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Temporal and spatial analysis for end-of-life power batteries from electric vehicles in China

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ABSTRACT

This study aims to model the temporal and spatial characteristics of end-of-life (EOL) power batteries from electric vehicles (EVs) in China. A Stanford estimation model is used, assuming that the lifetime of power batteries obeys a Weibull distribution. We collected the sales data for two types of power batteries used in four types of EVs from 2009 to 2018 in mainland China and predicted the sales data from 2019 to 2030 according to the Chinese government's plan. The results present a complete picture of EOL batteries in China: (1) the generation of retired power batteries in China is predicted from 2020 to 2036, including 112 k tonnes in 2020 and 708 k tonnes in 2030; (2) the potential economic value of retired batteries for echelon and recovery utilization is analyzed; and (3) the generation of retired power batteries in 20 provinces was estimated and compared with their collection station numbers. Considering the weight of different batteries and the service life increase caused by technology upgrades, our predictions for the quantity of retired batteries are lower and more accurate than others' predictions. Large-scale battery retirement will come later than previously anticipated. We should plan the number of recycling sites in main provinces based on the accurate retired amount.

1. Introduction

The development of the new energy automobile industry is conducive to solving the energy, environmental and technological problems in China caused by oil-fueled automotives. In 2018, China imported 46.190 million tons of crude oil, and its dependence on foreign oil was 70.90% (Zheng, 2019). According to World Bank statistics, China has become the country with the highest carbon dioxide emissions (Zhi and Zhao, 2018). The development of China's fuel automobile industry is limited by technology, and the core parts, such as engines and gears, rely on imports. Therefore, the Chinese government promotes the development of new energy automobile industry. In 2009, China implemented the "Ten Cities and Thousands of Vehicles" Energy Saving and New Energy Vehicles Demonstration and Promotion Application Project (Wu, 2009). The government selected 13 cities to promote new energy vehicles with preferential policy and planned to sale at least 1000 cars in each city. After that, China introduced a series of tax reductions and subsidy policies to promote the development of the new energy automobile industry (Li et al., 2016). In 2016, China produced 517 thousand new energy vehicles and 507 thousand of them were sold (Du et al., 2019). According to the data from "Road Map of Energy Conservation and New Energy Vehicle Technology" redacted by China Society of Automotive Engineers (CSAE), China's new energy vehicle promotion will exceed 15 million by 2030 (CSAE, 2017). However, with the promotion of electric vehicles (EVs), the number of end-of-life (EOL) batteries from EVs will also grow rapidly (Wang and Wu, 2017).

EOL batteries are potentially harmful to the environment and human health.Lithium damages the central nervous system and free cobalt is potentially carcinogenic to humans. Copper, iron and nickel are all linked to the production of reactive oxygen species, which can lead to DNA damage and premature aging (Golmohammadzadeh et al., 2018; Winslow et al., 2018). Electrolytes and organic solutions in electrolytes contain many toxic elements. If they are leaked, they will not only cause water and soil pollution but also affect human health (Liu et al., 2019). On the other hand, power batteries contain many valuable resources and have a high value of recycling. Taking the ternary material battery as an example, its cathode contains valuable

Abbreviations: EOL EV LIB, End-of-life electric vehicle lithium-ion battery; TLB, Ternary lithium battery; LIPB, Lithium iron phosphate battery

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Nomenclatures

LIB	Lithium-ion battery
TLB	Ternary lithium battery
LIPB	Lithium iron phosphate battery
EOL EV batteries	End-of-life electric vehicle batteries
EPC	Electric passenger car
ECV	Electric commercial vehicle
BEPC	Battery-electric passenger car
BEPC-TLB	Battery-electric passenger car driven by ternary lithium battery
BEPC-LIPB	Battery-electric passenger car driven by lithium iron phosphate battery
HEPC	Hybrid electric passenger car
HEPC-TLB	Hybrid electric passenger car driven by ternary lithium battery
HEPC-LIPB	Hybrid electric passenger car driven by lithium iron phosphate battery
BECV	Battery-electric commercial vehicle
BECV-TLB	Battery-electric commercial vehicle driven by ternary lithium battery
BECV-LIPB	Battery-electric commercial vehicle driven by lithium iron phosphate battery
HECV	Hybrid electric commercial vehicle
HECV-TLB	Hybrid electric commercial vehicle driven by ternary lithium battery
HECV-LIPB	Hybrid electric commercial vehicle riven by lithium iron phosphate battery
Ni	Nickel
Co	Cobalt
Mn	Manganese
Cu	Cuprum (Copper)
Li	Lithium
Al	Aluminum
CSAE	China Society of Automotive Engineers
SSRI	Sinolink Securities Research Institute
ZC	Zhiyan Consulting
CRN	China Report Net
MIIT-PRC	Ministry of Industry and Information Technology of People's Republic of China
MST-PRC	Ministry of Science and Technology of the People's Republic of China
FEV	First Electric Vehicle
DCHP	Department of Commerce of Hainan Provincial
SG-NPSC	State Grid Nanjing Power Supply Company
NE	Ningde Era
PESN	Polaris Energy Storage Net
ATCRR	Alliance of Technology and Compulsory Resource Recovery
LEM	London Metal Exchange
SNMN	Shanghai Nonferrous Metal Net
CPN	Chemical Products Network
PBC	People's Bank of China

metals, including cobalt (5–20%), nickel (5–12%), manganese (7–10%), and lithium (2–5%) (Li et al., 2019). Recycling materials from EOL batteries, such as graphite, electrolytes and aluminium, could reduce environmental pollution and improve resource efficiency (Cusenza et al., 2019; Oliveira et al., 2015). In addition, retired power batteries can be reused by echelon utilization, which is expected to reduce the waste of power batteries and provide energy storage capacity for other scenarios (Bobba et al., 2019; Faria et al., 2019). Analyzing the temporal and spatial characteristics of EOL batteries in China is helpful for the government to formulate policies and solve the problems caused by EOL batteries.

According to the current studies, we found that the quantity of EOL EV batteries directly relates to the sales, weight, lifespan distribution and technology of batteries (Ai et al., 2019; Richa et al., 2014). Ai et al. considers two life span scenarios (i.e., constantly at 3–8 years and dynamically increasing over time) and use three probability distribution functions (i.e., uniform, truncated normal, and Weibull) to predict the number of short-term and long-term EOL EV batteries in the United States (Ai et al., 2019). Richa et al. (2014) use the material flow analysis method to estimate the quantity of EOL EV batteries in the United States from 2015 to 2040 under different scenarios (such as different life distribution and battery sales), and find that sales volume and battery technology had the greatest impact on the amount of waste products. However, we believed that the weight of different models is ignored by previous researchs. Qiao et al. (2019) estimated the environmental and economic benefits of recycling electric vehicles and batteries based on the recycling technology in China. But they did not further predict the number of retired electric vehicles and batteries in China. Some predictions for EOL batteries in China have been made, but their assumptions are not sufficiently precise. Some researchers assume that the life of power batteries obeys a uniform distribution, and average weight is taken according to the maximum and minimum weight of power batteries for each type of vehicle, such as the research done by Sinolink Securities Research Institute (SSRI) and Ganzhou Haopeng (GH) (GH, 2017; SSRI, 2017). In reality, power batteries in the same models generally have different lifespans due to various of usage scenarios, and the sales volume of different models also affect the total battery weight. EVTank predicts the generation of retired power batteries in China from 2018 to 2022 using new energy vehicle sales data from 2009 to 2018 (EVTank, 2018). Due to the lack of continuous and complete sales data, it is impossible to make long-term predictions. Finally, previous studies focused on national-level predictions, such as the research made by China Automobile Technology Research Center (CATRC), which cannot provide support for establishing recycling sites (CATRC, 2018a,b).

Compared to previous studies, our prediction results regarding the number of EOL EV batteries will be more accurate. Firstly, we summarize the sales of different vehicles in China from 2009 to 2018, and then predict the sales of this vehicles from 2019 to 2030 according to the government's promotion plan for the new energy vehicles. The continuous sales data support the mid-long term prediction for EOL batteries. Secondly, considering the battery weight and life distribution of different models, a Stanford estimation model is used to predict the quantity of EOL batteries in China from 2010 to 2036. Thirdly, to

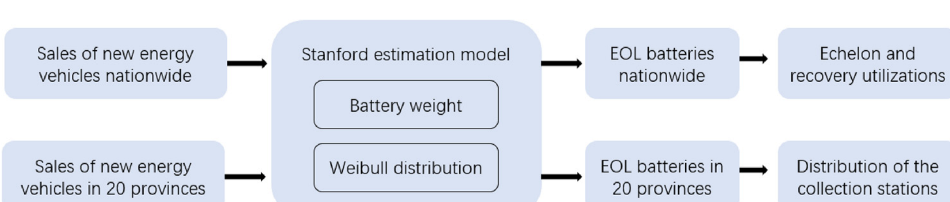

Fig. 1. Methodology flow chart used in this study.

illustrate the economic value of EOL batteries, the potential economic value of echelon and recovery utilization are quantized, according to the prediction of EOL batteries. In addition, the spatial distributions of EOL batteries and collection stations in 20 provinces are compared. We will provide suggestions for the government to formulate mid-long term recycling management policies and plan the spatial layout of recycling enterprises.

2. Methods and data

The study methods of this paper can be found in Fig. 1. First, according to the sales of new energy vehicles and government promotion plans, we predict the sales of new energy vehicles in China and 20 provinces. Second, the battery weight of different models is calculated and the battery life is assumed to follow the Weibull distribution. The Stanford estimation model is used to predict the quantity of EOL batteries in the whole country and 20 provinces. Third, the potential value of echelon and recovery utilizations are estimated based on the number of EOL batteries and the price of resources. Fourth, the number of collection stations in 20 provinces is collected and the differences between the number of EOL batteries and collection stations in 20 provinces are compared.

2.1. Scope of study

2.1.1. Temporal and spatial scope

We collected and predicted the sales of new energy vehicles in China from 2009 to 2030. The growth trend of EOL batteries in the mid-long term can be illustrated based on above data, and the number of EOL batteries in China from 2010 to 2036 is projected. For example, the average life of batteries sold in 2030 is 15 years, and the proportion of batteries with a five-year life is about 1%. So we infer that the retired proportion before 2036 of batteries sold between 2031 and 2035 is very small. In terms of 20 provinces, we only collected and predicted the sales of new energy vehicles from 2014 to 2020 because of the sparse data. To reduce the impact of batteries sold before 2014, the estimated period of EOL batteries will start from 2018 and end in 2022. According to the research of Zhiyan Consulting (ZC), the import and export volume of China's new energy vehicles in the first half year of 2018 accounted for a small proportion of the total sales, and the difference between import and export volume was small (ZC, 2018). So in this paper, the sales volume of new energy vehicles refers to the statistics of relevant departments, assuming that all new energy vehicles in China are sold domestically, without considering the quantity of imports and exports.

2.1.2. EV and battery types

In 2015, the sales of EV batteries reached 15.7 GW h in China, where ternary lithium batteries (TLBs) and lithium iron phosphate batteries (LIPBs) accounted for 96% (Wang and Wu, 2017). TLB is a lithium battery which uses lithium nickel-cobalt-manganate as cathode materials, and LIPB uses lithium iron phosphate as cathode materials (Raugei and Winfield, 2019). There are other batteries, such as lithium manganate battery and lithium cobalt oxide battery. In this study, TLBs and LIPBs were selected for research. The EV and battery types in this study are listed in Table 1. In our study, "HEPC and HECV" also include the plug-in electric vehicles. The two models were not counted separately in the sales data.

2.2. Sales data of EVs

2.2.1. Sales of EVs in China from 2009 to 2030

a) Total sales of EVs in China from 2009 to 2018 First, we collected the sales data for EVs and the quantity of power batteries installed in China from 2009 to 2018 (see Table 2). The data with “***” come from the “2010 Annual Report on the ‘Thousands of Vehicles in Each Ten Cities’ Pilot Project of Demonstration and Generalization of Energy-efficient and New-energy Automobiles” formulated by Ministry of Science and Technology of the People's Republic of China (MST-PRC), which only collected the EV sales data in pilot cities (MST-PRC, 2011). In the early stages, EVs were mainly sold in pilot cities. The data with “**” come from our estimation according to the proportion of each type of car sold each year. The data with “*” come from the published literature “2015 energy saving and new energy automobile yearbook” (CATRC, 2015). China Association of Automobile Manufacturers (CAAM) provides other data (CAAM, 2019).

b) Total sales of EVs in China from 2019 to 2030 Second, we predict the total annual sales of new energy vehicles from 2019 to 2030. According to the Road Map of Energy Conservation and New Energy Vehicle Technology (see Table 3), the sales of new energy vehicles exceed 7% of the total sales in 2020, 15% in 2025 and 40% in 2030 (CSAE, 2017). Based on this, we estimate the total sales of new energy vehicles in 2020, 2025 and 2030. Assuming that the total sales of new energy vehicles in the year between two adjacent time nodes continuously increase, the total sales of new energy vehicles in the year 2019–2030 can be estimated (see TABLE A1).

c) Classified sales of EVs in China from 2016 to 2018 Third, we estimate the consumption of two types of batteries in four types of vehicles from 2016 to 2018. The quantity of power batteries installed in different types of new energy vehicles from 2011 to 2018 is collected in Fig. 2 and TABLE A2. These data were collected by Gasgoo (2019) and CRN (2018). The detailed sales from 2016 to 2018 are estimated in Table 4. The classified installation quantity to different types of vehicles is based on the registration data from vehicle production certificates (Cui, 2019). If we assume that the energy storage of power batteries is the same in the same type of vehicle, the proportion of power batteries installed will be equal to the proportion of new energy vehicles sold.

d) Classified sales of EVs in China from 2009 to 2015 Fourth, according to a statistical method of sales of different types of new energy vehicles in 2016–2018, the sales of different types of new energy vehicles in 2009–2015 are estimated (Fig. 3). TABLE A2 shows that before 2011, all types of power batteries are LIPBs, and the installation quantity of TLBs is zero. In 2012, the installation quantity of TLBs began to grow rapidly. Given the proportion of sales of eight types of EVs in 2011 and 2016 and assuming that sales of EVs will change in a fixed proportion in 2012-2015. TABLE A3 contains the specific

Table 1
EV and battery types in this study.

Type	TLB	LIPB
Battery-electric passenger car (BEPC)	Battery-electric passenger car driven by ternary lithium battery (BEPC-TLB)	Battery-electric passenger car driven by lithium iron phosphate battery (BEPC-LIPB)
Hybrid electric passenger car (HEPC)	Hybrid electric passenger car driven by ternary lithium battery (HEPC-TLB)	Hybrid electric passenger car driven by lithium iron phosphate battery (HEPC-LIPB)
Battery-electric commercial vehicle (BECV)	Battery-electric commercial vehicle driven by ternary lithium battery (BECV-TLB)	Battery-electric commercial vehicle driven by lithium iron phosphate battery (BECV-LIPB)
Hybrid electric commercial vehicle (HECV)	Hybrid electric commercial vehicle driven by ternary lithium battery (HECV-TLB)	Hybrid electric commercial vehicle riven by lithium iron phosphate battery (HECV-LIPB)

Table 2
Classified sales of EVs in China from 2009 to 2018.

Year	EPC			ECV			Total
	Battery-electric	Hybrid electric	EPC total	Battery-electric	Hybrid electric	ECV total	
2009	49***	623***	672***	455***	2838***	3293***	3965***
2010	857***	1110***	1967***	1481***	2440***	3921***	5888***
2011	2203**	1469**	3672	1570**	2917**	4487	8159
2012	5628**	1407**	7035	2015**	3741**	5756	12791
2013	10048*	396*	10444*	1640*	2788*	4428*	14872*
2014	38832*	16848*	55680*	15963*	13856*	29819*	85499*
2015	146719	60663	207382	100763	22947	123710	331092
2016	257000	79000	336000	152000	19000	171000	507000
2017	468000	111000	579000	184000	14000	198000	777000
2018	788000	265000	1053000	196000	6000	202000	1255000

Data source: MST-PRC, CATRC and CAAM.

Table 3
Sales planning of vehicles in China from 2020 to 2030.

Year	Annual sales(million units)	Percentages of EV(%)
2020	30	7
2025	35	15
2030	38	40

Data source: CSAE.

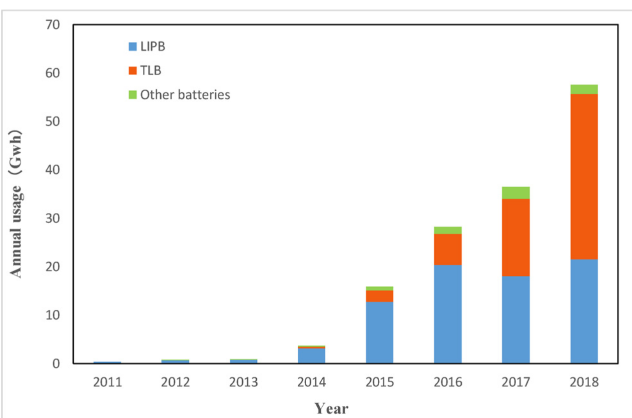

Fig. 2. Annual installation quantity of lithium-ion batteries (LIBs) in China From. 2011 to 2018.

assumptions, and these assumptions turn to market share here for the sake of observation.

e) Classified sales of EVs in China from 2019 to 2030 Finally, according to a statistical method of the classified sales of EVs in 2016–2018, the classified sales of EVs from 2019 to 2030 are estimated. The proportion of sales is uncertain in the future, so we estimate it at a fixed value referring to the current development of the battery and automotive industries. TABLE A4 points out all of the sales assumptions for EVs in China from 2009 to 2030. To facilitate observation, Fig. 4 represents these assumptions in terms of market share.

2.2.2. Sales of EVs in 20 provinces

The sale data of 20 provinces from 2014 to 2017 are derived from the Yearbook of Energy Conservation and New Energy Vehicles (CATRC, 2019). According to the promotion plans of the provinces in 2018–2020 collected by Electric Vehicle Resources (EVR), the annual total sales is predicted (EVR, 2018). If there is no promotion plan, we assume that the proportion of the sales volume of provinces in the national total sales volume in 2018–2020 is equal to the proportion in 2017. Then we supplement the sales of the four models from 2018 to 2020 according to the proportion of the sales of the four models from 2014 to 2017 in the total sales.

Table 4
Annual consumption of electric passenger car LIBs (EPC-LIBs) and electric commercial vehicle LIBs (ECV-LIBs) in China from 2016 to 2018.

Power system	Battery type	Unit	2016	2017	2018
Battery-electric	LIPB	Gwh	3.23	2.74	3.29
	TLB	Gwh	4.63	8.92	26.32
	Others	Gwh	0.01	0.21	0.53
Usage of BEPC-LIB		**Gwh**	**7.87**	**11.87**	**30.14**
Hybrid electric	LIPB	Gwh	0.80	0.10	0.00
	TLB	Gwh	0.20	1.36	3.41
	Others	Gwh	0.01	0.05	0.05
Usage of HEPC-LIB		**Gwh**	**1.01**	**1.51**	**3.46**
Total usage of EPC-LIB		**Gwh**	**8.88**	**13.38**	**33.60**
Battery-electric	LIPB	%	41	23	11
	TLB	%	59	75	87
	Others	%	0	2	2
Usage of BEPC-LIB		**%**	**100**	**100**	**100**
Hybrid electric	LIPB	%	79	7	0
	TLB	%	20	90	99
	Others	%	1	3	1
Usage of HEPC-LIB		**%**	**100**	**100**	**100**
Total usage of EPC-LIB		**%**	**100**	**100**	**100**
Battery-electric	LIPB	Gwh	15.54	14.61	19
	TLB	Gwh	1.44	5.86	3.63
	Others	Gwh	1.34	1.57	1.5
Usage of BECV-LIB		**Gwh**	**18.32**	**22.04**	**24.13**
Hybrid electric	LIPB	Gwh	0.14	0.23	0.07
	Others	Gwh	0.29	0.47	0.19
Usage of HECV-LIB		**Gwh**	**0.44**	**0.7**	**0.26**
Total usage of ECV-LIB		**Gwh**	**18.76**	**22.74**	**24.39**
Battery-electric	LIPB	%	85	66	79
	TLB	%	8	27	15
	Others	%	7	7	6
Usage of BECV-LIB		**%**	**100**	**100**	**100**
Hybrid electric	LIPB	%	32	33	27
	Others	%	66	67	73
Usage of HECV-LIB		**%**	**100**	**100**	**100**
Total usage of ECV-LIB		**%**	**100**	**100**	**100**

Date source: Cui, 2019.

2.3. Battery weight

Ministry of Industry and Information Technology of the People's Republic of China (MIIT-PRC) have released “Recommended vehicle types catalogue for new energy vehicle promotion and application (batch 1, 2018)” (MIIT-PRC, 2018). We estimated the battery weight of the four types of vehicle from 2009 to 2030 according to this catalogue.

Battery weight of BEPCs from 2009 to 2019: We divide BEPCs into subcompact cars and non-subcompact cars. Most of the subcompact car batteries in the catalogue weigh approximately 150 kg, and non-subcompact car batteries are approximately 300 kg. According to statistics

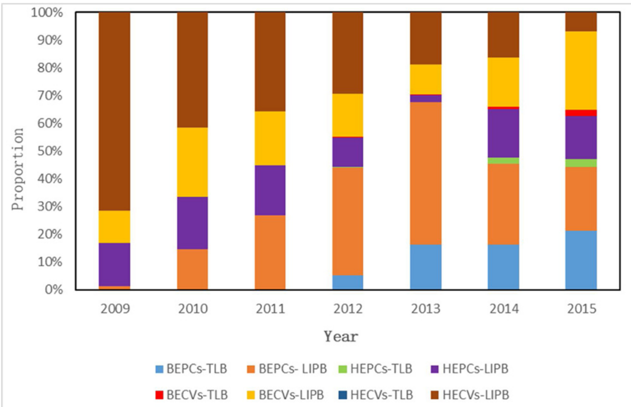

Fig. 3. Sales of eight models accounted for the proportion of total sales from 2009 to 2015.

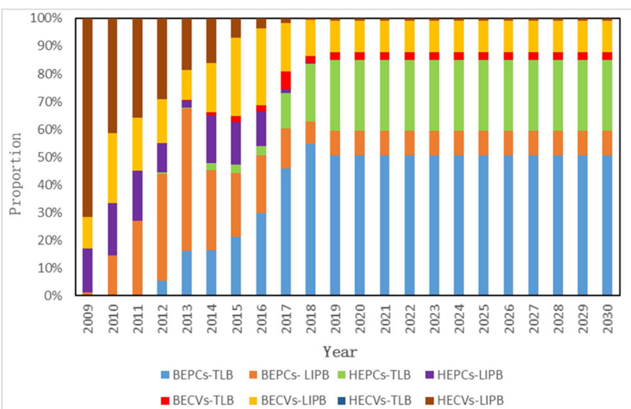

Fig. 4. Sales of eight models accounted for the proportion of total sales.

from First Electric Vehicle (FEV), we make the following assumptions. The percentage of A00 class cars sales to EPCs was 70% from 2009 to 2013, decreased to 60% between 2014 and 2016 and was 30% from 2017 to 2019 (FEV, 2017; FEV, 2019).

Battery weight of BEPCs from 2020 to 2030: "Technology roadmap for energy saving and new energy vehicles" explained the development of EV range and battery specific energy, but recently some vehicle types have met the requirement of future EV range (CSAE, 2017). We take the battery capacity of these excellent cars and divide it by the planned specific energy to estimate the future battery weight.

Battery weight of HEPCs from 2009 to 2030: The battery capacity of this vehicle type is approximately 10–15 kW h, and the minimum specific energy requirement for the battery is 125 Wh/kg in the 2019 subsidy policy, so we estimate the weight of the battery at approximately 100 kg.

Battery weight of BECVs from 2009 to 2030: The BECVs are divided into battery-electric buses and special vehicles. We assume that the average weight of the bus battery is 1500 kg and the average weight of the special vehicle battery is 500 kg according to TABLE A5. In the "Thousands of Vehicles in Each Ten Cities" project from 2009 to 2013, electric buses were the main vehicles, so we assume that electric buses account for 90% of ECVs sold during this period. TABLE A6 explained the sales of electric buses and special vehicles from 2014 to 2017 and we assume that in 2018–2030, the two percentages will be 50% according to the previous situations.

Battery weight of HECVs from 2009 to 2030: We refer to the study from Sinolink Securities and assume that the battery weight is 235 kg, which is similar to the battery weight in the catalogue (SSRI, 2017).

2.4. Battery lifespan

2.4.1. Average battery lifespan

The average life span of a car in China was 15–20 years in 2013(Xue et al., 2013). With the development of automobile technology, the life of automobile will increase for now, the life of the car is longer than that of the battery. On the other hand, new EVs rarely use used batteries. Therefore, we mainly consider the battery life in the waste estimation.

We assume that when the battery quality can't meet the requirement of the EVs, the batteries will reitre. There are three main factors affect the service life of power batteries: battery capacity and decline rate, which are related to the type of EV (Smaller battery capacity means frequent charge and greater decline rate, so the battery's life is shorter); technology and battery materials; and the use scenario (Ai et al., 2019). In the Road Map of Energy Saving and New Energy Vehicle Technology, the development plan points out that the average service life of a power battery should be higher than 10 years in 2020, 12 years in 2025, and 15 years in 2030 (CSAE, 2017), which is the standard for the batteries in passenger cars. These batteries in commercial vehicles will have a shorter life because of their higher frequency of use and frequent charging. According to the BYD official data, the warranty period of batteries in passenger cars in 2018 is approximately 8 years. According to the Yutong bus official data, the warranty period of batteries in commercial vehicles in 2018 is approximately 5 years. In addition, in 2018, the Department of Commerce of Hainan Provincial (DCHP) issued a notice which requires passenger car manufacturers to provide no less than 8 years of quality guarantee and commercial vehicle manufacturers should provide no less than 5 years of quality guarantee (DCHP, 2018). Assuming that the average battery life of commercial vehicles is three years shorter than that of passenger vehicles and the average battery life of commercial vehicles and passenger vehicles will increase by a certain value from 2009 to 2030, as follows (Fig. 5).

2.4.2. Probability distribution of battery life

The Weibull distribution can simulate a variety of product life cycles and is also used to predict the generation of e-waste. In this paper, a Weibull distribution with two parameters is used, where F (t) represents the retirement probability of power batteries from the initial application year to the t year. The range parameter β represents the life cycle of products, which is usually equal to the average life of power batteries (Barré et al., 2013). The shape parameter α determines the shape of the probability density function. Based on the research of Ai et al., the shape parameter is 3.5, and the range parameter is equal to the average life of the power battery (Ai et al., 2019). Because the average life of EPC power batteries is different from that of ECV power batteries, two Weibull distribution functions are used to calculate the life distribution of EPC-LIBs and ECV-LIBs.

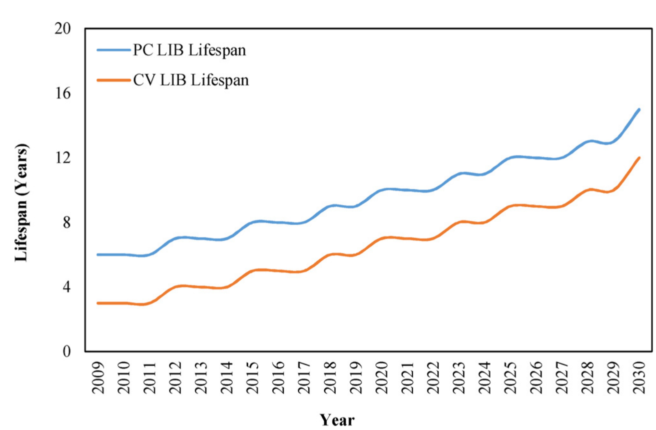

Fig. 5. Lifespan Assumptions Adopted in This Study.

$$F(t;\beta,\alpha) = 1 - e^{-(t/\beta)^{\alpha}} \tag{1}$$

Figs. 6 and 7, TABLE A14 and TABLE A15 illustrate the percentage of LIBs reaching EOL with different average lifespans. The Weibull distribution is related to many distributions with different shape parameters, and when the shape parameter is 3.5, the Weibull distribution is approximately normal. The shorter the average life, the steeper the curve, which means that the time that LIBs reach EOL is more concentrated. The annual EOL batteries from existing EVs peaked earlier and at a higher rate compared to the longer lifespan.

2.5. Estimation model of battery retirement

In this paper, the Stanford estimation model is used to predict the retirement of power batteries in China from 2010 to 2036 (Song et al., 2016; Tian et al., 2014). It is assumed that the weight of TLBs and LIPBs in the same type of vehicle is the same for each year. The volume of EOL power batteries in China (Q_E) in some years is estimated as below:

$$Q_E = \sum_i S_{ijk} \cdot W_{ij} \cdot P_{ij} \tag{2}$$

Where S_{ijk} is the sales of vehicle type j with battery type k before i years; W_j is the average battery weight of vehicle type j before i years; P_{ij} is the probability that vehicle type j sold before i years will replace its battery after i years.

2.6. Economic value of EOL batteries

The advantages of LIPBs are their low cost, long cycle life, good thermal stability, high safety, and more suitability for echelon utilization, and TLBs have high precious metal content and high value of resource regeneration (Liu et al., 2018). The recovery utilization refers to the metal resources recycling of retired batteries, smelting, and sellingto the market as new material (Qiao et al., 2019). The echelon utilization refers that when batteries cannot meet the needs of the EVs because of the decrease in energy density, they can be used in other scenarios, which don't need a high energy density, such as energy storage of power grid (Jiang et al., 2018). This mode stores electric power during low demand periods and releases it during peak demand periods, which makes profits from their price gap. According to State Grid Nanjing Power Supply Company (SG-NPSC), the largest energy storage power stations in China is built in Jiangsu province, total storage capacity about 268,600 Kwh (SG-NPSC, 2019). In addition, retired batteries can also be reused in energy storage of communication stations and in low-speed EVs (Casals et al., 2019).

Ningde Era (NE) has estimated the value of cascade utilization and recycling of retired batteries (EnergyTrend, 2018; NE, 2019). After retirement, LIPBs can be used as energy storage batteries for at least five years. If the batteries are directly scrapped and recycled, the economic benefit of the recovery of LIPBs per ton is approximately 1428 dollars (Based on the exchange rate published by the People's Bank of China. 1 USD = 7.0026 RMB.). However, if they are used as echelon utilization, the profit of the former is 3–4 times greater. In the term of retired TLBs, the recovery price is approximately 5712–7140 dollars/ton. We assumed that all retired TLBs can be directly used for regeneration; all retired LIPBs can be used for echelon utilization, and then they will be discarded after five years to eventually enter the field of regeneration.

If the power battery is retired when the specific energy drops to 80%, we can estimate the total capacity of retired LIPBs according to the weight and average specific energy of retired LIPBs. We make statistics on the battery specific energy of EVs using LIPBs in the recommended catalogue of the first batch of new energy vehicles in 2018, and the results are shown in Fig. 8 and TABLE A9 (MIIT-PRC, 2018). Using these percentages as weights, the weighted mean is 138 Wh/kg. Assuming a 5% increase in specific energy per year, the results are shown TABLE A10. There are many ways of echelon utilization, and the economic value of commercial energy storage is estimated as an example. According to Polaris Energy Storage Net (PESN), researchers generally believe that the peak-valley price difference of 0.7 yuan per kilowatt-hour is the lowest standard for developing commercial energy storage and some provinces have exceeded this price (PESN, 2018). Taking 0.7 yuan per kilowatt-hour as an example, the author estimates and assumes that the number of cycles of retired LIPBs is 1500, charging and discharging once a day, using for 300 days per year, and completely discarding after five years.

"China Power Battery Recycling and Treatment Industry Status and Development Report 2017″ redacted by Alliance of Technology and Compulsory Resource Recovery (ATCRR) provides the information of material composition (ATCRR et al., 2018). Compared with LIPBs, TLBs contain a lot of Ni, Co, Mn, and otherelements. According to the prices of these materials, Ni, Co and Mn have high recycling value. The recovery rate comes from the Requirements for Recycling Materials of Vehicle Power Batteries (draft for comments) (CATRC, 2018a,b). The prices of the main materials on November 13, 2019 come from the London Metal Exchange (LEM), Shanghai Nonferrous Metal Net (SNMN), and Chemical Products Network (CPN) (CPN, 2019; LEM, 2019; SNMN, 2019). Because China has rich iron and phosphorus mineral resources, which have low market value, we do not make a market value estimation here. The exchange rate released by the People's Bank of China (PBC) is 1 USD = 7.0026 RMB on November 13, 2019 (PBC, 2019). The recovery rates and prices of major materials are in Table 5.

3. Results and discussion

3.1. Mid-long term sales in China

3.1.1. Classified sales of EVs in China

Fig. 9 and TABLE A11 note the sales of different EV types from 2009 to 2030. The sales of EVs grow from approximately 4000 to approximately 15 million from 2009 to 2030. From the year 2009 to 2018, the annual average growth rate is approximately 90% (the annual average growth rate = $[(S_{2018}/S_{2009})^{1/9} - 1] \times 100\%$, S_{2018} represents the sales in 2018 and S_{2009} represents the sales in 2009), while starting from the year 2018 until 2030, the growth rate will be over 23%. Because of the constantly increasing of personal demand for EPCs, the percentage of ECVs to total sales fell from 83% in 2009 to 16% in 2018. As our estimation, EPCs accounted for 85% of total sales, while ECVs accounted for 15% of total sales starting in 2019.

3.1.2. Sales of TLBs and LIPBs

Fig. 10 and TABLE A12 illustrate the sales of both kinds of batteries in 2009-2030. Overall, the sales of both batteries are increasing. The sales of LIPBs grew from 1.38 kilotons in 2009–2102.04 kilotons in

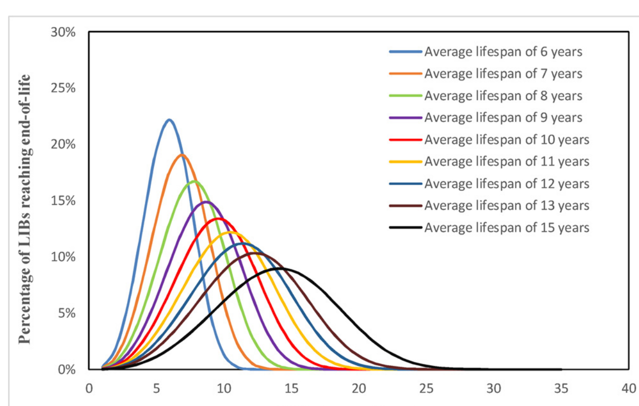

Fig. 6. Lifespan distribution of EPC-LIBs.

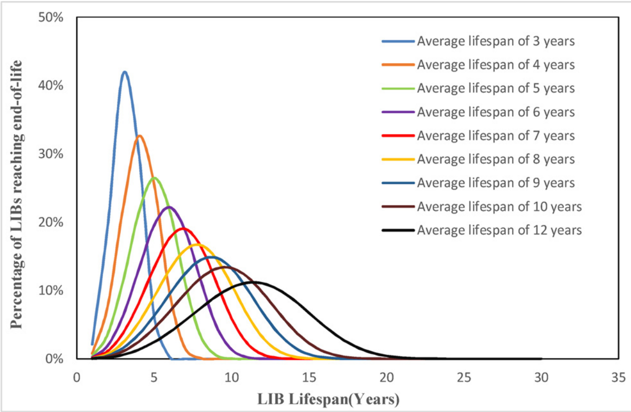

Fig. 7. Lifespan distribution of ECV-LIBs.

2030, while the sales of TLBs grew from 0.17 kilotons in 2009–2669.3 kilotons in 2030. From the year 2012 to 2018, the annual average growth rate of TLBs was approximately 234%, while starting from the year 2018 until 2030, the growth rate will decrease to 22%. For the annual growth rate of LIPBs, from the year 2009 to 2018, it was approximately 73% and from 2018 to 2030, it will decrease to 22%. Prior to 2017, LIPBs sold more than TLBs because early commercial vehicles sold more and they used more LIPBs. After 2017, with the growth of passenger car sales, sales of TLBs exceeded sales of LIPBs.

3.1.3. Sales of EVs in 20 provinces

Fig. 11 and TABLE A13 describe the sales of EVs in 20 provinces in China from 2014 to 2020. Compared to inland provinces, the coastal provinces have developed economies, larger populations and more policies to support the development of the EV industry, so there is more demand for EVs in these areas. Guangdong had the highest total sales with more than 700 thousand, while Gansu had the lowest total sales with less than 30 thousand. The annual sales calculated from the sales plans in some provinces does not increase continuously. For example, the sales in Shanghai were approximately 61 thousand units in 2017, but they will be 43, 50 and 60 thousand units in 2018, 2019 and 2020 according to the provincial sales plans. Overall, the sales plan is not exactly in line with the reality.

Table 5
Recovery rates and prices of major materials for TLBs and LIPBs.

Major material	TLB (%)	LIPB (%)	Recovery rate (%)	Price ($1000/ton)
Li	1.9	1.1	85	$ 10.0
Ni	12.1	0	98	$ 15.5
Co	2.3	0	98	$ 35.0
Mn	3.2	0	98	$ 1.6
Cu	13.3	13.8	90	$ 5.8
Al	12.7	13.3	90	$ 1.8
Steel	8.9	9.4	95	$ 0.6
Plastic	4.2	4.6	95	$ 1.2

Annotation: The London metal exchange doesn't supply the prices of manganese and plastic, which are supplied by Chinese prices.

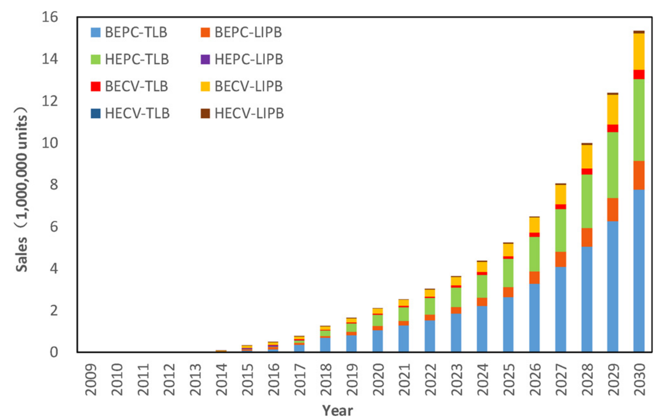

Fig. 9. Classified sales of EVs in China from 2009 to 2030.

3.2. In-use and retirement of power batteries

3.2.1. Battery weights for different types of vehicles

Fig. 12 and TABLE A7 illustrate the battery weights of different EV types from 2009 to 2030. HEPCs and HECVs have fixed battery weights. The battery weight of BEPCs is relatively stable, approximately 200 kg, while the battery weight of BECVs generally decreases because electric bus sales account for a larger proportion in previous years, but decrease in the future.

3.2.2. Retirement of batteries from 2010 to 2036

The amount of EOL LIBs is shown in Fig. 13 and TABLE A 16.

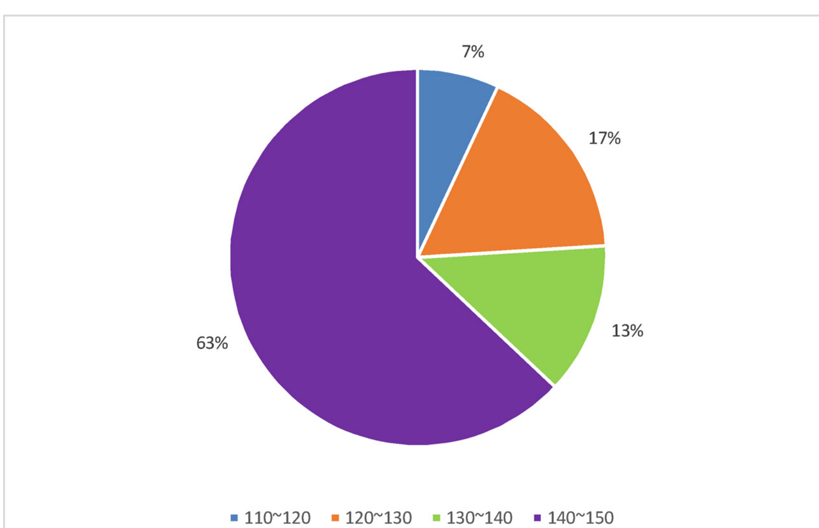

Fig. 8. Specific energy of the first batch of recommended EVs powered by LIPBs in 2018 (Unit: Wh/kg).

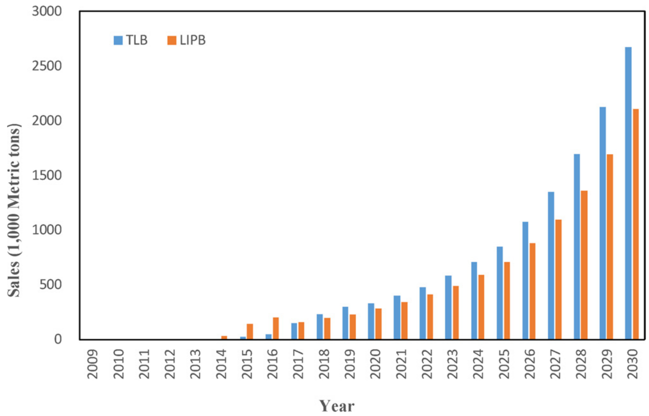

Fig. 10. Sales of two kinds of batteries from 2009 to 2030.

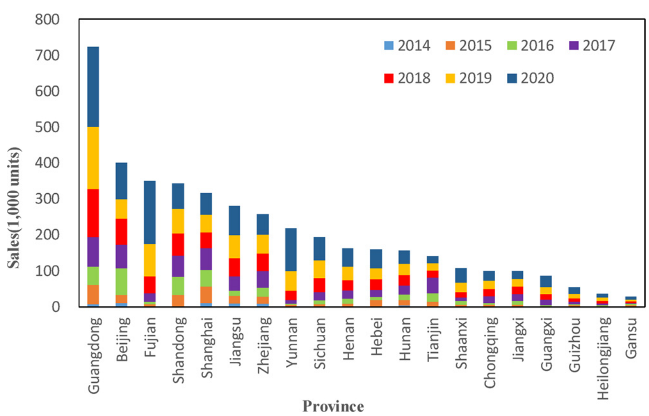

Fig. 11. Sales of EVs in 20 provinces from 2014 to 2020.

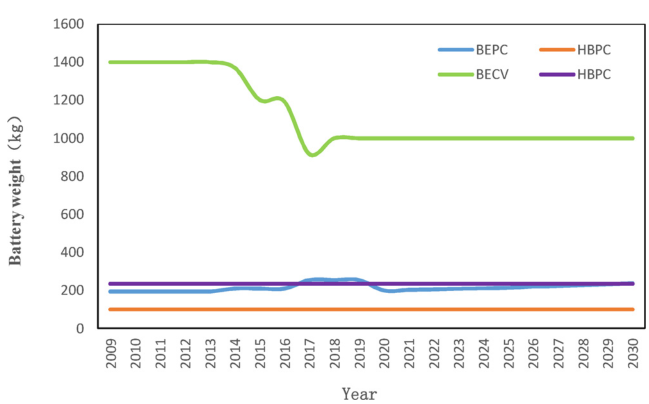

Fig. 12. Weight assumptions of EV LIBs from 2009 to 2030.

According to our study, the amount of EOL LIBs increased from approximately 28 tons to 1.5 million tons in 2010–2036 and will increase from 2020 to 2036 with an average annual growth rate of 18%.

The retired scale of commercial vehicles and passenger vehicles differs slightly each year. Although commercial vehicle sales accounted for 15% of total sales in 2019–2030, it can be seen from the "power battery quality" that the battery weight of ECV s is approximately 5–6 times that of electric passenger vehicles. Moreover, the life of commercial vehicle power batteries is shorter, which will also increase the retirement of commercial vehicle power batteries in the future. ECVs will prefer to LIPBs because LIPBs have cheaper costs and better security, while TLBs will be more suitable for EPCs thinks to their longer vehicle range. Therefore, there are many EOL batteries from BECVs-LIPB and BEPCs-TLB. In the year 2036, the EOL batteries from BECVs-

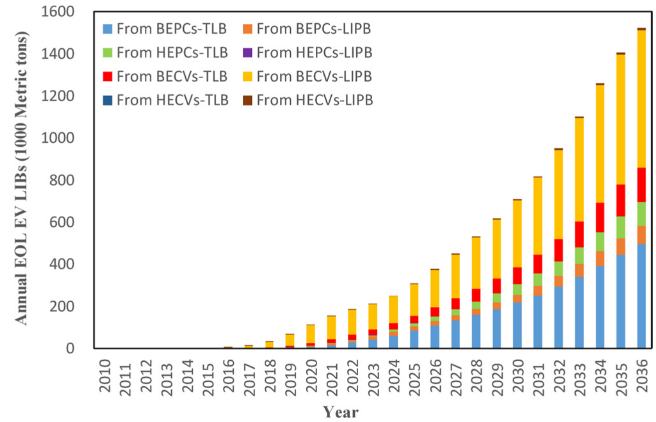

Fig. 13. Annual EOL batteries by vehicle types from 2010 to 2036.

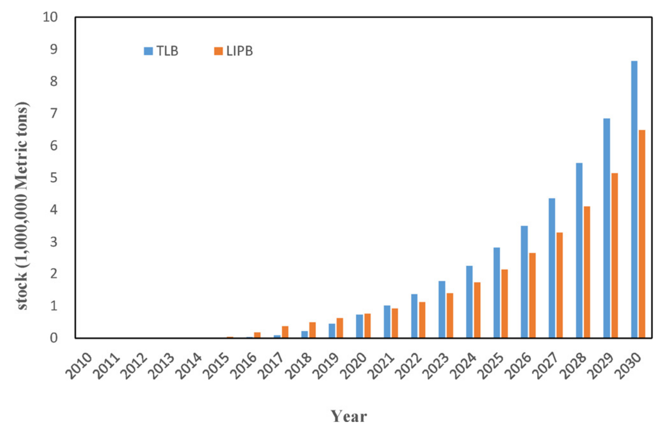

Fig. 14. In-use amount of two kinds of batteries from 2010 to 2030.

LIPB accounts for 43% of the total, while from BEPCs-TLB accounts for 33% of the total.

3.2.3. In-use power batteries from 2010 to 2036

Fig. 14 and TABLE A17 illustrate the in-use amount of both batteries from 2010-2030. Both types of batteries increase gradually, and the trend of their retention is similar to that of sales. The stock of LIPBs increased rapidly from 2016, approximately 170,000 metric tons, while the stock of TLBs increased rapidly from 2018, approximately 220,000 metric tons. From 2016 to 2030, the annual average growth rate of the stock of LIPBs will be approximately 30%, while from 2018 to 2030, the annual average growth rate of the stock of TLBs will be approximately 35%. Before the year 2020, the stock of LIPBs is clearly greater than TLB, but the stock of TLBs will exceed the other after 2020.

3.3. Comparisons with other retirement estimations

The main reasons for the deviations of the predicted values from different organizations are as follows: new energy vehicle sales prediction, battery life hypothesis, estimation method, probability of annual scrapping and battery weight hypothesis, etc. Table 6 and Fig. 15 show the comparison among our study and other studies (EVTank, 2018; GH, 2017; SSRI, 2017). We only have the prediction results of EVTank, lacking the information of the research process, so its research was not summarized in the table.

The predicted results of these organizations are significantly larger than our study. Taking Guojin Securities Research Institute for example, the discarded LIBs used in commercial vehicles (assuming a three-year battery life) and passenger vehicles (five years) will reach 400,000 tons and 100,000 tons, respectively, in 2020, with a total weight of

Table 6
Summary of EOL EV LIB studies for China in 2020.

Researcher	EV type	Assumption of LIB weight	Assumption of LIB lifespan	Battery life distribution	Model
SSRI	HECV	235 kg	3 years	Missing data	Missing data
	BECV	1900 kg			
	HEPC	275 kg	5 years	Missing data	Missing data
	BEPC	550 kg			
GH	HECV	235 kg	3 years	uniform distribution	Missing data
	BECV	1900 kg			
	HEPC	275 kg	5 years	uniform distribution	Missing data
	BEPC	550 kg			
Our study	BEPCs-TLB BEPCs-LIPB HEPCs-TLB HEPCs-LIPB BECVs-TLB BECVs-LIPB HECVs-TLB HECVs-LIPB	Consider the effect of the sales of different models on the total weight	Based on the development plan and actual situation, dynamic growth is assumed	Weibull distribution	Stanford estimation model

Data source: SSRI and GH.

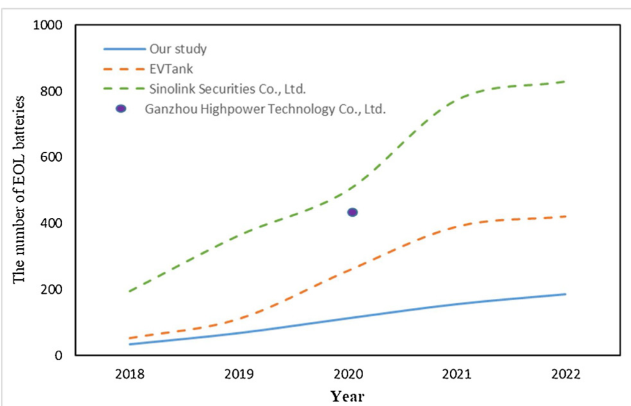

Fig. 15. Comparison for the number of EOL batteries (Unit: kiloton).

approximately 500,000 tons. In 2022, the values for commercial vehicles and passenger vehicles are approximate 560,000 tons and 260,000 tons, respectively, with a total weight of approximately 820,000 tons.

The disadvantage of this hypothesis is that it ignores the effect of sales of different models on the total battery weight. For example, in EPCs, most of the minicars in the recommended catalogue of the first batch of new energy vehicles in 2018 have batteries weighing 150–200 kg and compact EPCs have batteries weighing approximately 300 kg (MIIT-PRC, 2018). According to the data of the first electric network, from 2013 to 2015, the proportion of A00 class cars in EPCs has been approximately 60% and declined in 2016 (FEV, 2017). In 2018, it accounted for less than 30% of all EPCs (FEV, 2019). In addition, according to the new energy vehicle recommended catalogue in 2018, most hybrid EVs have a battery energy storage of approximately 10 kW h-15 kW h and a battery pack weight of approximately 100 kg. Therefore, the assumption of this unit in the table may enlarge the scale of retirement for power batteries.

The prediction results of this organization are obviously higher than those of this paper because: (1) the former assumes that the average lifespan of batteries is short and constant, but this paper assumes that the average lifespan of batteries is long and will be prolonged with technological progress; (2) the former assumes that all power batteries are retired with average life, but this paper assumes that retired power batteries follow a Weibull distribution to avoid centralized abandonment of batteries; (3) the former uses a larger battery weight assumption, such as EPC and hybrid passenger car battery pack weights, which is approximately twice as much as we assume; and (4) the sales volume of new energy vehicles predicted by the former is slightly higher than that predicted in this paper.

3.4. Echelon and recovery utilizations

3.4.1. Potential quantity

TABLE A18 and Fig. 16 indicates the potential of echelon and recovery utilization of EOL LIBs from 2010 to 2036. Overall, the potential of the three business models is expanding, and the growth rate of echelon utilization is less than that of recovery utilization. The potential of echelon utilization is greater than that of recovery utilization from 2010 to 2023, but the potential for recycling is growing faster from 2024 to 2036, and it will exceed the potential for echelon utilization. LIPB technology developed much earlier, and more ECV-LIPBs were sold in this period. In the near future, the retired batteries mainly come from LIPBs, which means that echelon utilization industry will have better development and the scale of recycling industry is relatively smaller. However, the demand and retirement of TLBs are increasing with the development of TLB and the growth of passenger car sales.

3.4.2. Potential economic value

LIPBs are used for echelon utilization and are recycled after 5 years. The potential of echelon and recovery utilizations is shown in Fig. 17 and TABLE A19. The economic value created by the three business models increases year by year. The economic value of annual echelon utilization is the highest because the cycle of echelon utilization is five years, so the annual cascade includes the retirement of LIPBs in the last

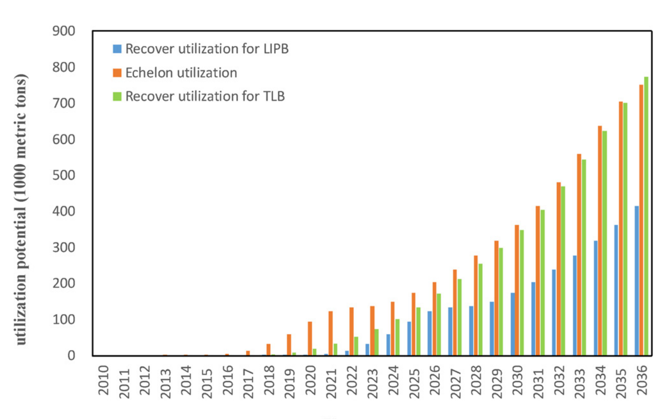

Fig. 16. Potential of echelon and recovery utilizations from 2010 to 2036.

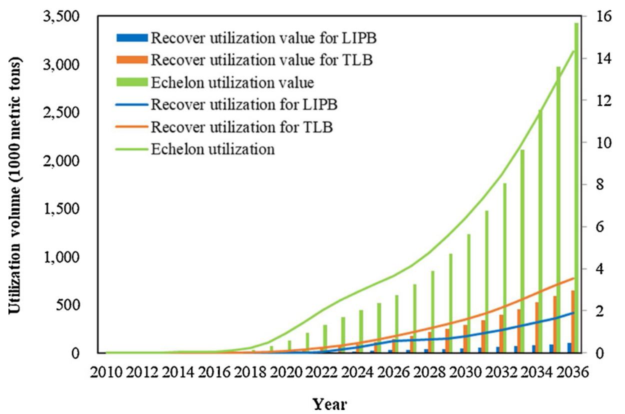

Fig. 17. Annual economic value of echelon and recovery utilizations from 2010 to 2036.

five years. LIPBs for recycling have the lowest economic value, mainly because they have a small amount of precious metals. TLBs for recycling also have high economic value because they contain more nickel, cobalt, manganese, lithium and other precious metals.

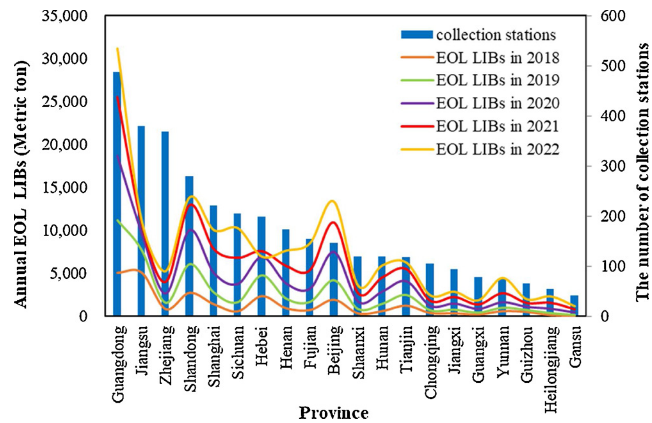

Fig. 19. Quantity of retired batteries from 2018 to 2022 and collection stations in 20 provinces.

3.5. Spatial distribution of EOL batteries

Fig. 18 illustrates the spatial distribution for EOL batteries in 20 provinces from 2018 to 2022 and the number of collection stations. According to the guidelines for the construction and operation of new energy vehicle power battery collection stations, collection stations shall be established by new energy vehicle enterprises and echelon

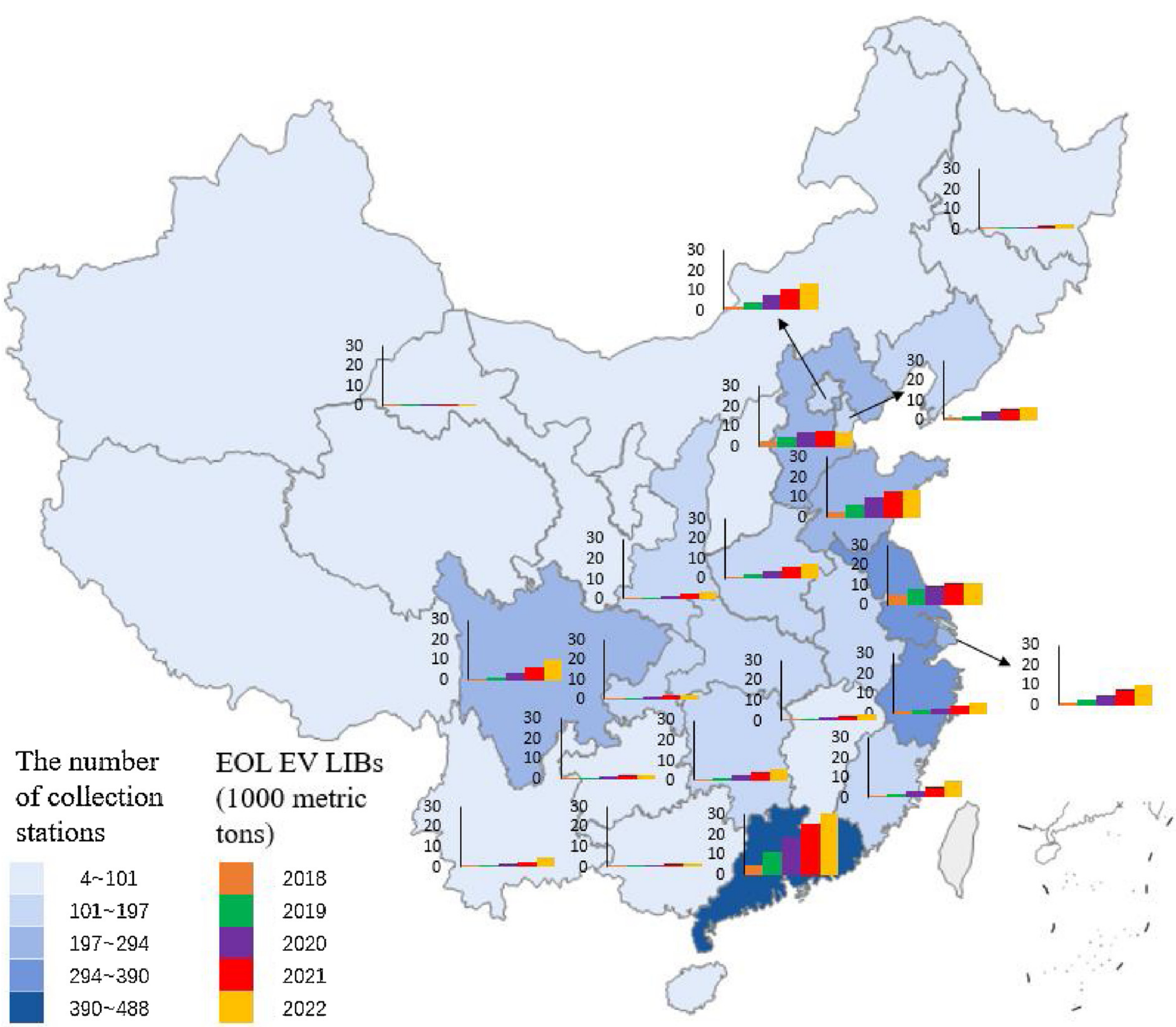

Fig. 18. Distribution of the collection amount of EOL EV-LIBs in 20 provinces.

utilization enterprise (MIIT-PRC, 2019a,b). After being selected, disassembled and assembled, the batteries flow to the recycling and cascade fields. Overall, the coastal provinces have more collection stations than inland provinces. Fig. 19 shows the generation of retired power batteries in 20 provinces from 2018 to 2022 and the number of collection stations in 20 provinces before July 1, 2019 (MIIT-PRC, 2019a,b).

We compare the retired quantity and collection station numbers in Fig. 19 and Fig. 20. Guangdong, Beijing, and Shandong will be the top 3 generators of retired batteries in 2022, with each generating more than 15 k tonnes. On the other hand, Guangdong, Jiangsu, and Zhejiang rank top 3 for the number of collection stations in 2019, which are higher than 300 in each province. Overall, 15 tonnes of retired batteries are recovered on average by each collection station nationwide, in China. The recoverable weight range for each station is from 5 to 30 tonnes. The average collection amount for each collection station in 8 provinces are less than 10 tonnes, while there are 5 provinces that have more average collection amount than 20 tonnes.

Although the average recycling capacity varies greatly among different provinces, we believe that most of them have sufficient recycling capacity. When building recycling station, companies take into account some institutions' predictions about EOL batteries. From the discussion above, we can see that the quantity of EOL batteries predicted by these institutions is even higher. According to the new energy vehicle power battery recycling service network construction and operation guidelines, the main task of the recycling station is to collect and temporarily store EOL batteries and the storage time shall not exceed one month for general collection stations (MIIT-PRC, 2019a,b). We believe that the main problem is not the recycling capacity of the collection stations but the standardization of the collecting, storage and transportation process.

In the recycling stage, there are some illegal recyclers, whose recycling technology is backward but the cost of recycling is low. By raising the price, these enterprises obtain a large number of retired power batteries. These enterprises will cause more environmental harm and reduce the profits of legitimate enterprises. The government should strengthen the supervision of this stage, for example, severely punish illegal recyclers and subsidize legal recyclers. Different types of batteries should be managed differently during storage and transportation due to different safety characteristics. For example, EOL batteries are stored separately and packaged differently according to the characteristics of different types of batteries. However, these management methods will greatly increase the cost of enterprises, so the government should balance the cost of enterprises and the safety management of batteries when publishing policies.

4. Conclusion

In this paper, we present a complete and accurate picture of EOL batteries in China for the first time. Considering the weight of different batteries and the service life increase caused by technology upgrades, our predictions are lower and more accurate than others' predictions. The generation of retired power batteries in China is predicted from 2020 to 2036, including 112 k tonnes in 2020 and 708 k tonnes in 2030. The retired LIPBs from BECVs and TLBs from BEPCs occupy the majority of retired batteries. The potential economic value of retired batteries for echelon and recovery utilizations are analyzed. Compared with the other two utilizations, the echelon utilization value is higher and can reach 15 billion U.S. dollars in 2036. The generation of retired power batteries in 20 provinces was estimated and compared with their collection station numbers. Overall, 15 tonnes of retired batteries are recovered on average by each collection station nationwide, in China.

Large-scale retired batteries will come later than previously anticipated. The echelon and recovery utilization capacities of the recycling industry for retired LIPBs and TLBs should be planned more rationally. Recycling enterprises should not blindly expand the recycling capacity, but should pay attention to the standardized management in collecting process, storage process and transportation process according to policy requirements. In the storage process, the enterprise must pay attention to the safety problem, separates the dangerous battery. Government must balance the costs of recycling with environmental hazards and develop viable management policies. In addition, because the quantities and types of retired batteries in different regions are quite different, the number of collection stations in main provinces should be planned based on this accurate retired amount. This study can provide data support for future research on the recovery of retired power batteries at national and provincial levels.

CRediT authorship contribution statement

Yufeng Wu: Methodology, Formal analysis, Data curation, Writing - original draft, Funding acquisition. **Liuyang Yang:** Software, Investigation, Writing - original draft, Formal analysis. **Xi Tian:** Conceptualization, Resources, Supervision, Project administration, Funding acquisition. **Yanmei Li:** Validation, Visualization. **Tieyong Zuo:** Writing - review & editing.

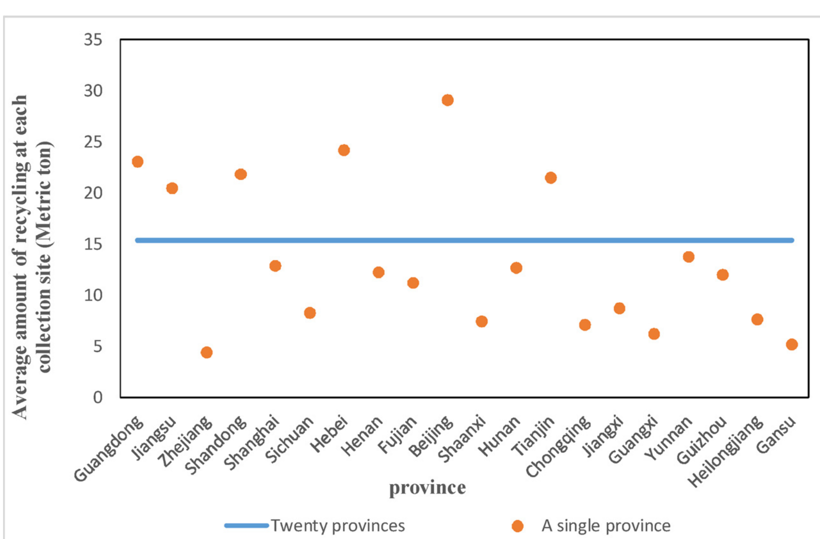

Fig. 20. Average collection amount for each collection station in the 20 provinces.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at https://doi.org/10.1016/j.resconrec.2019.104651.

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