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Electric vehicle recycling in China: Economic and environmental benefits

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ABSTRACT

With the rapid growth of electric vehicles in China, their benefits should be scientifically identified to support the industry development. Although the life cycle benefits of electric vehicles have been analyzed worldwide, the recycling phase has not been fully studied yet, especially in China. Actually, electric vehicle recycling is becoming more and more important because of the increasing demand of materials. Therefore, this study focuses on the economic and environmental benefits of electric vehicle recycling in China. Based on the technology adopted by leading enterprises, the gross income and reduction of energy consumption and greenhouse gas emissions are calculated to reveal the benefits. The life cycle economic and environmental impacts of recycling equipment are not included. The results indicate that the gross income per electric vehicle recycled is about 473.9 dollars, and the reductions of energy consumption and greenhouse gas emissions are about 25.6GJ and 4.1t CO_2eq, respectively. Furthermore, the environmental benefits per technology cost are about 241.3 MJ/dollar and 36.3 kg CO_2eq/dollar. The recycled metals are the major source of both economic and environmental benefits at present due to the huge amount, but the recycled cathode active materials will be more valuable with the development of traction batteries.

1. Introduction

Electric vehicles (EVs), especially Battery Electric Vehicles (BEVs), are designed in recent years to help deal with the increasingly serious environmental problems in the transportation sector in China. According to the Energy Saving and New Energy Vehicles Development Plan (2012–2020) (Chinese State Council, 2012), the ownership of New Energy Vehicles (NEVs) will reach 5 million towards 2020, and most of them will be EVs. The ambition is partly achieved in the past several years. Take EV industry as an example, China produced about 0.25 million EVs in 2015 and 0.38 million EVs in 2016, and the growth rate remained high in 2017 (China Association of Automobile Manufacturers (CAAM), 2017). Those evidences imply that EV development is a high priority in China now (Chinese State Council, 2015a), which ought to help China reduce the huge national Greenhouse Gas (GHG) emissions from fuel combustion (International Energy Agency (IEA), 2017). It might also help China achieve the emission reduction target in 2030, which aims to reduce 60–65% carbon emissions per unit of GDP in comparison with the level in 2005 (Chinese State Council, 2015b). Under such circumstance, scientific identification of the real benefits of EVs in China is quite necessary for the government to formulate detailed strategies on the development of EV industry (Hao et al., 2015).

Many scientists have already studied the entire life cycle performance of EVs in different regions. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (Argonne National Laboratory, 2017a) and the Ecoinvent Model (Ecoinvent Association, 2017) have already established comprehensive databases for further studies. Based on them, Hawkins has carried out complete life cycle assessments on different kinds of vehicles in Europe, revealing that the life cycle GHG emissions of an EV was about 200 g CO_2eq/km, about 10–20% lower than that of an ICEV. It could work for GHG emission reduction if well managed with the green battery production, low-carbon electricity and EV recycling (Hawkins et al., 2013). In the U.S., Mayyas has pointed out that an EV emitted about 60 t CO_2 during its lifetime, over 30% lower than it of an ICEV. This was not as good as expected due to the emissions rates in the U.S. electricity sector (Mayyas et al., 2017). On the other hand, Bauer has paid more attention to different phases of EVs' life cycle, indicating that the development of EV should be accompanied by manufacturing improvements as well as energy policies (Bauer et al., 2015). For more details, some scholars have broken the entire life cycle into specific phases. Bicer and Dincer (2017) and Huo et al. (2015) have both carried out Well-to-Wheel (WTW) assessments for of EVs. Qiao et al. (2017) has paid attention to

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the Cradle-to-Gate (GTG) performance of EVs. They have provided specific results for the environmental performance of EVs in each phase. These studies have pointed out that compared with Internal Combustion Engine Vehicles (ICEVs), EVs emit more GHG during the manufacturing phase and less GHG during the use phase. Therefore, reducing the GHG emissions of EV manufacturing will be one of the major concerns to seize further environmental benefits.

Under such circumstance, using recycled and recovered materials is considered an important method. In fact, EV recycling can help reduce about 35% of the energy consumption and GHG emissions during its manufacturing phase (Qiao et al., 2018). Scholars have already studied the recycling through different methods but none of them has built a systematic economic and environmental evaluation framework.

From the vehicle (without battery) point of view, Soo has estimated the environmental impacts of End-of-Life Vehicle (ELV) recycling in Australia and Belgium but did not analyze the economic benefits (Soo et al., 2017). Pan has studied the cost and environmental impacts of ELV recycling in China. The total cost was about 0.14 yuan/kg in 2016, and the results were informative since the author employed a real enterprise case (Pan and Li, 2016).

From the battery point of view, Gaines has estimated the life cycle cost of Li-ion battery comprehensively and pointed out that the battery recycling cost through hydrometallurgical process was about 5 dollar/kg in 2000 (Gaines and Cuenca, 2000), which was quite important for further studies. Based on this study, Gaines has predicted the future recycling techniques through economical and sustainable options (Gaines, 2014). Swain has systematically reviewed the existing Li-ion battery recycling techniques and estimated their environmental benefits (Swain, 2017). Dunn has analyzed the environmental benefits in different recycling scenarios in the U.S., but has not considered the economic problems (Dunn et al., 2015).

For entire EVs, only a few articles exist currently and most of them are not comprehensive enough. Delucchi has calculated the life cycle cost of EVs and ICEVs but the recycling process was simplified as a small part of battery disposal (Delucchi and Lipman, 2001). Noori has estimated the life cycle emissions and cost of EVs in the U.S., but the cost and revenue of recycling technique was not considered (Noori et al., 2015). Wu et al. (2015) and Rusich and Danielis (2015) have both considered this topic from the ownership perspective, but have not included the actual recycling techniques in factories. Kara has analyzed the life cycle cost of EV in Australia and the recycling cost was estimated through the given approximated price (Kara et al., 2017). Hao has studied the EV recycling process in details and estimated the environmental benefits, but the author has not paid attention to the economic problems (Hao et al., 2017b).

In short, existing literatures have provided important results about the recycling techniques, life cycle environmental impacts and life cycle costs of EVs separately. However, most of them have not studied the recycling techniques in details to reveal different impacts including the cost, revenue and GHG emissions of each recycling stage. Actually, for the economic and environmental affairs, many former studies are more concerned about the macro influence, which means that taking the whole life cycle of EV into consideration. These results are very important but must be supported by specific researches about each phase. Among all phases, EV recycling is extremely important because it can help reduce the high GHG emissions of EV manufacturing without improving the energy structure. The economic and environmental benefits of EV recycling are necessary for further studies and for the government and enterprises to make policies and strategic decisions, which are currently not available for most countries.

This study aims to provide a systematic and scientific evaluation on the EV recycling in both economic and environment sectors. China is chosen as the target region since it produced nearly half of the EVs worldwide (Organisation Internationale des Constructeurs d'Automobiles (OICA), 2016). In order to reveal the whole picture, the Life Cycle Assessment (LCA) framework is employed and China-specific database and factors are included in this study.

Table 1
Parameters of the EV model in China.

Vehicle specification		Vehicle without battery	Traction battery
Basic parameter	Type	A0 ~ A Class	NMC
	Weight (kg)	1300	164
	Capacity (kWh)	/	27
Material composition	Steel	66%	2%
	Aluminum	7%	26%
	Iron	2%	0%
	Copper	6%	25%
	Cathode active material	/	28%
	Others	19%	19%
Source		Argonne National Laboratory (2017a), Burnham (2012), CPCA (2017)	Argonne National Laboratory (2017b), Dunn et al. (2012), CAAM (2016)

Note: 1. 'Others' refers to the materials that are generally not recycled, including plastic, electrolyte, electronic parts, etc.

2. Methodology

2.1. Vehicle specification

Since this study focuses on the EV recycling in China, one of the most important things is to identify a typical EV model that can represent the general situation in China. According to the production and sales of EVs in China from 2016 to 2017, most of the EVs are among A0 to A class passenger vehicles with conventional materials (China Passenger Car Association (CPCA), 2017). Due to the lack of detailed parameters of EVs in China, this study employs most of the parameters of the same vehicle type and class from the Automotive System Cost Model (ASCM) as well as the GREET model (Argonne National Laboratory, 2017a), which are estimated based on a large range of resources, including dismantling reports and enterprise investigations. The parameters of several components are partly modified according to Burnham's research and assumptions about the weight (Burnham, 2012). As shown in Table 1, all the parameters have been scaled down because EVs in China are relatively smaller than those in the U.S. Furthermore, most of the components of an EV are similar with those of an ICEV. The traction battery is the major difference. Therefore, this study divided the entire EV into two parts: vehicle without battery and traction battery.

For more details about the traction battery, the reference traction battery is recognized through the market share and development trends in China. Most of the EVs produced currently in China use $Li(Ni_xCo_yMn_{1-x-y})O_2$ (NMC) batteries and $LiFePO_4$ (LFP) batteries. However, with the progress of technology, NMC battery is more likely to dominate the traction battery industry in China and has already occupied a larger market share (China Association of Automobile Manufacturers (CAAM), 2016). Therefore, this study considers NMC battery as the reference traction battery in EVs. Since the battery production technology in China is still developing, the detailed parameters of NMC battery are primarily employed from the Battery Performance and Cost (BatPaC) model (Argonne National Laboratory, 2017b). The parameters are revised according to Dunn's analysis on the energy density of battery, which is about 165 kW h/t (Dunn et al., 2012). Since the capacity of traction batteries of best-selling EVs in China is about 27 kW h, the weight of batteries can be estimated accordingly.

Table 1 presents the detailed parameters of EV model in China chosen in this study and its material composition. The weight of the vehicle without battery is about 1300 kg, while the capacity of NMC battery is about 27 kW h. Since the employed energy density of NMC battery is about 165 kW h/t, the weight of NMC battery in this EV model is about 164 kg. Generally, the NMC battery consists of metals, cathode active materials, graphite, electrolytes, plastic, thermal insulation, coolant, electronic parts, etc. The cathode active material is the most important part for traction battery. It significantly influences the cost, energy density and safety of the battery. As mentioned above, $Li(Ni_xCo_yMn_{1-x-y})O_2$ is used as cathode active material for NMC battery. Since the metals and cathode active materials account for about 81% of the total weight and are the major parts to be recycled, Table 1 only presents these two parts in detail. For more information, graphite is used as the anode material. Electrolytes include LiPF6, ethylene carbonate and dimethyl carbonate. Plastic refers to polypropylene, polyethylene and polyethylene terephthalate. The coolant is always glycol. All of these materials account for about 19% of the total weight.

The parameters of the EV model in this study are similar to Beijing Automotive Industry Corporation (BAIC) EC (1.1t, 20 kW h NMC battery), Jianghuai Automobile Company (JAC) iEV (1.3t, 23 kW h LFP battery) and Geely Emgrand EV (1.5t, 40 kW h NMC battery) (Ministry of Industry and Information Technology, 2017), which are the best-selling EV models in China 2017. Therefore, the employed EV model is typical enough to reflect the real situation in China, which ensure that this study has meaning both in theory and in reality.

2.2. Recycling process

Fig. 1 presents the entire process of EV recycling. End-of-life EVs are pre-treated and dismantled by the recycling enterprises at the beginning, which aims to separate different components and then send some of them to particular recycling institutions (Halabi et al., 2015). In addition, some special parts and fluids that are hard to recycle are removed and landfilled before dismantling in order to reduce the environment hazards (Santinia et al., 2011). Since this step is quite simple, it is generally carried out by manual labor, especially in China. After dismantling, the end-of-life EV is divided into two parts, which are recycled in different ways. The traction battery is the most important component of an EV, and the battery recycling is the most important stage of the entire EV recycling. Therefore, this study have comprehensively analyzed the technology and benefits of battery recycling, and briefly summarized the vehicle (without battery) recycling.

For the vehicle without battery, most components are shredded by machines before further treatments. Tires are recycled independently through ambient grinding, dynamic devulcanization and refining to get recoverable materials (Li et al., 2010). A few iron and copper scraps can be obtained in the shredding step (Belboom et al., 2016), but most of the valuable metals remain in the After Shredding Residue (ASR). The post-shredding treatment, also called ASR management, is the most important step among vehicle (without battery) recycling. According to the developed technology worldwide, mechanical sorting is applied to obtain materials, and thermal treatment is applied to generate energy (Cossu and Lai, 2015). Various methods are used to improve the efficiency and security of ASR treatment, including air classification, magnetic separation, cleaning, sinking, etc. Not only metals, but also plastics can be obtained through effective ASR treatments to get economic and environmental benefits (Duval and MacLean, 2007). However, due to the technology limitation in developing areas, most of the advanced ASR treatments are not available for the mainstream (Cheng et al., 2012). Enterprises in China have only employed the primary stage of ASR treatment, including magnetic machine and heavy media separation, aiming to get valuable metal scraps, which is profitable and requires low technology level (Li et al., 2016). Therefore, this study has revised the vehicle (without battery) recycling process according to the enterprise investigations and literatures, which can reflect the real situation in China.

For the traction battery, Li-ion battery was first recycled in late 1999 by Sony and Toxico, which was renamed as Retriev Technologies (Gaines and Cuenca, 2000). After years of development, there are now two major recycling technologies: pyrometallurgical process and hydrometallurgical process. Pyrometallurgical process mainly consists of smelting and leaching. The end-of-life battery is smelted into an alloy of iron, copper, cobalt and nickel first. Then the metals are recovered through leaching. Hydrometallurgical process mainly consists of caustic bath, sinking and sintering. It is more complicated and needs specific environment. The lithium salts can be dissolved through caustic bath. Then they are precipitated and dewatered through sinking. The salts are finally used to recover lithium carbonate.

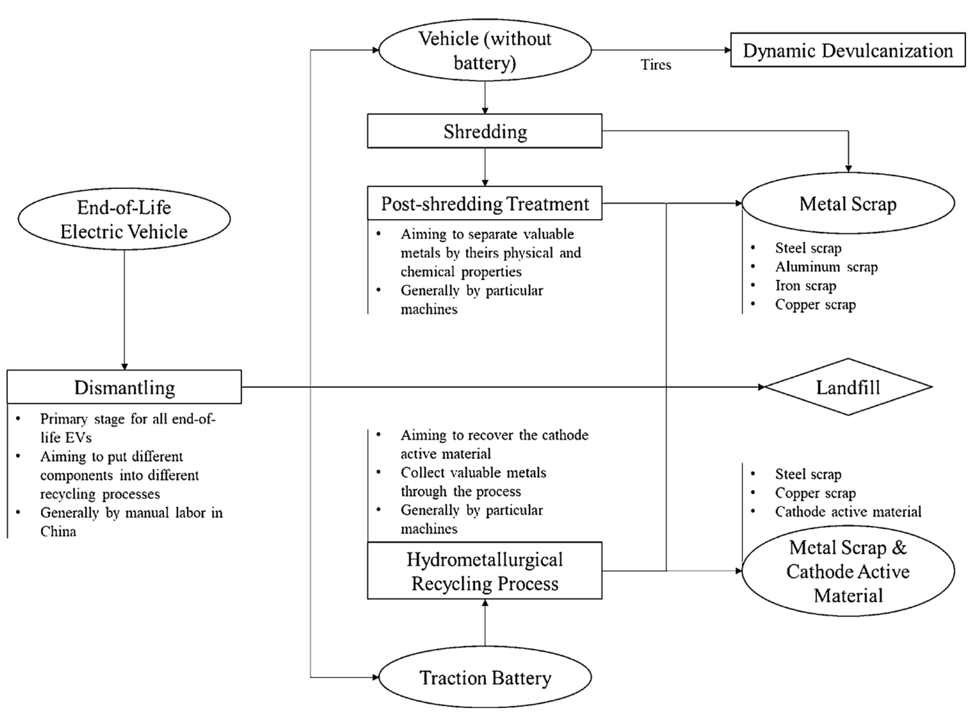

Fig. 1. End-of-life EV recycling process.

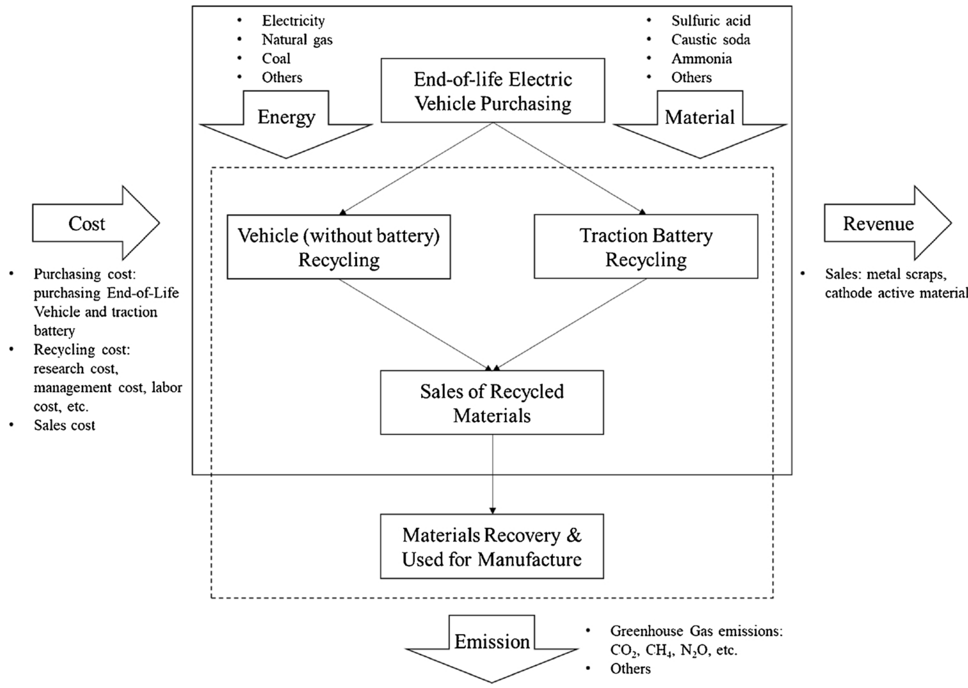

Fig. 2. Scope for evaluation of EV recycling.

Due to the fact that pyrometallurgical recycling process cannot recover lithium, hydrometallurgical process is more likely to be further developed (Georgi-Maschler et al., 2012). In other words, although pyrometallurgical process is adopted commercially now, it might not be suitable for new designed NMC or LFP batteries (Gaines, 2014). Furthermore, the leading battery recycling enterprises, such as Brunp, have already imported the original hydrometallurgical process once used by Retriev in early times (Xie et al., 2015). Actually, Retriev no longer uses hydrometallurgical process for battery recycling, but some other enterprises in Europe, such as Euro Dieuze and Recupyl, still adopt this technology. Therefore, this study employs the hydrometallurgical process as the reference technology, which aims to recover most of the cathode active material and a few metals.

2.3. Scope identification

In order to reflect the scientific economic and environmental benefits of EV recycling, this study has identified a complete scope for analysis as presented in Fig. 2, including purchasing end-of-life EVs, entire recycling process and sales of recycling products. The recovery process of metal scraps is also taken into consideration for environmental benefit evaluation. The manufacturing of new EVs using the recycled materials is considered as a reference when evaluating the environmental benefits since it can reduce the environmental impacts in comparison to manufacturing of EVs using virgin materials.

It is important to note that this study does not consider the fixed cost of adopting new recycling technology and devices, as well as their life cycle GHG emissions, which will be diluted with the increase of capacity. That is to say, since this study aims to evaluate the economic and environmental benefits of a completely established recycling process, the entry barrier for new entities is not considered. Therefore, the economic and environmental benefits will be higher than them seem to be.

The economic benefits can be evaluated by the cost and revenue of an EV recycling enterprise. In this study, cost is divided into purchasing cost and recycling cost, among which purchasing cost refers to the cost of purchasing an end-of-life EV, and recycling cost refers to the cost of the recycling process, including research cost, management cost, labor cost, etc. Revenue is defined as the income from sales of recycling products, such as steel scraps, aluminum scraps, cathode active materials, etc.

Battery recycling has different kinds of environmental benefits, including the reduction of GHG and SO_x emissions. Actually, battery recycling can bring significant SO_x emission reduction benefit (Gaines, 2014). According to the evaluation by other scholars, the SO_x emissions during the production of NMC/LFP cathode materials can be reduced by nearly 100% if they are recovered properly instead of produced from virgin materials. The reduction rate is high even for pyrometallurgical process which consumes huge amounts of energy because much SO_x is emitted directly and indirectly during the manufacturing process (Dunn et al., 2015). At the same time, further SOx emissions happen when the end-of-life battery is not treated well. The benefit of SO_x reduction is extremely important because it can evidently reduce air pollution, and it could be an important reason for battery recycling in the future (Gaines, 2014). However, as mentioned above, this study aims to reveal the energy consumption and GHG emission benefits, the specific SO_x emission reduction benefit is not estimated. Considering the specific technologies of virgin battery production and battery recycling, the environmental benefits are represented by the reduction of energy consumption and GHG emissions through recycling in this study.

Generally speaking, EV recycling process consumes different kinds of materials and energy and produces metal scraps and recovered cathode active materials. Life cycle GHG emissions from the consumed energy and materials have to be estimated and regarded as negative environmental impacts. At the same time, since the metal scraps can be used after recovery for manufacturing instead of virgin materials, the potential reduction of life cycle energy consumption and GHG emissions by the replacement have to be estimated and regarded as positive environmental impacts. The comprehensive environmental benefits are the difference between these impacts.

2.4. Calculation and data

Eqs. (1) and (2) evaluate the economic benefits of EV recycling. As formerly described, the benefits are considered as the revenue from sales of recycled products minus the cost of purchasing and recycling.

Furthermore, in order to keep comparability, all the cost and revenue are standardized based on the U.S. dollar value in China 2017 through the average inflation rate, average exchange rate and price level ratio of purchasing power parity conversion factor to market exchange rate.

$$IT = \sum PM,i \times QM,i - (CP + \sum CR) \tag{1}$$

In Eq. (1),

IT denotes the total economic benefits of EV recycling,
PM,i denotes the price per unit of material i recycled,
QM,i denotes the amount of material i recycled,
CP denotes the cost of purchasing,
$\sum CR$ denotes sum of the cost during recycling process.

$$V2017,C = [Vt,i + \prod_t^{2017} IFt \times (PL2017,C/PL2017,i)]/ER2017,U,i \tag{2}$$

Eq. (2) is used for the standardization of values in different countries and different years, where

$V2017,C$ denotes the standardized value in China 2017,
Vt,i denotes the value in country i currency and year t,
IFj denotes the inflation rate of country i in year t,
$PL2017,C$ and $PL2017,i$ denote the price level ratio of purchasing power parity conversion factor to market exchange rate of China and country i in 2017, respectively,
$ER2017,U,i$ denotes the country i currency against the U.S. dollar exchange rate in 2017.

Eqs. (3) and (4) evaluate the reduction of GHG emissions through EV recycling. The reduction of energy consumption can also be evaluated in this process. The life cycle energy consumption and GHG emissions from all the energy and materials input are taken into consideration, and the potential reduction is calculated through the difference between energy consumption and GHG emissions from recycled and virgin materials.

$$ET = \sum (MEV,i - RER,i) \times Qi - ER \tag{3}$$

In Eq. (3), ET denotes the total reduction of GHG emissions,
MEV,i and RER,i denote the life cycle GHG emissions of virgin and recycled material i, respectively,
Qi denotes the amount of material i consumed by the vehicle,
ER denotes the GHG emissions from recycling process.

$$ER = RY + \sum IPj \times EFj \tag{4}$$

In Eq. (4), RY denotes the GHG emissions from recycling process,
IPj denotes the input of energy or material j during the recycling process,
EFj denotes the life cycle GHG emission factor of energy or material j.

According to the equations, data essential to calculate the economic benefits are listed in Tables 2 and 3. Cost of vehicle (without battery) recycling is divided into purchasing cost, recycling cost and selling cost. Purchasing cost data are obtained through enterprise investigations in China, and recycling and selling cost (cost of sales dealers, products storage and transportation) data are collected from the Green Eco-Manufacturer ELV Recycling company in Fengcheng, Jiangxi province (Pan and Li, 2016). It employs a commonly used dismantling and recycling technology and collects metal scraps by machines, which is representative enough to reveal the situation in China. Furthermore, all of the costs are in the form of CNY value in China 2015, so it has to be converted to the USD value in China 2017 to ensure comparability.

Cost of traction battery recycling consists of purchasing cost and recycling cost, while selling cost is not considered due to the close cooperation between battery recycling enterprises and battery manufacturers in China. Purchasing cost is collected from the investigation of Chuangneng Recycling Company in Shenzhen, China, who pays attention to NMC battery recycling. Since the NMC battery recycling

Table 2
Cost and revenue of EV recycling.

Cost of recycling		2001 USD	2015 CNY	2017 USD
Vehicle (without battery) (per kg input)				
Purchasing		/	0.07	0.08
Vehicle recycling	Management	/	0	0
	Labor	/	0.01	0.01
	Maintenance	/	0	0
	Research cost	/	0.01	0.01
	Depreciation	/	0.02	0.02
	Other	/	0.02	0.03
Selling		/	0.01	0.01
Source		Pan and Li (2016); Enterprise investigation		
Traction battery (per kg input)				
Purchasing		3.86	/	2.87
Battery recycling	Combination	5.00	/	3.73
Source		Gaines and Cuenca (2000); Enterprise investigation		
Revenue (per kg)				
Steel scrap		/	/	0.27
Aluminum scrap		/	/	1.90
Iron scrap		/	/	0.16
Copper scrap		/	/	5.61
NMC		/	/	27.01
Source		Wind Financial Database (2017), China Bulk Commodity (2017)		

Note: 1. The unit "per kg input" refers to the value per kg of end-of-life vehicle (without battery) or battery input to the recycling process.
2. The cost of vehicle (without battery) recycling is provided in terms of CNY value in China in 2015 and the cost of battery recycling is provided in terms of USD value in the U.S. in 2001.
3. Values in different terms are standardized into USD value in China in 2017 through average inflation rate, price level and exchange rate as presented by Table 3.

technology employed in this study is the original hydrometallurgical process, which is adopted by some leading enterprises in China, such as Brunp, the recycling cost can be estimated through the original cost data provided in 2001 (Gaines and Cuenca, 2000).

In order to estimate the revenue of EV recycling, this study employs the average prices of metal scraps (Wind Financial Database, 2017) and ternary lithium commodity (China Bulk Commodity, 2017) in China 2017.

Furthermore, different costs and prices in different regions and years should be standardized into USD value in China in 2017 to ensure comparability. Therefore, this study takes average inflation rate, price level ratio and exchange rate into consideration as presented by Table 3. Average inflation rate are effective annual rate from 2001 to 2017 in China and the U.S. (International Monetary Fund (IMF), 2017). Price level ratio refers to the number of units of USD needed to buy the same goods in the China as one unit of USD can buy in the U.S. (World Bank, 2017). Exchange rate is the average CNY/USD exchange rate in the first half 2017 (International Monetary Fund (IMF), 2017).

Table 4 presents the environmental benefits of EV recycling. Several Chinese scientists have already estimated them in case of China 2025 (Hao et al., 2017b). They have assessed the energy consumption and GHG emissions of the entire grave-to-gate phase of EVs and material recovery in China. The technology employed in that study is also hydrometallurgical process, including caustic bath, sinking and sintering, which is the same as in this study. Their data are collected from the GREET model and some battery recycling enterprises like Brunp in China, and the life cycle GHG emission factors of different materials and energy are generated based on China's situation. This study has modified the results according to the updated vehicle model assumption and calculated the environmental benefits through Eqs. (3) and (4).

The major products of vehicle (without battery) recycling are metal scraps, including steel, aluminum, iron and copper scraps. Most of the scraps cannot be used directly for manufacturing. According to Hao's

Table 3
Macroeconomic parameters for calculation.

Parameters	2011–2015	2015–2017	2017
Average inflation rate (U.S.)	2.2%	1.2%	/
Average inflation rate (China)	2.4%	1.7%	/
Price level ratio (CNY/USD)	/	/	0.52
Exchange rate (CNY/USD)	/	/	6.62
Source	International Monetary Fund (IMF) (2017)		World Bank (2017), International Monetary Fund (IMF) (2017)

Note: 1. Exchange rate changes continuously and this is the average exchange rate in the first half 2017.

Table 4
Environmental benefits of EV recycling.

Environmental impacts	Vehicle (without battery)	Traction battery
Energy consumption (MJ/kg)	13.18	15.20
GHG emissions (kg CO_2eq/kg)	2.36	4.21
Products (kg/kg)		
Steel scrap	0.65	0.18
Aluminum scrap	0.04	0
Iron scrap	0.23	0
Copper scrap	0.03	0.10
NMC	0	0.25
Reduction of energy consumption compared with virgin materials (MJ/kg)		
Recycled steel	32.46	
Recycled aluminum	57.40	
Recycled iron	0.84	
Recycled copper	19.28	
NMC	125.36	
Reduction of GHG emissions compared with virgin materials (kg CO_2eq/kg)		
Recycled steel	4.40	
Recycled aluminum	15.40	
Recycled iron	0.37	
Recycled copper	4.65	
NMC	38.87	
Source	Hao et al. (2017b); Original calculation	

Note: 1. The units "MJ/kg", "kg CO_2eq/kg" and "kg/kg" refer to the energy consumption (MJ), GHG emissions (kg CO_2eq) and recycling products (kg) per kg of end-of-life vehicle (without battery) or battery input to the recycling process, respectively.

study (Hao et al., 2017b), the data about the recovery of steel scraps, aluminum scraps, iron scraps and NMC cathode active material are collected from recycling enterprises in China, and the energy consumption and GHG emissions of recovery of copper scraps are imported from GREET model because of the lack of data in China. For example, steel scraps should be recovered through electric arc furnace process before being used instead of virgin steel, which causes about 1.79 kg CO_2eq/kg and saves 4.40 kg CO_2eq/kg in comparison with virginal production. Aluminum scraps should be refined through secondary ingot casting process, and it can save about 15.40 kg CO_2eq/kg in comparison with primary ingot production. Iron and copper scraps also needs further treatments like refining. Some of these metal scraps can be obtained through battery recycling as well, but the most important product of battery recycling is the cathode active material. Actually, some kind of post-recycling treatment is necessary for the cathode active material recovery. For NMC batteries, the sub-final recycled products should be sintered with lithium carbonate at the end of the process and get the final NMC materials, meaning that the recovery of NMC materials is included in the battery recycling process.

3. Results and discussion

3.1. Overview

Based on the vehicle specification and data presented in Tables 2–4, the comprehensive economic and environmental benefits of EV recycling can be calculated through Eqs. (1)–(4). This study divides the entire EV into vehicle (without battery) and traction battery, which is

Table 5
Economic and environmental benefits of EV recycling.

Benefits	Vehicle (without battery)	Traction battery	Total
Cost (dollar per EV)			
Purchasing	98.1	470.5	568.6
Technique	97.1	611.1	708.2
Sales	12.9	/	12.9
Total	208.1	1081.6	1289.7
Revenue (dollar per EV)			
Steel scrap	228.9	8.0	236.9
Aluminum scrap	101.3	0.0	101.3
Iron scrap	5.3	0.0	5.3
Copper scrap	225.1	91.6	316.7
Cathode active material	0.0	1103.5	1103.5
Total	560.6	1203.1	1763.7
Potential reduction of energy consumption per technology cost (MJ/dollar)			
Recycled steel	195.2	1.1	196.3
Recycled aluminum	28.4	0.0	28.4
Recycled iron	−0.3	0.0	−0.3
Recycled copper	8.0	0.5	8.5
Cathode active material	0.0	8.4	8.4
Total	231.3	10.0	241.3
Potential reduction of GHG emissions per technology cost (kg CO_2eq/dollar)			
Recycled steel	23.3	0.1	23.4
Recycled aluminum	8.2	0.0	8.2
Recycled iron	0.1	0.0	0.1
Recycled copper	1.9	0.1	2.1
Cathode active material	0.0	2.6	2.6
Total	33.5	2.9	36.3
Net profit per EV recycling			
Gross income (dollar)	352.4	121.5	473.9
Reduction of energy consumption (MJ)	21,709.5	3921.9	25,631.4
Reduction of GHG emissions (kg CO_2eq)	3030.8	1109.7	4140.6

Note: 1. The units "MJ/dollar" and "kg CO_2eq/dollar" refer to the reduction of energy consumption and CO_2 emissions per recycling technology cost, respectively.

necessary for further analysis. All the results are shown in Table 5. In short, the total gross income per EV recycled is about 474 dollars. Since the revenue is estimated through the price of recycling products, it has to be mentioned that the net present value might be reduced because the scraps are always recovered after about 10 years and the inflation rate is likely to keep positive. The potential reduction refers to the amount reduced in the manufacturing phase if recycled materials replace virgin materials, when the energy consumption and GHG emissions during the recycling and recovery phase are also taken into consideration. The potential reduction of energy consumption and GHG emissions are 2.6GJ and 4.1t CO_2eq, respectively.

For more details, as presented in Fig. 3, the technology cost of battery recycling is extremely higher than that of vehicle (without battery) recycling, causing the relatively low gross income. On the other hand, although NMC battery only accounts for about 11% of the total weight, the economic and environmental benefits of NMC battery recycling account for over 30% of the total benefits. Further discussion will be carried out in the following sections.

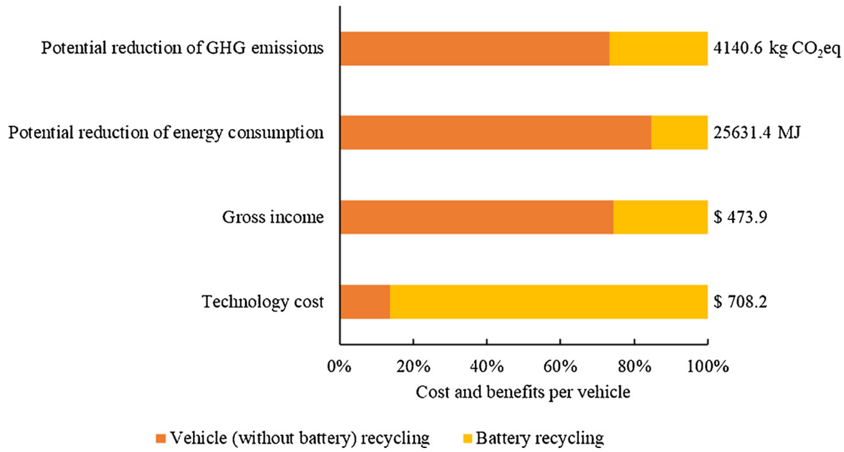

Fig. 3. Overall economic and environmental benefits of EV recycling.

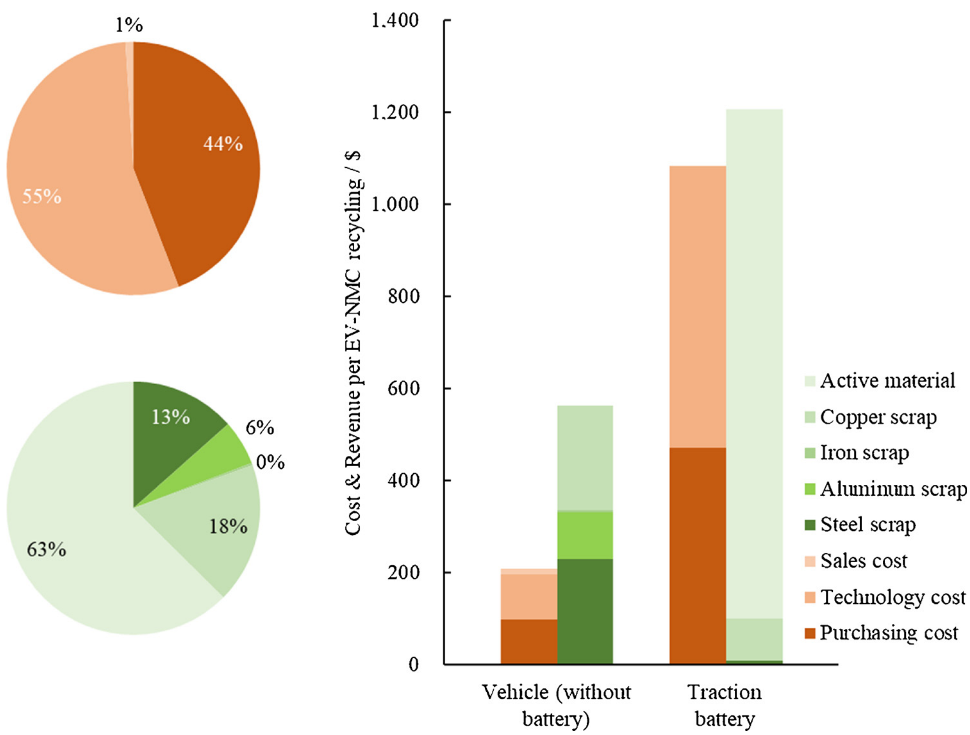

Fig. 4. Cost and revenue of EV recycling.

3.2. Discussion

Considering the cost and revenue of EV recycling, according to Fig. 4, the technology cost accounts for about 55% of the total cost, followed by the purchasing cost, which accounts for 44% of the total cost. Sales cost is extremely low due to the close relationship between recycling enterprises and manufacturers. Although the cathode active material (NMC) only accounts for about 4% of all the products by weight, the revenue of it accounts for about 63% of the total revenue, revealing its high value. In contrast, the value of steel scraps is much lower, but it still brings about 13% of the total revenue due to the larger weight. The results have clearly indicated the importance and large potential market of battery recycling.

On the other hand, the cost and revenue of traction battery are both higher than those of vehicle (without battery) recycling, which is mainly caused by the recycling technologies and products. As mentioned in former sections, the vehicle (without battery) recycling technology is mature and relatively simple, which can be conducted manually in some steps, while battery recycling consists of complex physical and chemical processes consuming a large number of materials input. However, the major product after battery recycling is the cathode active material, such as NMC, which brings extremely large benefits to the battery recycling enterprises.

Comprehensively speaking, the gross income of vehicle (without battery) recycling is about 352 dollars, which is higher than that of battery recycling, 122 dollars. However, the gross income of battery recycling per unit of weight will be higher as it only accounts for about 11% by weight. Furthermore, the gross income of battery recycling will be higher with the development of recycling technology, which is currently at a primary stage.

For the environmental benefits, Fig. 5 presents the reduction of energy consumption and GHG emissions per technology cost. Since the environmental benefits are obtained through the technical process, the purchasing cost and sales cost are not included. Clearly, the total values are about 241.3 MJ/dollar and 36.3 kg CO_2eq/dollar. The reduction through vehicle (without battery) recycling is much higher than that

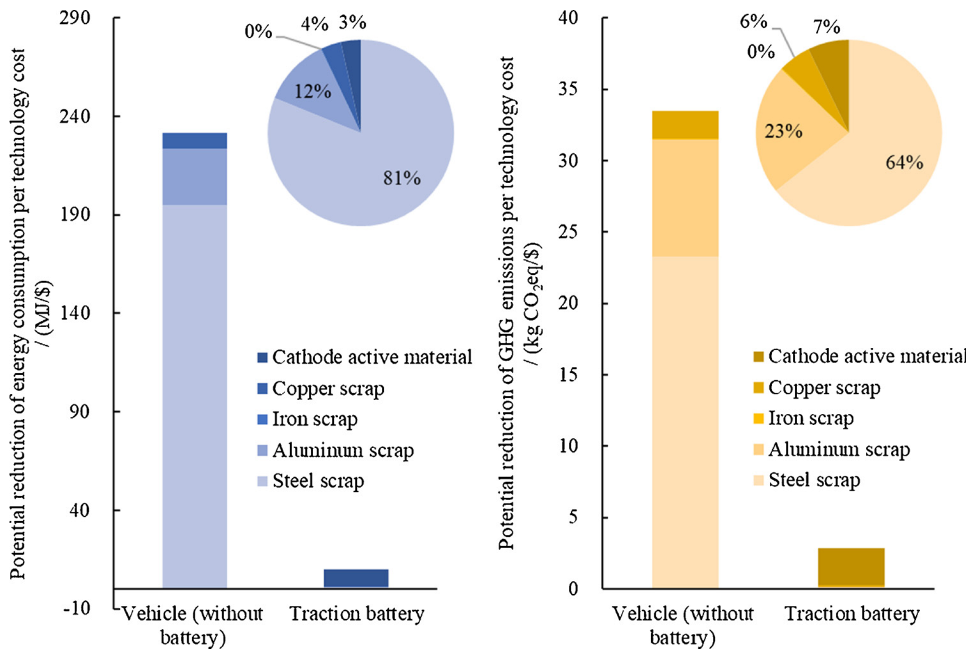

Fig. 5. Environmental benefits per technology cost of EV recycling.

through battery recycling. The huge amount of recycled steel brings about 81% of the total reduction of energy consumption per technology cost, and the number for GHG emissions is about 64%. Aluminum recycling is also an important source of environmental benefits (Hao et al., 2016), which brings about 12% and 23% of the total reduction of energy consumption and GHG emissions per technology cost, respectively.

Since the energy consumption and GHG emissions of battery recycling is relatively high, battery recycling seems to contain low environmental benefits. However, it can provide recycled cathode active material, which is the most important and expensive part in the traction battery (Hao et al., 2017a). On the other hand, the environmental benefits of battery recycling is more likely to be improved with the development of technology since the it is not developed enough in China.

Comprehensively speaking, the economic benefits and environmental benefits both reflect the importance of vehicle (without battery) recycling at present, while the development of battery recycling technology is essential in the future. Actually, due to the large weight and mature technology, vehicle (without battery) recycling brings relatively large benefits in both fields. However, it is not likely to be significantly improved in the near future since the vehicle (without battery) recycling and metal recovery technology is relatively stable. On the other hand, with the development of EVs in China, the demand for Li-ion batteries is increasing, and the recycled cathode active material will be more valuable, which will bring more benefits to battery recycling.

4. Conclusion

In this study, the economic and environmental benefits of EV recycling in China have been estimated based on the current recycling technology. The fixed economic and environmental influence of adopting advanced recycling technology and purchasing recycling devices is not included according to the scope of this study. The results indicate that the gross income per EV recycling is about 473.9 dollars, and the reductions of energy consumption and GHG emissions are about 25.6GJ and 4.1t CO_2eq, respectively. If taking technology cost into consideration, the values are about 241.3 MJ/dollar and 36.3 kg CO_2eq/dollar. Due to the huge amount of metal scraps obtained through vehicle (without battery) recycling, it is the major source for both economic and environmental benefits at present. However, battery recycling can provide cathode active material, which will be more valuable with the development of EVs in China. On the other hand, since the battery recycling technology adopted in China has not been fully developed, there will be some potential benefits in the future. Furthermore, the gross income per EV recycling is significantly influenced by the recycling products. The accuracy of recycling products is more likely to influence the reliability of the results in this study.

There are also some limitations in this study. For example, the assumptions about EV model and recycling technology are made based on the average situation in China, which may cause deviations if considering specific affairs. Furthermore, although this study has provided a scientific evaluation on the economic and environmental benefits of EV recycling in China at present, further studies based on other technologies are necessary to improve timeliness and accuracy.

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