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REVIEW ARTICLE

Generation and management of waste electric vehicle batteries in China

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Abstract With the increasing adoption of EVs (electric vehicles), a large number of waste EV LIBs (electric vehicle lithium-ion batteries) were generated in China. Statistics showed generation of waste EV LIBs in 2016 reached approximately 10,000 tons, and the amount of them would be growing rapidly in the future. In view of the deleterious effects of waste EV LIBs on the environment and the valuable energy storage capacity or materials that can be reused in them, China has started emphasizing the management, reuse, and recycling of them. This paper presented the generation trend of waste EV LIBs and focused on interrelated management development and experience in China. Based on the situation of waste EV LIBs management in China, existing problems were analyzed and summarized. Some recommendations were made for decision-making organs to use as valuable references to improve the management of waste EV LIBs and promote the sustainable development of EVs.

Keywords Waste electric vehicle batteries · Generation · Management · Reuse · Recycling · China

Introduction

Accounting for around one quarter of global energy use, the energy consumption of the transportation field increases the global energy crisis and environmental pollution. Scientists are seeking energy-saving and environment protection measures to attack the problem. As the representative of energy-saving and environmentally friendly vehicle, electric vehicles (EVs) have become the inevitable trend of development of the automobile industry (Lang et al. 2013; Ma et al. 2012; Richardson 2013). To date, over 1.15 million EVs are on roads in the world (Chiang et al. 2017), and their international sales will reach the range between 5.2 million and 19.8 million in 2020. Powering these EVs clearly requires large-scale use of energy storage systems.

Due to their lightweight, high energy density, and long cycle life, lithium-ion batteries (LIBs) have been considered as a promising energy storage solution and widely applied in EVs (Lu et al. 2013). Generally, LIBs are considered to have reached their end of life in EV application when losing more than 20% of their original capacity (Williams and Lipman 2010), and the average life span could be anywhere between 5 and 10 years (Dinger et al. 2010). With LIBs reaching its end of life, a large number of waste EV LIBs have been entering the waste stream. It was estimated that the global annual quantity and weight of waste LIBs would surpass 25 billion units and 500,000 tons, respectively, in 2020 (Zeng et al. 2012).

EV LIBs consist of a cathode, an anode, a separator, an electrolyte, and a casing. The cathode-active material is either lithium iron phosphate or a mix of lithium and other metals such as nickel and manganese. In the case of waste EV LIBs, especially electrolytes and various metals of them, if treated improperly, they could lead to environmental pollution and health risks. For example, poisonous substances (such as P_2O_5) could be produced in the process of direct combustion of the electrolyte, which could destroy the ozone layer when entering the atmosphere; if

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the concentration of lithium in the blood of human body reaches 20 mg/L, the effects can be deadly (Shin et al. 2005). However, residual energy storage capacity and various metals in the waste EV LIBs are valuable and could be employed for cascaded use in stationary applications and recycled in a proper manner, respectively. Therefore, cascaded use and recycling of waste EV LIBs are highly advantageous from an environmental as well as an economic point of view. In recent years, the management and recycling of waste EV LIBs have been a new research hotspot.

In China, the government has taken the development of the EV industry as a national strategy, and relevant departments have issued a series of policies and measures to promote the development of EVs vigorously since 2009. With the continual development and application of EVs, a large number of waste EV LIBs have been generating and output of them reached 10,000 tons in 2016. The management and recycling of the waste EV LIBs have brought about widespread attention in China. Relevant departments or agencies have begun to put forward laws or policies to manage waste EV LIBs, and set up demonstration projects to promote the reuse, recycling, and disposal of them (SINA finance and economics 2017).

This paper presented the generation trend of waste EV LIBs and emphasized on management development and experience of them in China. Further, the current situation and the existing problems of waste EV LIBs management in China were analyzed. Some recommendations were proposed for policy making and legislative bodies to use as valuable references to further perfect the management of the waste EV LIBs and promote the sustained development of EVs.

Generation of waste EV LIBs and corresponding potential for recycling

As a developing country with large population and insufficient resources per capita, China put forward a series of policies to develop clean energy technologies as well as EVs. The number of EVs has been rapidly increasing with time, which was accompanied by an increasing tendency of the amount of waste EV LIBs.

In order to study the tendency, a system dynamics model of the EV new increment and a scrap prediction model of waste EV LIBs generation were developed by Hou (2015). The simulation results (see Fig. 1) showed that the amount of EVs new increment rose from 7700 units in 2012 to 2,717,100 units in 2025 at a compound annual growth rate (CAGR) of 52.0% from 2012 to 2025. Based on the above results and the life span of EV LIBs, the amount of waste EV LIBs in 2012 ~ 2025 was predicted. From 2012 to 2025, the amount of waste EV LIBs increased from 700 to 464,000 tons at a CAGR of 59.0%. By and large, about 1,132,000 tons of waste

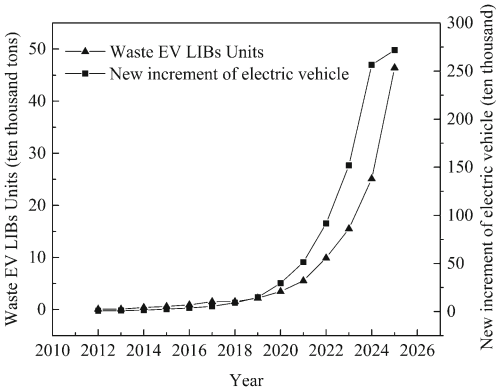

Fig. 1 Generation of waste EV LIBs and new increment of EVs per year in China. Source: (Hou 2015)

EV LIBs entered the waste stream between 2014 and 2025 and the amounts presented markedly had an increasing tendency.

EV LIBs consist of various metals (lithium, nickel, iron, cobalt, aluminum, copper, manganese, steel), carbonaceous materials (graphite and carbon black), and other materials such as plastics, electrolytes, binder, and lithium salts. The typical proportion of each material in the EV LIBs is shown in Fig. 2, 1.4% lithium, 2.4% nickel, 3.3% iron, 4% cobalt, 4.3% aluminum, 5.71% copper, 8.81% manganese, 22.42% steel, 23.12% others (plastics, electrolytes, binders, and other non-metal like phosphorus), and 24.52% carbon (carbon black and graphite) (Richa et al. 2014). On the basis of the material composition and the amount of waste EV LIBs, large quantities of valuable materials have been entering EV LIBs waste stream. In 2025, approximately 6500 tons of lithium, 20,000 tons of aluminum, 26,400 tons of copper, and 40,800 tons of manganese and other materials would be contained in the EV LIBs waste stream, which showed great potential for recycling.

Strategy of waste EV LIBs treatment

The general life cycle of a product includes the process of extraction of raw materials, manufacturing, usage, and end of life. In terms of the high potential for energy storage and recycling, waste EV LIBs' life cycle should be extended by implementing a treatment strategy comprising reuse in EVs, cascaded use in stationary applications, recycling, and final disposal (see Fig. 3).

(1) Reuse in EVs: in the case of waste EV LIBs still met service requirements, they could be reused in EVs.
(2) Cascaded use in stationary applications: for the most part, waste EV LIBs' residual capacity amounted to less than 80% of their initial capacity, so they failed to meet the criteria for automotive service. There was still sufficient energy and power capacity, and could be employed

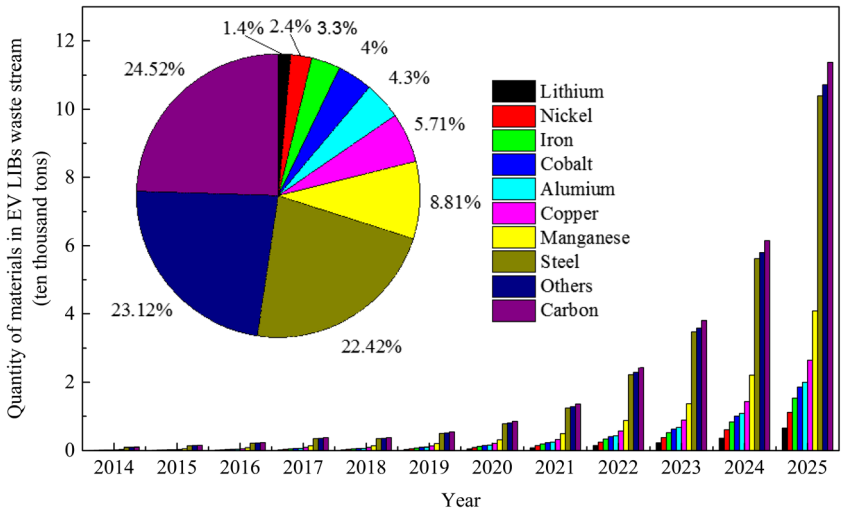

Fig. 2 Quantity of materials in EV LIBs waste stream in China

for cascaded use in less demanding applications such as renewable energy storage (Jiao and Evans 2016).

(3) Recycling: for the waste EV LIBs that were not accessible for cascaded use, valuable materials in them should be recycled and utilized to the greatest extent. The valuable materials obtained could be used as raw materials in the manufacturing of new EV LIBs.

(4) Final disposal: after the recycling process of waste EV LIBs, residual wastes may be toxic and harmful, so they should go through final disposal without causing more pollution problems.

Response to waste EV LIBs

With the rapid development of EVs, enormous waste EV LIBs were generated in China. In view of the substantial quantity, high potential risk, and valuable capacity of waste EV LIBs, government put forward related laws or regulations to manage them. Further EV manufacturers, LIBs manufacturers, LIBs recycling enterprises, and other stakeholders have taken measures to promote the research and practice of cascaded use and recycling of waste EV LIBs.

Laws or regulations related to waste EV LIBs management

In China, the technical policy for pollution control on waste battery, published on 9 October, 2003, is the first law or regulation especially for waste batteries. It regulated the pollution prevention and control of the whole recycling process of waste batteries and set up guidelines and basic principles for the recycling and resource utilization of waste batteries (MEP 2003). With the increasing amount of waste EV LIBs, a series of laws or regulations associated with the waste EV LIBs have been emphasized and implemented by government departments and agencies (see Table 1).

In February 2006, the National Development and Reform Commission, Ministry of Science and Technology, and Ministry of Environmental Protection of the People's Republic of China put forward the auto product recovery and usage technology policy, which proposed that EV manufactures should take responsibility for the collection and

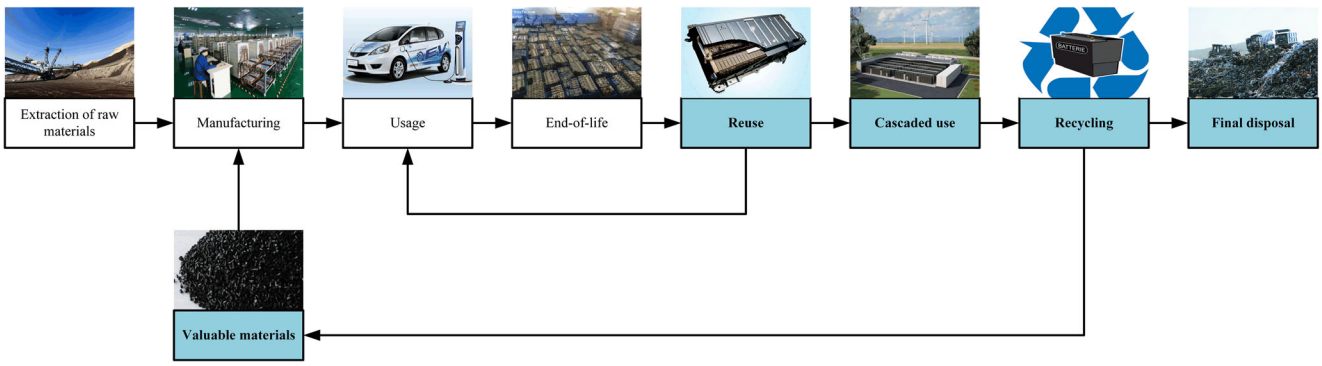

Fig. 3 Strategy of waste EV LIBs treatment

Table 1 Laws or regulations related to waste EV LIBs management in China

Effective date	Laws or regulations	Key points
2003.10	Technical policy for pollution control on waste battery	Regulating the pollution prevention and control of the whole recycling process of waste battery
2006.2	Auto product recovery and usage technology policy	Responsibility of EV manufacturers for the collection and recycling of EV batteries they sold
2012.6	Energy-saving and new energy vehicle development plan (2012 ~ 2020)	Stressing the construction of the management system of the cascaded utilization and recycling of waste EV LIBs
2016.1	Technology policy for the recycling of power battery (2015 edition)	Regulating stakeholders of EV battery; provisions on the recycling and utilization of waste EV batteries
2016.12	Interim measures for the administration of recovery and utilization of power batteries for new energy vehicles (draft for comment)	Detailed regulations of the life cycle management of EV battery

recycling of EV LIBs they sold, and then deliver them to qualified enterprises for reasonable treatment (CPG 2006).

For promoting the development of EVs, the energy-saving and new energy vehicle development plan (2012 ~ 2020) was published in June 2012. As the power source of EVs, LIBs' problems were described and regulated. The management system of the cascaded utilization and recycling of waste EV LIBs should be established. It was proposed to clarify responsibilities, rights, and obligations between stakeholders and guide EV manufacturers to strengthen the recycling of waste EV LIBs (CPG 2012).

With the aim of establishing the recycling network of waste EV LIBs, the National Development and Reform Commission, Ministry of Industry and Information Technology, Ministry of Environmental Protection, Ministry of Commerce, and General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China jointly issued the technology policy for the recycling of power battery (2015 edition) on 5 January, 2016, which regulated EV manufacturers, LIBs manufacturers, and cascaded use enterprises of waste EV LIBs, and dismantling enterprises of scrap EVs were the stakeholders of EV LIBs, and the EV manufacturers were the first responsibility body for the recycling of waste EV LIBs. The EV manufacturers and the LIBs manufacturers should designate at least an after-sale service network of their companies in the prefecture-level administrative region (or entrust other qualified institutions) to collect waste EV LIBs (MIIT 2016).

In order to strengthen the management of the recycling and utilization of waste EV LIBs and promote the sustained and healthy development of EV industry, on 1 December, 2016, the interim measures for the administration of recovery and utilization of power batteries for new energy vehicles (draft for comment) was launched by the Ministry of Industry and Information Technology. It regulated the standardized requirements of design and production of EV LIBs and extended producer responsibility for the recycling of waste EV LIBs. Relevant supervision and management rules were put forward to promote the comprehensive utilization of waste EV LIBs (NDRC 2016).

Further, some local governments have issued related policies or regulations to promote the implementation of producer responsibility system for waste EV LIBs. For example, Shanghai introduced the interim measures of Shanghai Municipality for encouraging the purchase and use of new energy vehicles to encourage EV manufacturers to recycle waste batteries in 2014. According to the measures, the EV manufacturers will receive 1000 yuan subsidies if recycling a set of waste EV battery. Similarly, with the purpose of establishing the recovery mechanism of waste EV LIBs, the Shenzhen government and EV manufacturers paid 300 yuan and 600 yuan, respectively, to collect and recycle the waste LIBs used in an EV (Environmental Protection Department of Jiangsu Province 2016).

Cascaded use of waste EV LIBs

Cascaded use of waste EV LIBs could effectively reduce environmental impact by extending the life span of EV LIBs and raise economic advantages by saving the cost of EV LIBs, which is attracting more and more attention around the world. In China, the National Grid, LIBs manufacturers, and EV manufacturers participated in the research and practice of the cascaded use of waste EV LIBs.

The State Grid Henan Electric Power Company cooperated with NARI-TECH and battery manufacturers to carry out the research on the basic theory, application technology, and demonstration and popularization of the cascaded use of waste EV LIBs. Located in Zhengzhou city, the demonstration project of cascaded use of waste EV LIBs in energy storage has been accomplished well, and the project has accumulated more than 45,000 kWh of electricity generations (China battery 2014).

Besides, Waltmal, BYD, Chery, and some LIBs manufacturers invested substantial resources for the research and development of the cascaded use of waste EV LIBs in smoothing the fluctuations of grid supply and demand, storing electricity from solar panels and wind farms, and so forth.

For example, Waltmal utilized the waste EV LIBs that have completed safety tests to build a power station, which charged at night and discharged during the day so that the cost of electricity consumption by the factory was reduced (Environmental Protection Department of Jiangsu Province 2016); BYD cooperated with a LIBs recycling enterprise called GEM to implement the project of the promotion, operation, and management of energy storage station and photovoltaic power plant, which promoted the cascaded use of waste EV LIBs in stationary applications (Environmental Protection Department of Jiangsu Province 2016).

Recycling measures of waste EV LIBs

With the growing amount of WEEE (waste electrical and electronic equipment), a certain number of recycling enterprises have been set up to recycle WEEE in China. As an important class of WEEE, waste EV LIBs received considerable attention. The recycling enterprises began developing the recycling technology for waste EV LIBs. In general, these enterprises extracted valuable metals from waste EV LIBs by the combined process using a mechanical method and hydrometallurgy.

For instance, as one of the world's core manufacturing base of raw materials of LIBs, GEM realized the industrial recycling of materials from waste power batteries. GEM adopted leading technology to recycle nickel, cobalt, manganese, copper, aluminum, iron, lithium, and other valuable metals from waste power batteries and produced a full series and multispecies of LIB raw materials from the metals including high-purity nickel sulfate, cobalt chloride, cobaltosic oxide, coarse spherical cobalt hydroxide, NCM precursor, NCA precursor, NCM ternary material, and NCA ternary material (GEM 2016).

Likewise, Hunan Brunp has formed a recycling technology for power batteries, mainly including nickel-hydrogen batteries and lithium-ion batteries (ternary, manganese, iron), and the total designed processing capacity was 10,000 tons/year. At present, Hunan Brunp has cooperated with numerous domestic power battery manufacturers and EV manufacturing enterprises by providing them with comprehensive power battery recycling and resourcing solutions (BRUNP RECYCLING 2016).

Summary and recommendations

Increasing usage of EVs would be accompanied with large-scale production of LIBs to power these EVs. When these LIBs reached their end of life, how to manage waste EV LIBs has drawn wide attention. Based on the strategy of waste EV LIBs treatment, China put forward related laws or policies or regulations to deal with the EV LIBs waste stream. Relevant enterprises such as EV manufacturers, power battery manufacturers, and LIBs recycling enterprises implemented a series of measures to promote the collection, cascaded use, recycling, and disposal of waste EV LIBs, which has achieved some phase fruits. However, systematic work on the waste EV LIBs was just beginning, and there remain many problems to be solved. It is necessary to improve the legal system, strengthen the research and development of cascaded use and recycling technology, and perfect other aspects of waste EV LIBs, which will contribute to the healthy and sustainable development of EV industry in China.

(1) The lack of detailed rules and unenforceability of existing laws or policies associated with waste EV LIBs reduced the implementation efficiency and effect of the related laws or policies. Although the technology policy for the recycling of power battery (2015 edition) defined the correlated responsibility parties in which EV manufacturers should take major responsibility for the recovery of waste EV LIBs, how to effectively determine and distribute the specific responsibility among parties is worthy of deeply discussing and analyzing, and corresponding specific regulatory measures or accountability mechanisms should be established in the policy. Further, the policy required EV manufacturers and LIBs manufacturers to designate after-sale service networks of their companies (or entrust other qualified institutions) to collect waste EV LIBs. With the aim of establishing and improving the collection system of waste EV LIBs, relevant supporting regulations or rules and incentives should be developed and implemented as soon as possible.

(2) Cascaded use of waste EV LIBs has great development potentialities and a good prospect, and some demonstration projects of the cascaded use of waste EV LIBs have been accomplished. Further generalization and application should be supported and implemented based on reference value of accomplished demonstration projects. Taking factors such as function, practicality, and safety into accounts, some level of testing and refurbishment was suggested to be applied to the cascaded use of waste EV LIBs. Correlative technical standards and specifications for the testing and evaluation of the classification, quality, and performance identification of the waste EV LIBs should be established.

(3) Qualified recycling enterprises have already formed various technologies for the recycling of portable LIBs. Compared with the portable LIBs, EV LIBs have a large volume, different components and high energy storage. It is vital to upgrade and reform existing recycling technologies to satisfy the situation of enormous waste EV LIBs. For example, discharge and dismantling technology for waste EV LIBs should be researched and developed to ensure the safe recycling of the waste EV LIBs.

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