [174]. In industry, calcination and pyrolysis are commonly used to remove binders and conductive agents from positive electrode materials. The principle of calcination and pyrolysis is based on the fact that the positive electrode material, PVDF and conductive agents undergo different thermal decomposition or transformation temperatures, and the temperature is controlled to decompose PVDF, thereby achieving further separation of positive electrode materials.

Recovery of metals

In the wet recovery process of waste Li-ion batteries, the efficient separation and recovery of various elements such as nickel, cobalt, manganese, lithium, copper, and aluminum from the positive electrode is a key task. First, inorganic acids are used to dissolve the powder of the positive electrode material, and the metal elements in the positive electrode material are leached into the solution in the form of ions. Due to the mixing of multiple metal elements in the leaching solution, low-cost methods must be used to effectively separate each metal. Today, extraction separation is widely used in industry to separate metals. The commonly used extractants include P204 (di (2-ethyl, hexyl) phosphate, also known as diisooctyl phosphate) and P507 (2-ethylhexyl phosphate mono-2-ethylhexyl ester). These extractants can be used to separate metals like nickel, cobalt, manganese, and lithium. Nickel, cobalt, and manganese ultimately exist in the form of sulphates, which then crystallize into nickel sulphate, cobalt sulphate, and manganese sulphate products with required purity. During the wet recovery process, sodium carbonate is added to the lithium rich solution for lithium precipitation, and the lithium element is ultimately recovered in the form of lithium carbonate.

The wet recycling process can provide high-purity metal element products and recover most of the metals from waste Li-ion batteries. The entire recycling process is under mild conditions, so the wet recycling process has become the preferred process for recycling waste Li-ion batteries in industry [175].

4.5.4 Environmental impact analysis

The recycling of waste Li-ion battery cathode materials has significant environmental benefits, but the emissions of pollutants during the recycling process also have adverse effects on the environment [176]. Therefore, it is necessary to analyze the pollution sources and provide practical and feasible pollution prevention and control measures to reduce their impact on the environment.

According to the analysis of the wet recycling process mentioned above, the pollution generation process and the impact on various environmental factors during the recycling of waste Li-ion battery cathode materials are analyzed as follows.

Sources of exhaust gas pollution

The sources of air pollution generated during the recycling process of positive electrode materials include all the stages: dismantling, crushing and screening, calcination and pyrolysis, acid leaching, extraction, and product drying. The main pollutants in exhaust gas are shown in the Table 4.7.

Table 4.7. Main pollutants in exhaust gas

Process	**Main pollutants**
Dismantling	Fluorides Nonmethane hydrocarbons
Crushing and screening	Solid particles containing nickel, cobalt, manganese, lithium, etc.
Separation (calcination and pyrolysis)	Solid particles containing nickel, cobalt, manganese, lithium Fluorides Nonmethane hydrocarbons
Acid leaching	Inorganic acids such as sulfuric acid
Extraction	Nonmethane hydrocarbons
Product drying	Solid particles containing nickel, cobalt, manganese, lithium, etc.

Gaseous pollutants generated in the process of positive electrode materials recycling can be divided into dust containing gases, acidic gases, and organic gases. Dust containing waste gas is mainly treated using cyclone dust collectors, bag filters, or water spray towers and their combination processes [177]. Acidic waste gas is mainly treated using alkaline spray towers. According to the concentration of pollutants in acidic waste gas and emission control requirements, single-stage, two-stage, or even three-stage alkaline spray towers can be used. Organic waste gas can be treated using adsorption or catalytic combustion processes, and the selection of organic waste gas treatment measures should be determined comprehensively based on the amount of waste gas, pollutant concentration, and other factors.

Water pollution sources

The wastewater is generated mainly from the discharge pretreatment and positive electrode material recovery processes. The pollutant composition in the wastewater generated is relatively simple, mainly composed of salts such as sodium sulphate, and the organic content is relatively low. Also, wastewater from acid leaching stage and extraction stage contains a large number of lithium cobaltate, lithium iron phosphate, methyl pyridinium alkanone, ultrafine carbon powder and low-molecular-weight esters. Although the wastewater volume is relatively small, its composition is complex, poorly biochemical and toxic. To provide wastewater treatment, three-effect evaporation or mechanical vapor recompression (MVR) evaporator is generally used for desalination [178]. After desalination treatment, the water can be reused as pulping water, and the wastewater is not discharged.

Solid waste

In the dismantling process of Li-ion batteries, plastic connectors, circuit boards, high-voltage wiring are separated and become a waste. A lot of other waste are also generated, such as powders, collectors and pool electrode material casings [179]. Storage of industrial solid waste should meet environmental protection requirements such as leakage prevention, rain prevention, and dust prevention.

To prevent a pollution, the recycling process should be continuously optimized to reduce pollutants generation and decrease their impact on the soil and groundwater environment. Secondly, anti-leachate measures should be strengthened to effectively prevent pollutants from entering the soil and groundwater environment. Finally, soil and groundwater tracking and monitoring should be carried out as required, and timely detection and measures should be taken to eliminate pollution sources.

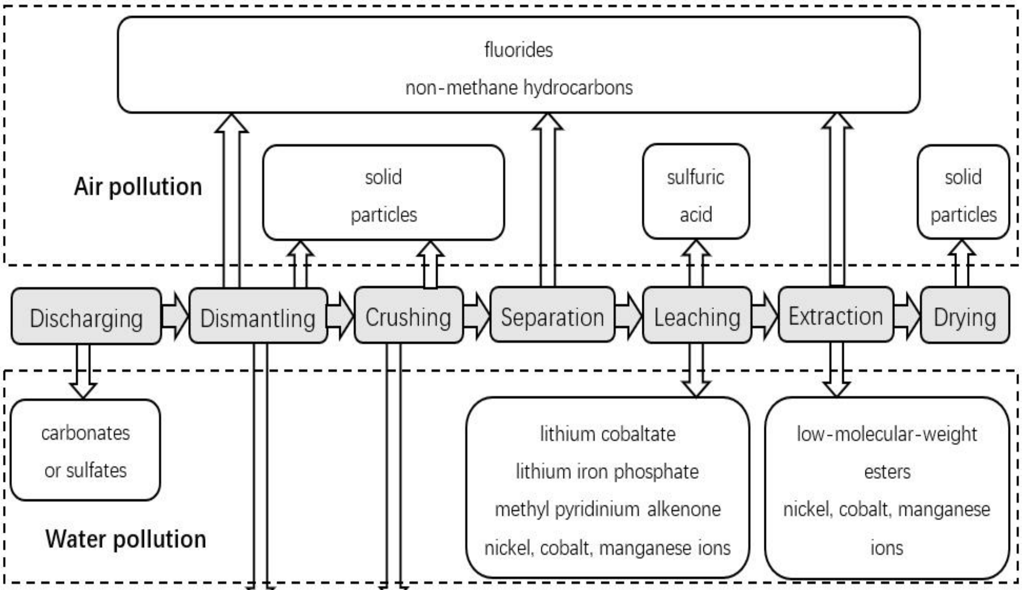

Figure 4.6 – Environmental pollution during waste lithium-ion battery cathode recycling

Noise pollution sources

The noise sources in the process of positive electrode materials recycling mainly include crushers, fans, and pumps [180]. Low noise equipment is preferred, as well as the equipment with anti-vibration foundation. Silencers must be installed at the inlet and outlet of the fans. The above-mentioned comprehensive noise reduction measures can effectively reduce the impact of noise emissions on the external environment during the recycling process.

4.6 Optimization of waste battery management and recycling methods

4.6.1 Advantages and disadvantages of waste battery recycling technologies

The recycling process of waste dry batteries, whether dry, wet or a combination of dry and wet, has high technical requirements and potential secondary pollution risks.

Therefore, when determining the technical route, it is necessary to consider both economic feasibility and environmental protection. In view of the limitations of the above-mentioned processes, industry experts are still constantly improving the process. In recent years, the biofiltration, leaching technology and ultrasonic assisted leaching technology are improved based on the wet method. Due to mild reaction conditions, high product purity and good economic benefits, they have gradually become the current research hotspot [181].

Generally speaking, waste dry batteries are recycled based on the harmlessness and resource utilization. As discussed in previous chapters, there are four main treatment methods: manual sorting, dry method, wet method, and dry-wet method. The basic principles, advantages, and technical defects of various methods for waste zinc / alkaline battery processing are analyzed in the Table 4.7 [182-184].

Table 4.7. Comparation of waste dry battery processing methods

Process methods	**Basic principles**	**Process advantages**	**Technical defects**
Manual sorting	According to the battery components, the carbon rods, copper caps, zinc case and various residues are manually sorted out and processed in the corresponding way	Simple and easy, environmentally friendly	Time-consuming and labour-intensive, poor economic benefits
Wet method	The roasting process converts ammonium chloride, mercurous chloride, etc. in the battery into gas phase and recovers them in the condensation device. The high-valent metal oxides are reduced to low-valent oxides. The roasting product is leached with acid, and then the valuable metals are recovered from the leaching solution by electrolysis	The products obtained by electrolysis or ion resin exchange methods have higher purity	The process is complicated, washing and acid leaching are both major pollution-producing links, the production process consumes a lot of energy and has high production costs
Dry method	Under atmospheric pressure conditions, there are two forms. One is to heat the dry battery at a relatively low temperature to volatilize the mercury first, and then recover zinc and other heavy metals at a higher temperature. The other is to roast the dry battery at a high temperature to volatilize the volatile metals and their oxides, and the residues are used as metallurgical intermediates or treated separately	The vacuum method has the advantages of short process, low energy consumption, little environmental pollution and high comprehensive utilization rate of useful ingredients	The vacuum method has a high one-time investment cost.
Wet and dry method	A method of separating different components of a battery at different temperatures through evaporation and condensation in a vacuum to achieve comprehensive recycling. During evaporation, components with high vapor pressure enter the vapor, while components with low vapor pressure remain in the residual liquid or residue; during condensation, vapor condenses into liquid or solid at a lower temperature Combining the advantages of dry and wet methods, mercury and part of zinc are first recovered by roasting, and then manganese and the remaining zinc are recovered by leaching and electrowinning	The recycling effect is relatively good	The process is complicated and the cost is high

4.6.2 New waste battery recycling technologies

The environmental pollution caused by waste batteries and the harm to human health make the recycling of waste batteries an urgent problem. However, the current common processes such as manual sorting, wet method, dry method and wet-dry method have limitations. Ultrasonic assisted and bioleaching are processes based on the improvement of wet method, which can effectively improve the metal leaching rate. In particular, bioleaching uses microorganisms to produce acid, which has the advantages of low energy consumption, low secondary pollution and economic benefits. If the problem of long process cycle can be solved and the leaching conditions can be further optimized, this technology will have broad prospects in the recycling of waste batteries.

Ultrasonic assisted leaching technology

Ultrasonic waves can produce various complex effects in liquids, such as mechanical effects, cavitation, thermal effects and chemical effects. Among them, cavitation can produce a large high temperature and high-pressure environment in a very short time and very small space, opening up a new channel for leaching reactions. Therefore, in recent years, ultrasonic treatment technology has begun to be introduced in the wet treatment of waste batteries. Due to the high cobalt recovery, ultrasonic assisted leaching is currently mainly used for cobalt leaching experiments. Zhang Yonglu et al. [185] studied the leaching kinetics of cobalt in the H_2SO_4–H_2O_2 system under ultrasonic field conditions. The experiment found that the use of sulfuric acid is mainly to maintain the pH in the reaction, and hydrogen peroxide can convert Co^{3+} into Co^{2+}. Increasing its dosage can increase the cobalt leaching rate. With the increase of ultrasonic action time, the leaching rate of cobalt also increased significantly. Zhao Kun et al. [186] designed an orthogonal experiment to explore the effects of ultrasonic time, hydrogen peroxide dosage, leaching temperature and other factors on the leaching rate of cobalt. The results show that ultrasonic technology can significantly improve the leaching rate of cobalt. The optimal leaching conditions obtained by the orthogonal experiment are ultrasonic time of 20 min, volume ratio of sulfuric acid to hydrogen peroxide of 5:1, and leaching temperature of 80°C. At this time, the leaching rate of cobalt can reach more than 99%. Compared with traditional acid leaching, adding ultrasonic assistance to the H_2SO_4–H_2O_2 system increases the reaction rate due to the cavitation effect of ultrasound, thereby greatly increasing the leaching rate of metals, and the leaching effect is good under experimental conditions. However, due to the high energy consumption of ultrasound, there is a cost bottleneck, which makes it difficult to apply on a large scale. There are still limitations such as high acid consumption and high pollution in the chemical system.

Bioleaching technology

Bioleaching is a process that uses the redox, complexation, adsorption and dissolution of microorganisms and their metabolites to separate and extract heavy metals and sulphur from waste batteries. Bioleaching technology is widely used in the mining industry to extract metals from ores. Later, it was gradually applied to heavy metal extraction from urban sludge and soil bioremediation technology.

At the end of the 20th century, foreign experts introduced this technology into the study of heavy metal leaching from waste batteries. The earliest foreign experiment in this area can be traced back to C. Cerruti et al. [187] who leached metals from waste nickel-cadmium batteries at pH 2.0 and temperature 30°C with an aeration rate of 120 L/h. After 93 days, the leaching rate of cadmium reached 100%, the leaching rate of nickel was 96.5%, and the leaching rate of iron was 95.0%. There are two types of experimental devices used in China to study this process. One type is a combination of bioreactor + sedimentation tank + gold leaching tank designed by Zhu Nanwen et al. [188]. Thiobacillus is cultured and propagated in an aerated bioreactor, and the supernatant flows into the sedimentation tank. After sedimentation, most of the activated sludge is concentrated and part is refluxed. The leachate in the sedimentation tank enters the gold leaching tank to extract metals from waste battery materials. By comparing the sludge retention time of 5, 4, and 3 days, it was found that the nickel leaching rate was the highest when the retention time was 4 days, reaching 75.6%. The other type uses a conical flask as the main reactor. Sun Yan, Wu Feng etal. [189] used a conical flask reactor to study the effect of temperature on metal leaching rate in the range of 15~35 °C.

The results show that the higher the temperature, the faster the rate of pH decrease and SO_4^{2-} concentration increase in the system, and the leaching rate of heavy metals Ni and Co in the electrode material also increases accordingly.

This is because under the condition of a certain initial pH, the higher the temperature, the faster the proliferation and growth of Acidithiobacillus, and the stronger its biological oxidation ability. Under the condition of 35°C, the leaching rate of various metals reached the highest level, with the leaching rate of Ni being 98.0% and the leaching rate of Co being 77.9%. Zhu Qingrong et al. [190] compared the leaching efficiency of biological leaching technology and chemical leaching technology, and compared the leaching efficiency of nickel-cadmium batteries, zinc-manganese batteries, and lithium-ion batteries in biological leaching systems and sulfuric acid leaching systems under the condition of pH 2.0.

The experimental results show that the pH of both systems increased after adding different batteries, but the pH of the sulfuric acid leaching system increased more significantly, and even became alkaline [191-193].

This is because the organic acids and proteins in the biological leaching system have acid-base buffering capacity. In addition, since the microorganisms in the system can produce acid, the acid consumption of biological leaching technology is relatively small.

After 9 to 12 days of leaching, nickel concentration can reach 274 mg/L, zinc concentration is 545 mg/L, manganese concentration is 370 mg/L, lithium concentration is 70 mg/L, and cobalt concentration is 306 mg/L, while the leaching concentrations of various metals in the corresponding chemical system are less than 10 mg/L, and cobalt is not even leached. Therefore, the biological leaching is more effective than the chemical system in leaching heavy metals from waste batteries. At present, the biological leaching technology mostly uses 9K culture medium, and the strains used are Thiobacillus ferrooxidans and Thiobacillus thiooxidans. Under the conditions of pH = 2~3 and 30°C, it can achieve a good leaching effect of heavy metals. This technology has the advantages of good leaching effect, small secondary pollution, economic and environmental protection, but it is still in the experimental stage, the process cycle is long, and the leaching conditions need to be optimized [194].

The following questions and prospects are suggested for the process of bioleaching of waste battery metals:

1) Optimize the pretreatment processes such as crushing and sorting of waste battery materials to reduce the interference of impurities on the bioleaching of heavy metals.

2. The leaching rate of different heavy metals in bioleaching is related to the type and activity of bacteria. The knowledge how to optimize the combination of bacteria and enhance their activity can improve the leaching effect;

3. Compared with the chemical system leaching method, the bioleaching cycle is longer. In-depth research on the mechanism and kinetics of metal leaching by microorganisms is one of the possible ways to solve this problem.

At present, this technology has not been applied on a large scale due to high costs and administrative management reasons.

The process of bioleaching of waste battery metals based on wet method has good performance in environmental and economic benefits.

The next experimental direction should be to improve its leaching conditions and shorten the process cycle, which may realize large-scale industrial application.

4.6.3 Optimization of waste battery management in China

Through research, here are some measures and suggestions.

Technical recommendations

The following tasks are in the focus:

- Systematic research and development on universal and intelligent dismantling technology, selective separation and purification technology, and safe transportation technology, and develop universal and intelligent dismantling equipment.

- Strengthen the research on the mechanism of metal recovery from positive electrode materials, with a focus on breakthroughs in selective separation and purification technologies for various metals.
- Strengthen research on negative electrode materials and electrolyte recycling, and develop clean, environmentally friendly, and short process recycling processes.
- Pay attention to the precise inspection technology and standardization research of waste power batteries, especially the detection and testing technology and standards related to high-altitude drop simulation, thermal shock, vibration, impact, external short circuit, heavy object impact, etc. in the transportation process, effectively reducing the cost and industrialization difficulty of safety packaging technology, safety box design technology, and in-process monitoring technology, and unifying transportation labelling.

Recommendations for industry

- Expand the scale of pilot projects for battery recycling and utilization, and strengthen the promotion of mature experience.
- Promote leading industrial companies to expand their production scale, strengthen the construction of recycling and sales channels, continuously improve industrial technology, and enhance the efficiency of whole component recycling.
- Intensify the promotion of whitelist, suggest that industry regulatory authorities and financial institutions provide certain loan subsidies, tax reductions, and low interest loans to whitelist companies, and encourage whitelist companies to strengthen their recycling channel layout.
- Promote collaboration between upstream and downstream industries, encourage business model innovation, and facilitate strong alliances between qualified and technologically advanced third-party recycling enterprises and power battery production enterprises in the industry.

It is suggested that the industry regulatory department or leading backbone enterprises take the lead in encouraging qualified transportation enterprises to join, and form industry alliances with battery recycling enterprises, battery production enterprises, and automobile manufacturers to build a healthy and orderly power battery recycling industry ecosystem, and promote the realization of the domestic circulation of the power battery industry.

Policy recommendations

- Establish a dynamic adjustment mechanism for the price of waste batteries based on the market price of precious metals.
- Standardize market recycling channels, strictly implement the producer responsibility system for recycling, and increase penalties for unqualified and non-technical small workshops engaged in power battery recycling by market supervision departments.
- On the basis of ensuring transportation safety, fully leverage the monitoring role of the traceability platform, comprehensively cover the entire circulation process of waste batteries, and optimize the approval mechanism in a timely manner.
- Promote research on carbon footprint and strengthen research on carbon emission accounting policies.

International cooperation recommendations

- Strengthen communication and cooperation in the field of waste battery recycling, and promote technological exchange.
- Promote qualified battery recycling companies to expand their production capacity overseas, further extend the industrial chain, and form a regional resource recycling system.
- Make full use of multilateral and bilateral international cooperation mechanisms, promote the establishment of a global market mechanism for the free flow of battery resources, and strive to build a new ecosystem of global power battery industry for win-win cooperation.

Suggestions for standardization of waste battery recycling

Based on the comparison of standardization of waste battery recycling in China and abroad, and in combination with the needs of China's waste battery recycling standard system construction, the following suggestions are proposed.

1. Take the lead in formulating standards that are urgently needed and technologically mature within the industry. Priority should be given to researching and establishing important basic standards such as urgently needed terms and definitions, safety requirements, etc. in the field of waste battery management. For mature common technical standards related to waste battery recycling, such as residual energy detection, chemical analysis, and cascade utilization, both domestically and internationally, priority will be given to releasing and implementing them in the form of a series of standards.

2. Strengthen technological research and innovation, promote the transformation of scientific and technological achievements into technical standards. Technological innovation is the key to improving the recycling rate and quality of waste battery management. Only by overcoming the challenges of green treatment and recycling of waste battery resources can the recycling and reuse of valuable metals such as nickel, cobalt, manganese, and lithium be promoted towards industrialization. Therefore, it is necessary to vigorously promote the research and development of advanced recycling technologies, accelerate the pace of scientific and technological achievements transformation, strengthen the research on key technical standards for waste battery recycling (such as battery ecological design, carbon footprint accounting, etc.), improve the standard level through technological innovation, and lead the optimization and upgrading of the industry through standard application.

3. Improve the market-oriented construction of the recycling system, clarify the responsible parties and recycling goals. Under the guidance and constraints of relevant legal frameworks such as ecological environment protection and resource recycling, in accordance with the laws of economic and social development, a sound market-oriented system for recycling renewable resources should be established.

Combined with the extended producer responsibility system, the responsibilities and obligations of all parties involved in the recycling and utilization of waste batteries should be further clarified, and reasonable recycling targets should be set to guide enterprises to increase the share of recycled materials used to better meet market demand. At the same time, the construction of a standard support system should be accelerated for the development of circular economy, strengthening the traceability of waste battery management, promoting upstream and downstream cooperation in the industrial chain, and the development of the waste battery recycling industry.

4. Integrate standard systems and certification systems such as environmental footprint and resource recycling, and promote international cooperation and mutual recognition. Actively participate in ISO IEC and other international standardization activities, closely monitor the new trends and directions in the standardization of waste battery recycling internationally, and fully draw on advanced recycling technologies and management experience from abroad. Timely conduct applicability analysis and comparison of key technical indicators of international standards, increase the adoption of international standards, and enhance the consistency between Chinese standards and international standards. Actively participate in and lead the formulation of international standards and rules for certification of recycled materials, power battery cascade utilization products, deepen international cooperation and mutual recognition, and promote the "going global" of Chinese standards.

5. Pay attention to publicity and guidance, and enhance the awareness of recycling waste batteries in the whole society. At important time points such as National Ecology Day, National Energy Conservation Promotion Week, and World Environment Day, various forms of publicity and education activities will be carried out with themes such as "Green Recycling into Communities" and "Resource Recycling into Schools" to widely promote the dangers of waste lead-acid batteries, the importance of recycling and reusing waste batteries, and related policy measures. Innovate publicity methods, enrich publicity means, make full use of our media, the Internet and other information platforms, popularize knowledge about waste battery

recycling through multiple channels and dimensions, spread the concept of green and low-carbon, improve the initiative of the public to participate in waste battery recycling, and strive to create a good atmosphere for the participation of the whole society.

4.7 Conclusion to the Chapter 4

Countries like the EU and the US started recycling used batteries relatively early, but some still face profitability challenges. China's used battery recycling rate is low, a stark contrast to its massive battery production and consumption. Despite gradual improvements in technology and policies, the recycling system still suffers from inefficiency and insufficient resource integration. This chapter focuses on the recycling of cathode materials from used lithium-ion batteries, systematically elaborating on mainstream recycling technologies, their environmental impact, and optimization recommendations across the entire chain, from technology to policy.

A detailed comparison of various recycling technologies is presented: hydrometallurgy (mild conditions, high product purity) is currently the industry's preferred method; pyrometallurgy (large processing capacity but high energy consumption, low lithium recovery rate) is mostly used as a supplementary method. Bioleaching and ultrasonic-assisted leaching have shown environmentally friendly and efficient potential in the laboratory, but have not yet been widely adopted due to long cycles and high costs. A systematic tabular comparison of the principles, advantages, and disadvantages of dry, wet, and combined dry-wet methods provides a basis for technology selection.

Recycling has a dual environmental effect: it alleviates the strategic pressure of China's heavy reliance on imported cobalt and lithium resources, and in the future, recycled metals could meet more than half of the raw material needs for battery materials, reducing the mining of primary minerals. The entire recycling process may generate waste gas containing heavy metals/fluorides, high-salinity/toxic wastewater, and waste residue, which must be controlled.

Addressing the challenges of China's recycling system, the chapter proposes systematic optimization suggestions covering multiple levels: developing key technologies such as intelligent dismantling and selective purification, and strengthening research on negative electrode and electrolyte recycling; expanding pilot projects, promoting a "whitelist" system, and encouraging alliances between upstream and downstream enterprises; establishing a linkage mechanism between waste battery prices and metal prices; severely cracking down on illegal "small workshops"; and utilizing traceability platforms for full-process monitoring; formulating urgently needed standards, promoting mutual recognition of domestic and international standards, and encouraging enterprises to expand their production capacity overseas and participate in the global resource cycle.

CONCLUSIONS

This study aims to solve the current recycling and application problems of waste batteries, that is, by analyzing the types of waste batteries, storage, laws, recycling efficiency, and the current status of recycling methods, it puts forward optimization suggestions and establishes a sustainable waste battery management system. Taking into account the impact of environment, safety, resources, economy and other aspects, efficient and environmentally friendly waste battery management is very relevant nowadays.

The research results lead us to the following conclusions.

1. This study analyzed the types and resource value of waste batteries. The research indicates that waste batteries contain large amounts of heavy metals such as mercury, cadmium, and lead, as well as corrosive electrolytes. If landfilled or incinerated with household waste, they will severely pollute soil and groundwater and harm human health through the food chain. They also contain a large amount of precious metals, possessing enormous recycling potential and providing an important basis for resource recycling and environmental protection.

2. China lacks specific laws on waste battery recycling. Existing regulations are principled but lack operability, with unclear liability definitions, and lag behind advanced international management systems. This study improved the legal and policy framework for waste battery recycling. Through scientific argumentation, the importance of legislation was emphasized, and drawing on international experience, suggestions were made to improve the regulatory system and build a complete industrial chain to achieve the dual goals of resource recycling and environmental protection. Specific legislation should be accelerated to clarify the extended producer responsibility system; a linkage mechanism between waste battery prices and metal market prices should be established; and a traceability platform should be used to implement full-chain monitoring.

3. The waste battery logistics system was further improved. This study proposes a unified and standardized solution for logistics nodes and recycling

networks, encouraging multi-party cooperation and participation, providing a practical approach to improving recycling efficiency.

4. The classification and evaluation of waste battery treatment technologies have been improved. By comparing physical, chemical, thermal, and biological methods, the development direction of mainstream technologies has been clarified, providing a scientific basis for technology selection. Hydrometallurgy is currently the industry's preferred method, producing high-purity products, but it may generate secondary pollution. Pyrometallurgy has the advantage of large processing capacity, but it has high energy consumption and low lithium recovery rate, and is often used as an auxiliary method. Cutting-edge technologies such as bioleaching and ultrasound-assisted leaching have shown environmentally friendly and efficient potential in the laboratory, but their long production cycles and high costs have prevented large-scale application. While recycling brings resource benefits, the process (dismantling, crushing, leaching) may generate waste gas containing heavy metals and fluorides, high-salt toxic wastewater, and waste residue, which must be controlled.

5. This study employs quantitative analysis, combining data on China's battery production, sales, and import/export. The study uses the Weibull lifetime distribution model to estimate the amount of waste batteries generated in China, and performs calculations based on average battery life and recycling rates. Waste lithium and lead-acid batteries are the main contributors to the growth in waste battery generation, accounting for 99% of China's approximately 10.5 million tons of waste batteries generated.

6. Waste batteries generated annually in China contain significant amounts of metals such as zinc, manganese, copper, nickel, cobalt, silver, and lithium. Improving recycling rates can significantly reduce dependence on primary mineral resources. The metal resource potential of waste batteries is assessed: nickel-cadmium batteries contain over 20% cadmium, more than 200 times that of ore; recycling can significantly reduce energy consumption and pollution. Recovering lead from lead-acid batteries is 38% more energy-efficient and less costly than

extracting lead from ore. Lithium-ion batteries contain 5-20% cobalt, 5-10% nickel, and 5-7% lithium, thus possessing high recycling value. Button batteries contain metals such as silver, nickel, and zinc, and have great recycling potential, but recycling them is quite difficult.

7. This study details recycling methods for lithium-ion, lead-acid, and nickel-cadmium batteries, and proposes suggestions combining process and environmental improvements to enhance resource recycling efficiency.

8. China's waste battery management faces a contradiction between its massive and rapidly growing volume and its inefficient recycling system and extremely low collection rate. Solving this contradiction requires systematic and coordinated reforms and construction from multiple aspects, including improving mandatory laws, building market-driven mechanisms, breaking through key technologies, and implementing full-chain supervision, to truly transform this vast "urban mine" into a sustainable resource supply and achieve a balance between environmental and economic benefits. This study, through analyzing the current situation, improving methods, and developing technologies, provides theoretical support and practical guidance for establishing a sustainable waste battery management system, and has significant demonstrative value for promoting the modernization of waste battery management in China.

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ANNEXES

Annex A

Acts of implementation of research results

МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
ВІННИЦЬКИЙ НАЦІОНАЛЬНИЙ ТЕХНІЧНИЙ УНІВЕРСИТЕТ
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Проректор з науково-педагогічної роботи
та організації освітнього процесу
Вінницького національного технічного
університету
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АКТ
впровадження результатів дисертаційної роботи Сунь Сяодуна «Обґрунтування наукових засад управління та рециклінгу відпрацьованих хімічних джерел струму» у навчальний процес

Комісія у складі професора Петрука В.Г., професора Кватернюка С. М. професора Петрука Р.В. склали цей акт про те, що на кафедрі екології, хімії та технологій захисту довкілля Вінницького національного технічного університету під час проведення лекційних та практичних занять з дисциплін «Поводження з відходами», «Ресурсозберігаючі технології та рециклінг» для студентів спеціальності G2 (183) «Технології захисту навколишнього середовища» використовуються такі результати дисертаційного дослідження:

1. Аналіз небезпечних компонентів відпрацьованих хімічних джерел струму.
2. Забруднення довкілля відпрацьованими хімічними джерелами струму.
3. Оцінка потоків відпрацьованих хімічних джерел струму.
4. Оцінювання ресурсного потенціалу відпрацьованих хімічних джерел струму.
5. Екологічно безпечне управління відпрацьованими хімічними джерелами струму.

« 04 » листопада 2025 р.

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Figure A.1 – Act of implementing the results of dissertation research into the educational process

Annex B

List of Sun Xiaodong's publications

[1] **Sun, X.**, & Ishchenko, V. (2025). Optimization of the collection system for waste batteries. *Environmental Safety and Natural Resources, 54*(2), 23–33. https://doi.org/10.32347/2411-4049.2025.2.23-33

[2] **Xiaodong, S.**, Ishchenko, V., & Polyvanyi, S. (2025). Environmental impact and flows of waste batteries in China. *Environmental Problems, 10*(2), 156-167. https://doi.org/10.23939/ep2025.02.156

[3] **Xiaodong, S.** & Ishchenko, V. (2024). Environmental impact analysis of waste lithium-ion battery cathode recycling. *Journal of Ecological Engineering, 25*(7): 352-358. https://doi.org/10.12911/22998993/189187

[4] **Xiaodong, S.** & Ishchenko, V. (2023). Waste Lithium-Ion Batteries Management in China. *Visnyk of Vinnytsia Politechnical Institute, 2*, 21–27. (in Ukrainian). https://doi.org/10.31649/1997-9266-2023-167-2-21-27

[5] **Xiaodong, S.** & Ishchenko, V. (2025). Environmental Impact and Flows of Waste Batteries in China. In *Proceedings of the International Conference «European Green Dimensions: Fundamental, Applied, and Industrial Aspects»*, June 5−7, 2025 (p. 91). PMBSNU, Mykolaiv.

[6] **Xiaodong, S.** & Ishchenko, V. (2024). Analysis of current situation on recovery of used lithium-ion batteries in China. In *Proceedings of IX International Congress of Ecologists*, September 25–27, 2024 (pp. 84-55). Vinnytsia, VNTU.

[7] **Xiaodong, S.** & Ishchenko, V. (2024). Processing of waste lithium-ion battery cathode. In *Proceedings of LIII Conference of Vinnytsia National Technical University*, June 20–22, 2024 (pp. 1653-1654). Vinnytsia, VNTU.

[8] Ishchenko, V., **Xiaodong, S.**, Hlavatska, L., & Gritsuk, I. (2023). Hazardous Waste Generation and Management: a Case Study of Ukraine. In *Proceedings of International Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction*, October 8-11, 2023. Thessaloniki, Greece.

[9] **Xiaodong, S.** & Ishchenko, V. (2023). Study on waste batteries storage. In *Proceedings of International Conference “Energy efficiency in economies of Ukraine”*, November 21–23, 2023 (pp. 433-434). Vinnytsia, VNTU.

[10] **Xiaodong, S.** & Ishchenko, V. (2022). Waste batteries generation in China. In *Proceedings of All-Ukrainian Conference “Environmentally sustainable development of urban systems”*, November 2–3, 2022 (pp. 73-75). Kharkiv, BKNU.

Annex C

Input data on batteries import, export and production in China

Table C.1. Manganese dioxide batteries

Manganese dioxide	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2014	23574197	212831386		-189257189	
2015	27291025	221115496		-193824471	
2016	24515904	210842866		-186326962	
2017	22760778	0		22760778	
2018	18818511	183570682		-164752171	
2019	19767485	214603744		-194836259	
2020	22384950	606400068		-584015118	
2021	19119640	561827729		-542708089	
2022	9992357	495814967		-485822610	
2023	8083981	480844179		-472760198	

Table C.2. Mercury oxide batteries

Mercuric oxide	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2014		205		-205	
2015		283		-283	
2016		125		-125	
2017		185		-185	
2018		134		-134	
2019		25		-25	

Table C.3. Silver oxide batteries

Silver Oxide Battery	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2014	62,913	23,348	550,000	589565	500000
2015	59,032	448,020	600,000	211012	520000
2016	52,343	125,973	650,000	576370	540000
2017	54,753	0	700,000	754753	560000
2018	76,008	0	750,000	826008	580000
2019	101,363	10,767	800,000	890596	600000
2020	31,373	18,816	850,000	862557	620000
2021	67,755	47,253	900,000	920502	640000
2022	100,143	59,244	950,000	990899	660000
2023	81,544	67,830	1,000,000	1013714	680000

Table C.4. Lithium batteries

Lithium battery	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2014	2,449,273	2,025,187	370,370,370	370794456	100000000
2015	3,309,917	3,563,197	464,285,714	464032434	150000000
2016	3,226,878	4,105,575	586,206,897	585328200	250000000
2017	3,850,461	3,520,119	733,333,333	733663675	350000000
2018	0	0	875,000,000	875000000	500000000
2019	3,844,695	3,360,664	944,444,444	944928475	750000000
2020	3,861,425	11,553,234	1,100,000,000	1092308191	1000000000
2021	4,941,043	12,937,447	1,590,909,091	1582912687	1250000000
2022	4,487,348	13,531,752	2,600,000,000	2590955596	2000000000
2023	2,971,628	14,991,052	3,357,142,857	3345123433	3300000000

Table C.5. Air-zinc batteries

Air-zinc	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2014	51,320	52,739		-1419	50000000
2015	74,568	0		74568	52000000
2016	67,750	0		67750	54000000
2017	84,632	68,094		16538	56000000
2018	88,437	75,575		12862	58000000
2019	112,186	66,402		45784	60000000
2020	176,273	66,348		109925	62000000
2021	198,514	62,644		135870	64000000
2022	178,187	52,580		125607	66000000
2023	190,976	68,305		122671	68000000

Table C.6. Other primary batteries

Other batteries	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2014	5,425,601	2,193,854		3231747	
2015	967,088	1957529		-990441	
2016	494,819	2015480		-1520661	
2017	534,205	4,662,042		-4127837	
2018	1,912,738	9,609,085		-7696347	
2019	2,686,897	2,613,058		73839	
2020	1,813,979	2,674,093		-860114	
2021	2,111,944	5,420,183		-3308239	
2022	857,231	2,296,319		-1439088	
2023	1,195,188	1,579,046		-383858	

Table C.7. Lead-acid batteries

Lead-acid battery	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2014	76126044	531247303	6000000000	5544878741	6000000000
2015	97797760	646433053	6600000000	6051364707	6600000000
2016	111893070	822754398	7200000000	6489138672	7200000000
2017	104880904	723208292	7800000000	7181672612	7800000000
2018	99643462	747359954	8400000000	7752283508	8400000000
2019	98194184	751401618	9000000000	8346792566	9000000000
2020	71228305	826929598	9600000000	8844298707	9600000000
2021	44246153	774272975	10200000000	9469973178	10200000000
2022	42865605	875070391	10800000000	9967795214	10800000000
2023	28677661	984006613	11400000000	10444671048	11400000000
	20996759	1053546045	12000000000	10967450714	12000000000

Table C.8. Nickel-cadmium batteries

Nickel-cadmium	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2020	525536	5066526		-4540990	6500000.00
2021	743933	5788634		-5044701	6000000.00
2022	636314	4851473		-4215159	5500000.00
2023	485599	4956459		-4470860	5000000.00

Table C.9. Nickel-iron batteries

Nickel-iron	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2018	371	0		371	
2019	0	2,657,907		-2657907	
2020	0	13,607,622		-13607622	
2021	26	14563854		-14563828	

Table C.10. Nickel-metal hydride batteries

Nickel-metal hydride	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2014	3,409,052	7,719,416		-4310364	
2015	2,687,666	8,623,138		-5935472	
2016	3,666,580	8,457,762		-4791182	
2017	4,575,753	8,073,154		-3497401	
2018	3663234	7808815		-4145581	
2019	3,785,044	6,960,315		-3175271	
2020	3,377,229	6,977,243		-3600014	
2021	3,998,997	18,052,471		-14053474	
2022	4,909,524	18,019,355		-13109831	
2023	7,299,849	31,993,427		-24693578	

Table C.11. Other rechargeable batteries

Other batteries	Import	Export	Production	Sales (calculated)	Sales (from literature data)
2013	0	0		0	
2014	0	481004		-481004	
2015	14,756	4645547		-4630791	
2016	22,834	2,512,295		-2489461	
2017	24,523	3,798,718		-3774195	
2018	54,389	8,158,366		-8103977	
2019	117,133	3,968,081		-3850948	
2020	86,403	4,155,267		-4068864	
2021	256,892	6,763,009		-6506117	
2022	20,370	11,731,544		-11711174	
2023	22478	8541300		-8518822	