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ENVIRONMENTAL IMPACT AND FLOWS OF WASTE BATTERIES IN CHINA

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Abstract. An environmental impact of waste batteries was analysed (focusing on certain types like nickel-cadmium, lead-acid batteries). The study also 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 ye ars, 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.

Keywords: waste battery, waste flow, waste generation, battery, environmental impact.

1. Introduction

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 (Liu-Sullivan; Sullivan, 2023). However, the battery recycling rate is less than 2 %. 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" (Governmental, 2012), most of China's waste batteries are not managed as hazardous waste due to the wide variety of battery types and the lack of clear definition of their hazardousness. 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, 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 greater than 0.025 % of their

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weight from January 1, 2001 (Seabolt, 1984), and prohibiting the production and sale of batteries with a mercury content greater than 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" (China, 2013).

In China, the "Technical Policy on the Prevention and Control of Hazardous Waste Pollution" formulated by the state 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 (Novikova, 2022); 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, municipal waste disposal units should establish Classified collection, storage and treatment facilities for the effective management of waste batteries; promote the separate collection of waste batteries to avoid waste batteries containing mercury and cadmium mixed with household waste incineration facilities; waste lead-acid batteries must be recycled, and must not be disposed of by other means, and their collection and transportation must be included in the management of hazardous waste (Ministry, 2024).

Battery industry development and adjustment in China is currently focused on mercury-free alkaline zinc-manganese batteries, nickel-metal hydride power batteries, lithium-ion batteries, fully sealed maintenance-free lead-acid batteries, fuel cells, solar cells and other new high-energy batteries (Vasant; Sarakonsri, 2023).

The average annual growth of primary batteries is 200 million pcs, so the focus should be on adjusting the product structure, increasing the share of alkaline zinc-manganese batteries, and accelerating the manufacture of low-mercury and mercury-free batteries (Zhao, 2003). Other tasks are as follows: strictly prohibit the production of mercuric oxide batteries and battery paste, alkaline zinc-manganese batteries are encouraged to further improve the performance and non-mercury production; encourage non-mercury alkaline zinc-manganese batteries using electrolytic manganese dioxide and non-mercury zinc powder manufacturing technology, and further improve the quality of batteries (Handschuh-Wang et. al., 2024); nickel-cadmium batteries need to be gradually phased out, while increasing the share of non-mercury and non-cadmium batteries. According to the plans (Ryś, et al., 2024), the increase in manufacturing the certain types of batteries is expected, the annual numbers are as follows: nickel-metal hydride batteries – 0.8 billion pcs (with an average annual growth of 45 %), lithium batteries – 200 million pcs (with a high average annual growth rate of 108 %), lead-acid batteries average annual growth rate of 5 %.

The purpose of this study is to analyse environmental impact of waste batteries and evaluate their generation and flows in China in order to cope with the environmental challenges brought by waste batteries and promote the sustainable use of resources.

2. Materials and methods

Environmental impact of waste batteries was analysed through literature review focusing on certain types of waste batteries.

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:

$$POM(t) = P(t) + I(t) - E(t), \quad (1)$$

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 (Song et al., 2017). Import and export data for time period of 2014 to 2023 were retrieved from the United Nations Commodity Trade Statistics (UN, 2024). 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 analysed 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 (Song et al., 2017). 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 (2)–(4):

$$\left(\frac{T_{average}}{T_{max}}\right)^{\beta} = \frac{\beta-1}{-\beta \cdot ln0.01}; \quad (2)$$

$$\eta = T_{average} \cdot \left(1-\frac{1}{\beta}\right)^{-\frac{1}{\beta}}; \quad (3)$$

$$f(T) = \frac{\beta}{\eta} \cdot \left(\frac{T}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{T}{\eta}\right)^{\beta}}, \quad (4)$$

where $f(T)$ is the Weibull lifetime distribution function, in which β is the shape parameter (β > 0), η is a s cale parameter (η > 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 (Magalini et al., 2014). 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. (2)–(3), followed by lifespan distribution calculation according to Eq. (4).

3. Results and discussion

Environmental impact of waste batteries

The random discarding of used batteries will cause serious multiple pollution to the environment, affecting water bodies, soil and the entire ecosystem (Mrozik, et al., 2021). When used batteries are discarded in nature or mixed with household waste and landfilled, the outer metal of the used batteries will be corroded, causing the heavy metals, acids, and alkalis inside to leak out, which may enter the soil or water through infiltration and enter the human food chain through various channels. Due to the lack of economical and effective recycling technology, some waste batteries are usually treated along with household waste by incineration and landfilling. When waste batteries are incinerated, on the one hand, they may adhere to the equipment, causing blockage and corrosion (Wu et al., 2023). On the other hand, heavy metals such as mercury, thorium, arsenic, and zinc are easy to vaporize and volatilize at high temperatures. Some heavy metals react in the furnace to form chlorides, sulphides or oxides, which are easier to vaporize and volatilize than the original metal elements. After entering the atmosphere with the tail smoke, they will pollute the atmosphere and soil.

Battery users are scattered, and pollution sources are also scattered. After a long period of time, the pollution is caused by the pollution of water bodies and soil, and then through the accumulation effect of plants and animals, and finally enters the human body through the food chain, affecting human health and even causing serious diseases. For example, zinc-manganese batteries contain many heavy metals. When the human body absorbs these heavy metals to a certain extent, it will cause various diseases (Rehman et al., 2018).

One of the most dangerous type of battery is waste nickel cadmium battery. It is one of the main sources of cadmium in household waste: cadmium from waste nickel cadmium batteries accounts for about 92 % of the total cadmium in household waste. 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 accumulate 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 cause significant changes in microbial populations, such as decreasing the number and variety of microorganisms, decreasing microbial activity, and fluctuating microbial communities (Kotkunde et al., 2021).

Besides, an environmental risk is associated with waste 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. 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. If waste lead-acid batteries are directly placed in the environment, they may

break and release toxic substances and produce corrosiveness (approximately 2–3*L* of pH=0.8 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 (Wang et al., 2018).

Assessment of batteries quantity placed on the market

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. 1.

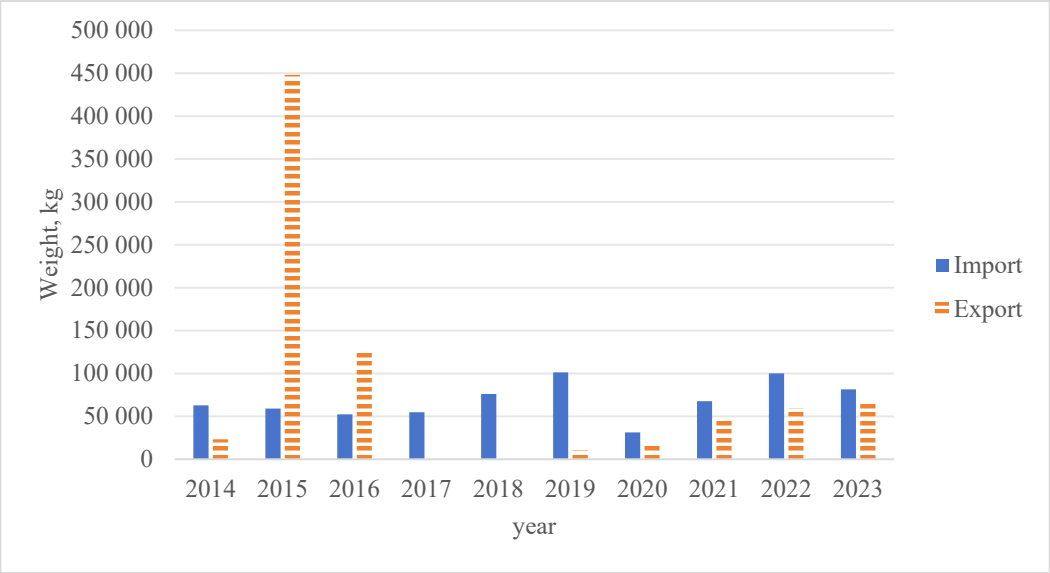


Fig. 1. Silver oxide primary batteries import and export

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 Fig. 2.

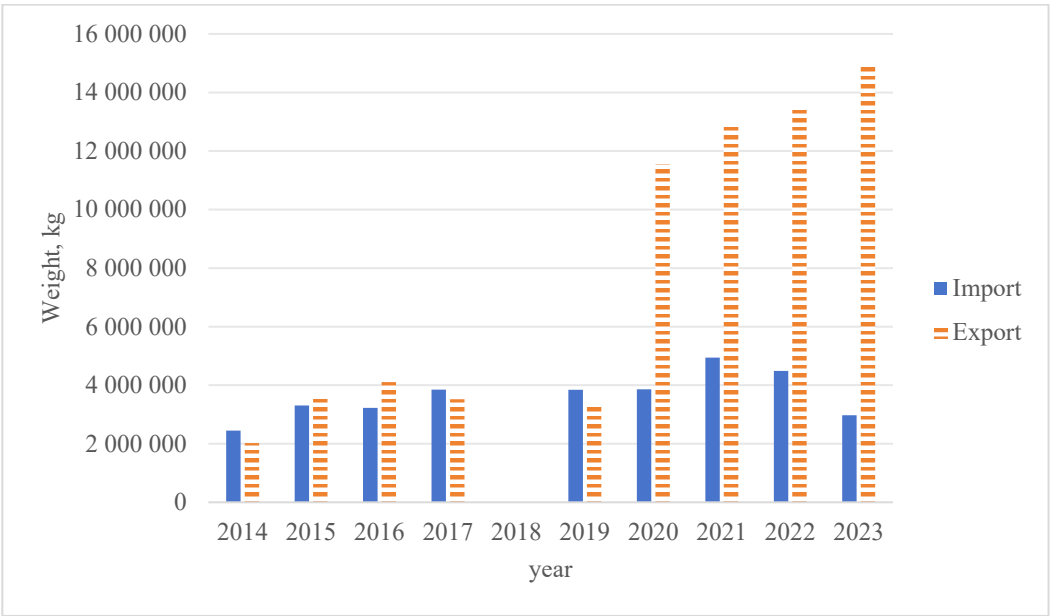


Fig. 2. Lithium primary batteries import and export

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 Fig. 3.

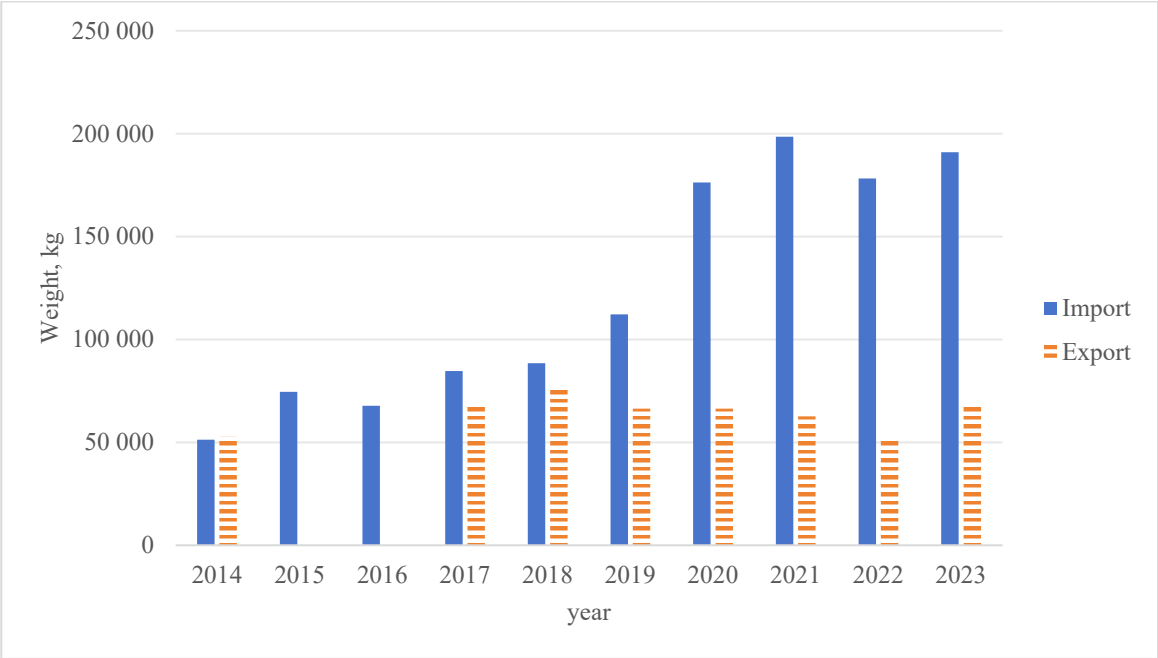


Fig. 3. Air-zinc primary batteries import and export

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 Fig. 4.

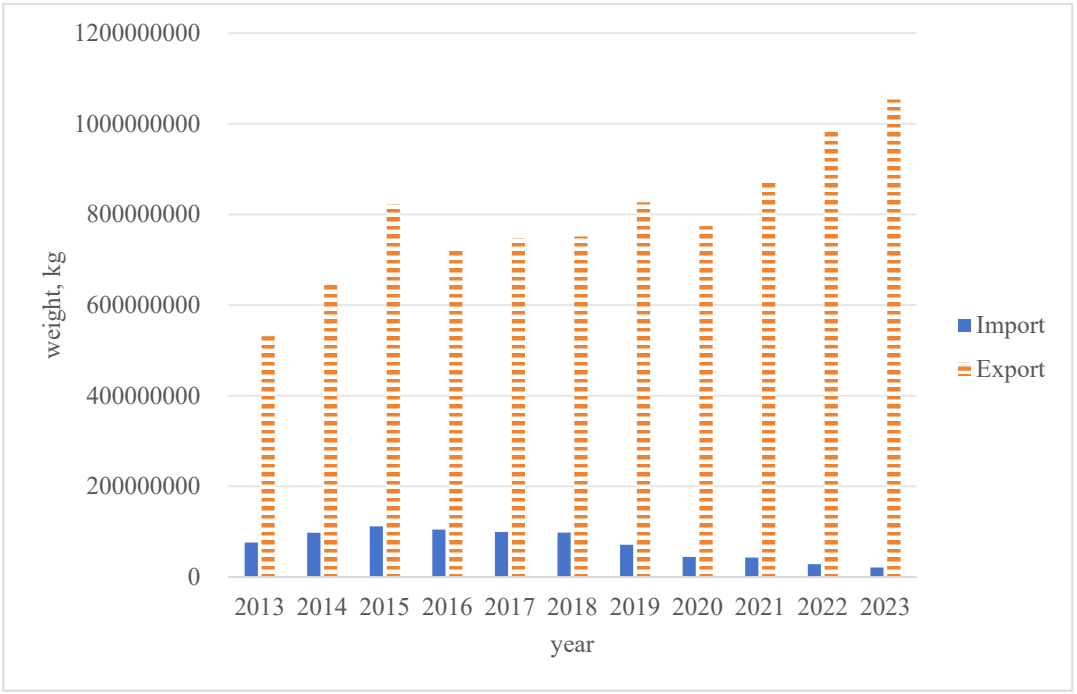


Fig. 4. Lead-acid batteries import and export

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 Fig. 5.

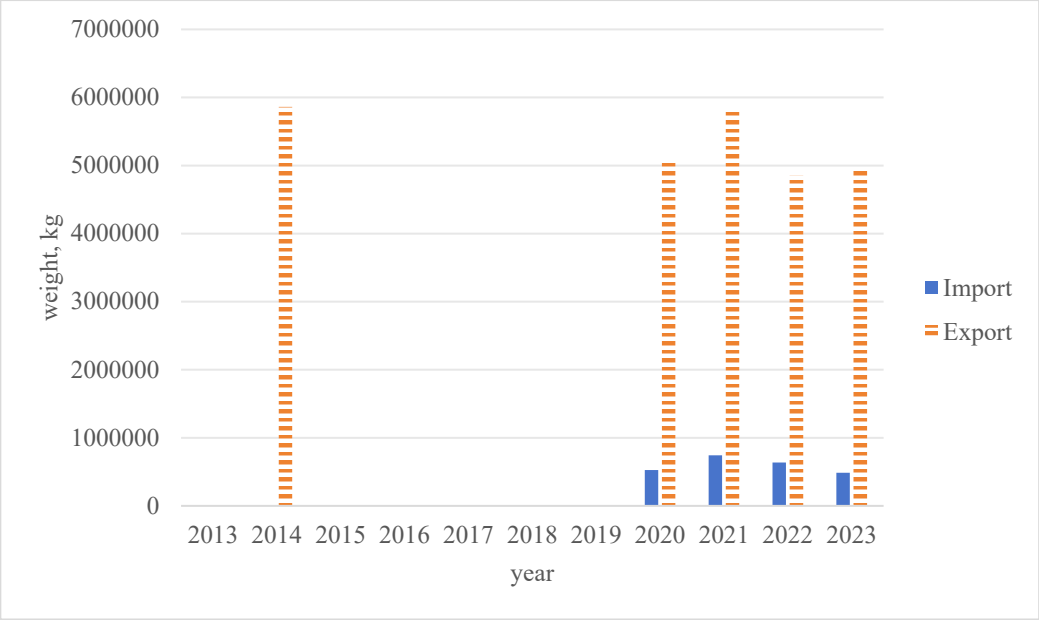


Fig. 5. Nickel-cadmium batteries import and export

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 Fig. 6.

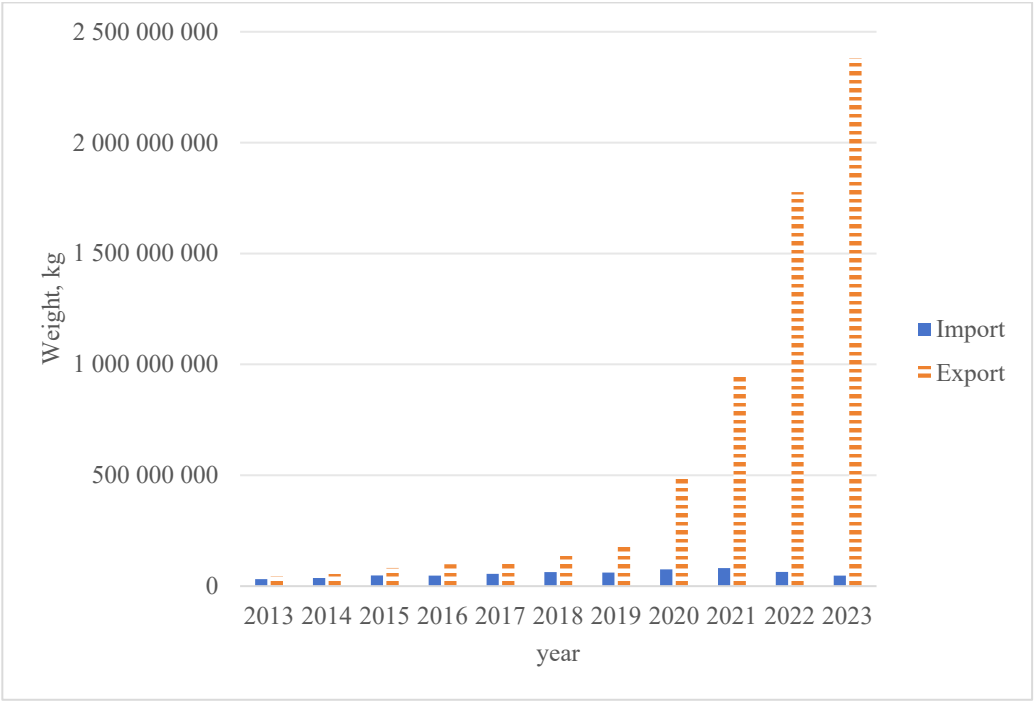


Fig. 6. Lithium-ion import and export

According to the Fig. 1–6, 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. 7–8).

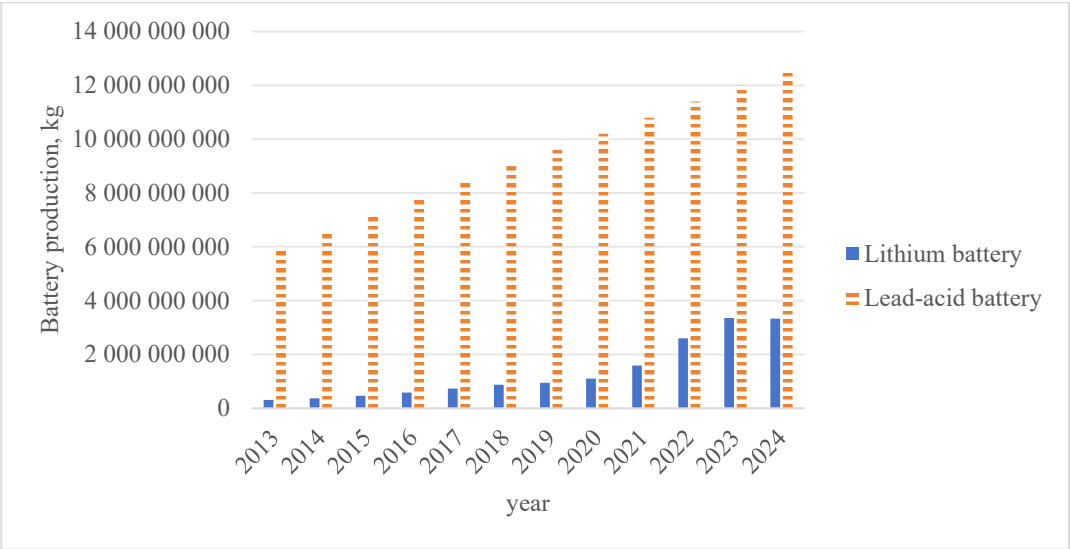


Fig. 7. China's lithium and lead-acid battery production

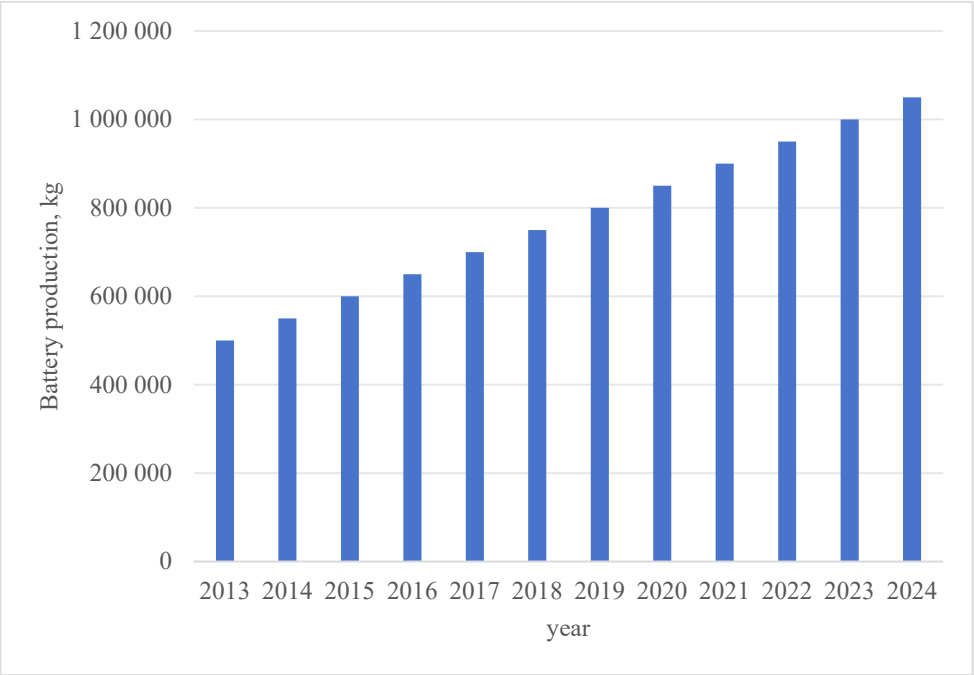


Fig. 8. China's silver oxide battery production

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 Table: both calculated by the Eq. (1) and searched (literature data).

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 (Karpinski et al., 2000). In this study, we use 2 years lifespan for lithium batteries.

Zinc-air battery has very short lifetime – up to 1 year (Sherman, 2019). 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 (Yang et al., 2024). 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 (Wengierek, 2021). In this study, we use 2 years lifespan for nickel-cadmium batteries.

Calculation of waste batteries generation

According to the Eq. (2)–(4), the specific trends of waste battery generation were obtained (see Fig. 9–13). 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).

According to Fig. 9–13, the waste batteries generation trends show the following characteristics:

Waste lithium batteries (Fig. 9). 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 batter*ies (Fig. 10). 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. 11) and waste lead-acid batteries (Fig. 12) 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. 13). This is mainly affected by environmental protection bans and nickel-cadmium battery market shrinks.

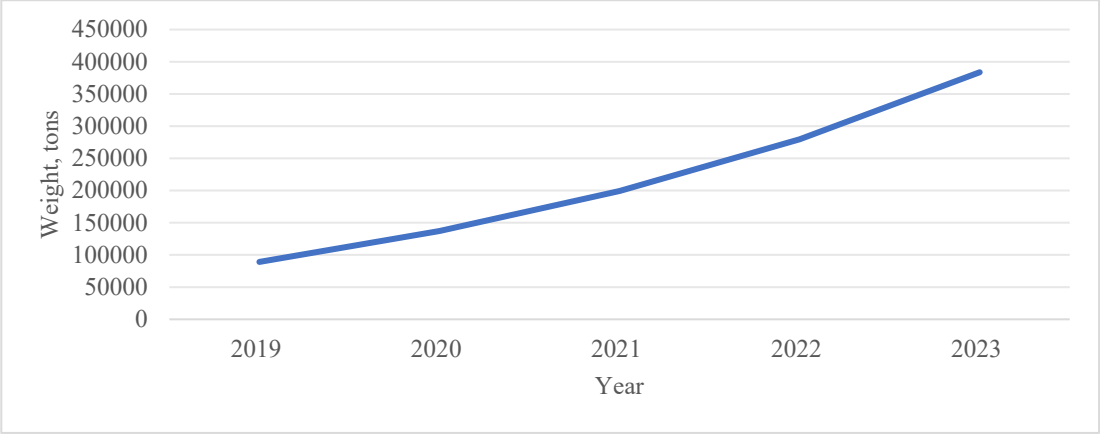


Fig. 9. Waste lithium battery generation

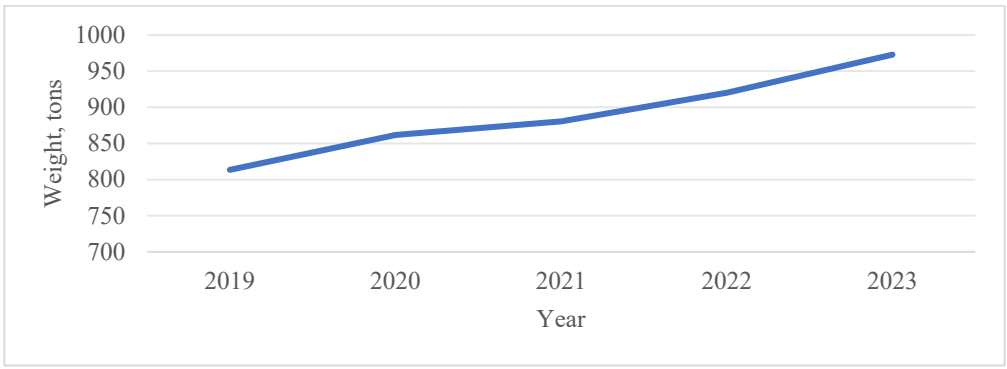


Fig. 10. Waste silver oxide battery generation

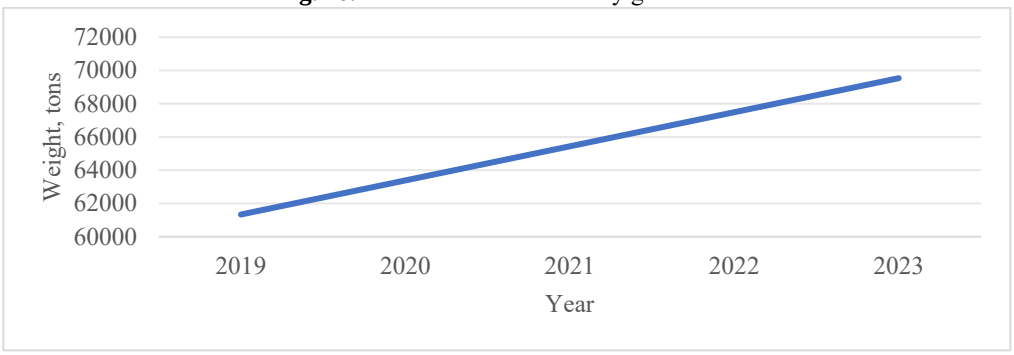


Fig. 11. Waste air-zinc battery generation

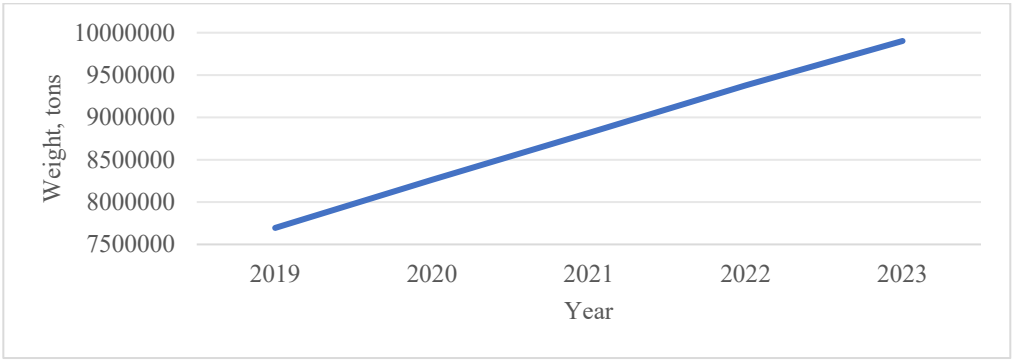


Fig. 12. Waste lead-acid battery generation

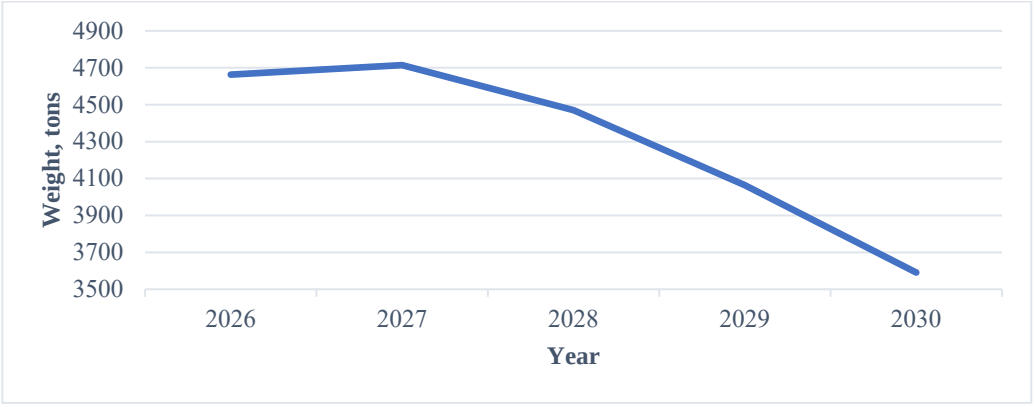


Fig. 13. Waste nickel-cadmium battery generation

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.

4. Conclusions

The most dangerous to the environment waste battery types are nickel-cadmium and lead-acid. They impact the soil and water environments, mainly by toxic heavy metals. Regarding the waste battery flow in China, the following may be summarised:

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.

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