Resources, Conservation and Recycling 122 (2017) 114–125

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The China 2025 case

Han Hao, Qinyu Qiao, Zongwei Liu, Fuquan Zhao*

State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 19 October 2016
Received in revised form 7 February 2017
Accepted 8 February 2017

Keywords:
Electric vehicle
Battery
Greenhouse gas emissions
Energy
Recycling
Life cycle assessment

ABSTRACT

Electric vehicle, as the most promising clean vehicle technology, has gained high priority in global transport technology roadmap. Although electric vehicles offer multiple benefits within the vehicle use phase, their energy consumption and greenhouse gas emissions within the vehicle production phase are much higher than conventional vehicles. Recycling is considered as an effective way to tackle this issue. By employing a life cycle assessment framework, this study compares the energy consumption and greenhouse gas emissions from electric vehicle production under the circumstances of no recycling and full recycling. Database is established based on the China 2025 case, where a large number of electric vehicles are expected to reach their end of life in the years to come. The results indicate that greenhouse gas emissions from electric vehicle production with and without recycling are 9.8 t CO_2eq. and 14.9 t CO_2eq., implying a 34% reduction through recycling. Specifically, the recycling of steel, aluminum and the cathode material of traction battery, among others, contribute to 61%, 13% and 20% of total reduction, respectively. Although the recycling of conventional vehicle components currently contributes the most to the overall reduction, the recycling of battery has a huge growth potential in the future. Based on the analysis, it is recommended that China should prioritize the recycling of electric vehicles, especially the batteries, to realize the cleaner production of electric vehicles.

1. Introduction

China has the world's largest vehicle market. Vehicle production in China reached 24.5 million in 2015, accounting for approximately one quarter of the global total (OICA, 2016). Over the past decade, China has given priority to the development of Electric Vehicles (EVs). China produced over 0.25 million EVs in 2015, four times higher than the 2014 level (CAAM, 2016a,b). The government aims that the sales of EVs and Plug-in Hybrid Electric Vehicles (PHEV) reach 2 million in 2020, and 5 million in 2025 (Chinese State Council, 2012). The life cycle environmental impacts of EVs can be divided into three phases: production, use and recycling. Many researches have revealed that although the energy consumption and Greenhouse Gas (GHG) emissions of EVs within the vehicle production phase account for a relatively small proportion when considering the whole life cycle, the values are much higher than those of conventional vehicles and cannot be ignored (Hawkins et al., 2013; Sharma et al., 2013; Tagliaferria et al., 2016). When it comes to the use phase, the dominant phase accounting for the largest proportion of the total life cycle energy consumption and GHG emissions of EVs, the values depend substantially on the energy structure in different regions (Nanaki and Koroneos, 2013). EVs can perform well only if non-fossil fuels are used for the power generation (Bauer et al., 2015). In China, the situation is severe due to limited manufacturing techniques and coal-dominated energy structure (Qiao et al., 2016), and the environmental benefits of EVs haven't met expectations (Wang et al., 2013). Recycling is considered as an effective way to tackle this issue.

Vehicle recycling has already attracted global attention. Globally, the number of End-of-Life Vehicles (ELVs) reached 40 million in 2010 and kept growing rapidly over recent years (Sakai et al., 2014). This leads to millions of tons of waste to be treated, within which huge potential of material recovery exists. In order to obtain

Abbreviations: ANL, Argonne National Laboratory; ASCM, Automotive System Cost Model; ASR, Automotive Shredder Residue; BatPaC, Battery Performance and Cost; BF-BOF, Blast Furnace-Basic Oxygen Furnace; CAAM, China Association of Automobile Manufacturers; EAF, Electric Arc Furnace; ELV, End-of-Life Vehicle; EV, Electric Vehicle; GHG, Greenhouse Gas; GREET, Greenhouse Gases Regulated Emissions and Energy Use in Transportation Model; ICEV, Internal Combustion Engine Vehicle; IPCC, Intergovernmental Panel on Climate Change; LCA, Life Cycle Assessment; NBSC, National Bureau of Statistics of China; NMC, $Li(Ni_xCo_yMn_{1-x-y})O_2$; OICA, Organisation Internationale des Constructeurs d'Automobiles; PHEV, Plug-in Hybrid Electric Vehicle.

* Corresponding author.
E-mail address: zhaofuquan@tsinghua.edu.cn (F. Zhao).

http://dx.doi.org/10.1016/j.resconrec.2017.02.005
0921-3449/

the largest environmental benefits from the treatment of ELVs, different strategies have been applied in many countries (Cossu and Lai, 2015). In the U.S., driven by the profit and regulations, about 95% of ELVs are recycled and over 80% of the vehicle by weight is recovered (Kumar and Sutherland, 2009). In Europe, the European Directive 2000/53/EC forces European Member States to take 85% of ELVs into recycling and the recovery rate should reach 95% by weight by 2015 (Santini et al., 2011). In Japan, the ELV recycling law has been put into force since 2005. Over 95% of ELVs are recycled (Zhao and Chen, 2011). In China, although a series of regulations have been promulgated since 2001, the recycling of ELV is still not well enforced, and many informal sectors are illegally treating ELVs, causing huge waste (Hu and Wen, 2015). Recently, much more detailed standards have been applied to ELV recycling (Zhao et al., 2016). For most of the regulations, the recycling requirements are based on the case of conventional Internal Combustion Engine Vehicles (ICEVs). As EVs only started to penetrate the market over recent years, there are still significant gaps in existing regulations on the recycling of EVs.

Under such circumstance, the energy consumption and environmental impacts of EV recycling should be evaluated to help the government enact new regulations. Currently, scholars have paid high attentions to the Life Cycle Assessment (LCA) of vehicle recycling from a grave-to-gate point of view. Gerrard and Kandlikar (2007) assessed the impacts of 2000/53/EC regulation on ELV recycling and analyzed the vehicle recycling techniques in Europe. Belboom et al. (2016) compared the life cycle environmental impacts of three different ELV dismantling techniques on the basis of industrial data in Belgium, finding that post shredding treatments could be developed for a higher material and energy recovery rate. Li et al. (2016) estimated the life cycle environmental impacts of end-of-life Corolla taxis in China. The author established a vehicle recycling scenario in China and took the material replacements into consideration, which formed a complete research framework for ICEVs. Cheng et al. (2012) studied the vehicle recycling in Taiwan and revealed that energy consumption during recycling process should be paid high attention.

Meanwhile, numerous studies focused on one or two stages of the vehicle recycling process. Halabi et al. (2015) carried out an LCA on advanced machine-based dismantling of ELVs, which provided an important supplement to this field. Vermeulen et al. (2011) conducted a study on the Automotive Shredder Residue (ASR) management, the most important stage after dismantling. The results indicated that ASR recovery might be a breakthrough for vehicle recycling. Cossu and Lai (2015) studied ASR management in another way. Their results revealed that energy recovery would play an important role. Besides, Diener and Tillman (2015) and some scholars evaluated the life cycle energy consumption and environmental impacts of the remanufacture for individual components, as well as the engine (Smith and Keoleian, 2004). And some other scholars studied the recovery of materials in recycled vehicles, for example, Ohno et al. (2015) evaluated the efficient and impacts of recovery of steel scrap derived by ELVs in Japan and provided important conclusions, and as well as copper (Brahmst, 2006) and plastic (Duval and MacLean, 2007).

On the other hand, with the development of EVs, more and more studies on the recycling of traction battery have been published in recent years. Espinosa et al. (2004) established original recycling models for different kinds of batteries, including lead acid, nickel–cadmium, lithium and Li-ion batteries. Georgi-Maschler et al. (2012) summarized the recycling process for Li-ion batteries developed before 2012. They evaluated different recycling techniques and put forward a new recycling process with a combination of pyrometallurgical and hydrometallurgical processes. Dunn et al. (2012) estimated the energy consumption and environmental impacts of Li-ion battery recycling, while the Grave-to-Cradle and Cradle-to-Gate stages were both taken into consideration. They formed an important life cycle model for traction batteries. On the basis of Dunn's results, Gaines (2014) discussed the impediments to overcome and raised a vision of recycling system for Li-ion batteries in the future. However, Richa et al. (2014) pointed out that only 42% of the end-of-life Li-ion battery by mass could be recycled with the primary technology. Ordoñez et al. (2016) compared physical and chemical recycling processes for Li-ion batteries, and revealed that techniques remained to be developed to improve the recovery rate. Xie et al. (2015) carried out an LCA on Li-ion battery recycling with the industrial data from one battery recycling plant in China. Simon et al. (2015) evaluated the metal requirements and impacts on reserves of active materials by Li-ion battery recycling in Europe. The author provided an important supplement to the future LCA system on Li-ion batteries. Furthermore, a monograph "Advances in Battery Technologies for EVs" was published in 2015, containing a detailed description of the comprehensively used recycling techniques (Scrosati et al., 2015).

A mature framework of vehicle recycling analysis and a rudiment of traction battery recycling model have been established by existing studies, which have laid the foundation for evaluating the environmental impacts of EV production from a life cycle perspective. However, existing studies also suggested that the grave-to-gate environmental impacts of EV recycling varied a lot among different techniques, implying significant regional disparities. When it comes to the situation in China, few studies have focused on this topic due to the lack of unified standards. Meanwhile, the Chinese government aims to achieve a 60% – 65% decrease in CO_2 intensity (CO_2 emissions per unit of Gross Domestic Product) by 2030 (Chinese Government, 2015). To realize this target in the transport sector, EV industry would be promoted to become much larger. Under such a circumstance, EV recycling ought to be fully developed to improve the environmental impacts.

To fill the research gaps, this study aims at estimating the impact of recycling on energy consumption and greenhouse gas emissions from EV production. According to the government's expectation of EV production and life span (Chinese State Council, 2012), the first large batch of end-of-life EVs should be treated around 2025, based on which a China 2025 scenario is developed. This study assumes that the recycling techniques in China would successfully reach the world's advanced level as planned (Chinese State Council, 2015). To reflect the overall situation, an LCA framework is employed and China-specific database is established. Furthermore, this study incorporates several results on similar topics from existing literatures as benchmarks.

2. Recycling techniques

2.1. Vehicle specification

A standard mid-size electric passenger car with conventional materials is chosen as the reference vehicle in this study. However, since the detailed specification of EV is unclear in China, this study imports the relevant factors from Burnham (2012) and Automotive System Cost Model (ASCM) (Das, 2004). For more details, the total weight is adjusted to match the average case results in model year 2010 provided by Autonomie, and the material compositions for different components are estimated based on enterprise investigations, dismantling reports, literature review and basic assumptions. On the other hand, several other researches have provided different material compositions of EVs, which may largely influence the results. For example, Bauer et al. (2015) carried out the LCA for EVs currently and in the future. The author simulated a 1977 kg EV in 2012 and a 1643 kg EV in 2030, and the mass reduction was mainly caused by the use of lightweight materials such as alu-

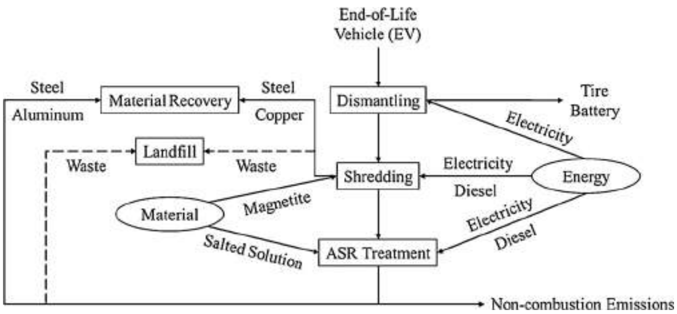

Fig. 1. Vehicle recycling process.

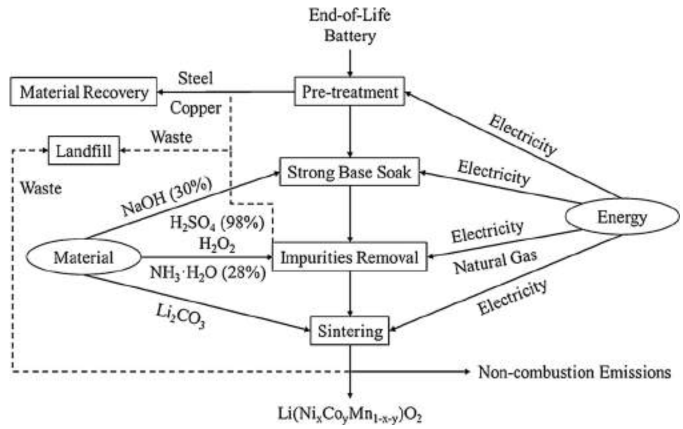

Fig. 2. NMC battery recycling process.

minum. Hawkins et al. (2013) employed the EV specification from Ecoinvent database and Daimler AG. The total weight of an EV without batteries was about 1900 kg, and the weight of a Li-ion battery was about 212 kg. It has been revealed that the total weight of an EV is in a downward trend due to the lightweight route, which may influence the environmental impacts of future vehicle recycling.

The use of $Li(Ni_xCo_yMn_{1-x-y})O_2$ (NMC) battery is dominating (CAAM, 2016a,b). Therefore, this study assumes that NMC battery would be recycled in 2025. However, with the lack of standard NMC battery production techniques in China, this study employs the estimation results from Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model established by Argonne National Laboratory (ANL) (ANL, 2016). For more details, the material inventory is normalized based on plenty of reports and literatures and presented by Battery Performance and Cost (BatPaC) model (Nelson et al., 2011), and the energy storage parameters are from Autonomie model. Dunn et al. (2012) combined the results and provided a generalized NMC battery specification for GREET.

Furthermore, standard radial tires which are widely used in China are considered as the reference tires in this study. And all the fluids in an EV including brake fluid, transmission fluid, windshield fluid, adhesives and powertrain coolant are taken into consideration on the basis of Burnham's research (Burnham, 2012).

The material compositions for all the parts mentioned are presented in Table 1.

2.2. Vehicle recycling

As shown in Fig. 1, vehicle recycling represents the main line of the EV recycling, including the recycling processes of almost all the components such as the body, chassis without battery, powertrain system, transmission system, traction motor, electronic controller and etc. Batteries and tires are sent to other enterprises after dismantling and their recycling processes are not included in this section. Most Chinese domestic vehicle recycling enterprises are currently in a primary stage, in which only rubber, steel and iron scraps are produced at low rates. However, as this study pays attention to the case in 2025, an advanced recycling model is established based on the techniques used by the famous vehicle recycling enterprise Comet Traitement SA in Belgium, the whole process consists of dismantling, shredding, post-shredding-treatments of metals, further treatments of plastics, minerals and phoenix (Belboom et al., 2016). The first three stages are basic vehicle recycling techniques, which aim to recycle the major materials, such as steel, iron and aluminum, of vehicles. These three steps have already been employed by several top enterprises in China (Li et al., 2016). The last three stages are focused on the recycling of specific materials and energy which require most advanced techniques and are hard to employed by China's enterprises. For example, the further treatment of phoenix aims to recover the metals and energy which were sent to landfill previously due to the high costs and limited techniques.

For more details, dismantling, shredding and ASR treatments are made up of several procedures. Batteries and tires are removed during dismantling with only a little energy and no materials input. Remains are shredded in a specific machine, allowing some steel and copper scraps to be picked straightly. After that, some other steel, copper and aluminum scraps in the residue are picked by magnetic machine and heavy media separation. Other potential outputs such as plastic scraps and recovered energy are sent to the landfill due to the steep technical requirements of recycling in China. It is worth mentioning that this study assumes the techniques can be adopted by China's future enterprises in spite of the difficulties. Actually, if China fails to develop the clean industrial system with advanced emission processing technology, more emissions will be produced even if the same techniques are employed.

2.3. Battery recycling

Detailed NMC battery recycling process is shown in Fig. 2. An optimized hydrometallurgical process is expected to be widely employed in China 2025 due to the high yield rate, which has been industrialized by Retriev Technologies, the leading battery recycling company in North America, (Georgi-Maschler et al., 2012) and adopted by one of the top battery recycling enterprises in China (Xie et al., 2015).

The whole process can be divided into five stages: pre-treatment, strong base soak, impurities removal and sintering. Pre-treatment consists of crushing and screening, aiming to separate steel, copper scraps and the active material powder. The steel and copper scraps are sent to other specific plants while the active material powder will be the input of remaining stages. Strong base soak aims to get rid of aluminum in the powder, which demands a huge amount of NaOH (30%) and gives up the opportunity to recycle aluminum scraps. After that, other impurities need to be removed by leaching, extraction and precipitation, with the consumption of much H_2SO_4 (98%), H_2O_2 and $NH_3{\cdot}H_2O$ (28%). Sintering is the final stage of battery recycling, aiming to produce NMC, and some other materials such as Li_2CO_3 are consumed.

2.4. Tire recycling

As a mature technique shown in Fig. 3, dynamic devulcanization dominates in China's tire recycling industry, which is chosen as the reference recycling technique in this study. In order to recycle iron and rubber, end-of-life tires are shredded and grinded before the dynamic devulcanization stage, and refined at last. After that, iron scraps are sent to the specific plants while the devulcanized rubber

Table 1
Material composition for the reference vehicle.

EV without batteries, tires and fluids (t)		NMC battery (t)		Others (t)	
Total	**1.70**(−)	**Total**	**0.17**(−)	**Fluids**	0.03
Steel	1.10(−)	Active Material	0.05(−)	Adhesives	0.01
Wrought aluminum	0.02(+)	Graphite/Carbon	0.03(−)	Others	0.02
Cast aluminum	0.09(+)	Copper	0.02(−)	**Tires**	**0.04(3)**
Average plastic	0.20(+)	Wrought Aluminum	0.03(+)	Steel	0.02
Others	0.29	Others	0.04	Rubber	0.02
Total (t)			**1.94**		

Note: 1. Numbers in the parentheses denote the replacements of the corresponding parts during life time (omit zero). 2. "+/−" in the parentheses denotes the upward/downward trend of the materials used in EVs.

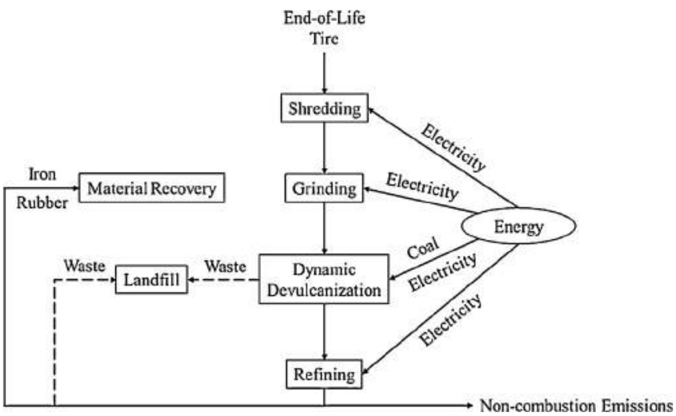

Fig. 3. Tire recycling process.

would be further treated to get styrene butadiene rubber (Li et al., 2010).

3. Methods and data

3.1. System boundary

A complete grave-to-gate life cycle model is employed in this study to reveal the energy consumption and GHG emissions in details, and the reduction can be estimated based on the amount of recovered materials. The system shown in Fig. 4 is formed by the expected vehicle recycling process in 2025 China, which is inferred from the current world's advanced techniques and China's development trend. The process is divided into three phases: 1) recycling process consists of vehicle recycling which means the vehicle dismantling, vehicle (without battery and tires) recycling, battery recycling and tire recycling; 2) material recovery represents the process with scraps as inputs in specific plants; 3) vehicle production consists of material production, components manufacture and assembly. Since recovery generally consumes less energy and produces less GHG, reduction exists when virgin materials are replaced by recovered materials.

3.2. Methods

The reduction of energy consumption and GHG emissions can be derived through Eqs. (1)–(6).

$$EC_{RP} = EC_{VRR} - EC_R \tag{1}$$

$$GE_{RP} = GE_{VRR} - GE_R \tag{2}$$

Where,

EC_{RP}/GE_{RP} denotes the total reduction of life cycle energy consumption (MJ)/GHG emissions (kg CO_2eq) per end-of-life EV;

EC_{VRR}/GE_{VRR} denotes the reduction of life cycle energy consumption (MJ)/GHG emissions (kg CO_2eq) per end-of-life EV per end-of-life EV when virgin materials are replaced by recovered materials;

EC_R/GE_R denotes the life cycle energy consumption (MJ)/GHG emissions (kg CO_2eq) per end-of-life EV from the whole recycling process.

$$EC_{VRR} = \sum_i m_i \sum_j \left(EC_{V,i,j} - EC_{R,i,j}\right) \tag{3}$$

$$GE_{VRR} = \sum_i m_i \sum_j EF_j \left(EC_{V,i,j} - EC_{R,i,j}\right) \tag{4}$$

Where,

m_i denotes the weight of recovered material i (t);

$EC_{V,i,j}$ denotes the consumption of energy j per t of virgin material $i$production (MJ/t);

$EC_{R,i,j}$denotes the consumption of energy $j$per t of material $i$recovery (MJ/t);

EF_j denotes the life cycle GHG emission factor of energy j (kg CO_2eq/MJ).

$$EC_R = \sum_k M_k \left(\sum_j EC_{k,j} + \sum_l N_{k,l} EC_{k,l}\right) \tag{5}$$

$$GE_R = \sum_k M_k (\sum_j EF_j \cdot EC_{k,j} + \sum_l N_{k,l} GE_{k,l} + GE_{k,NC}) \tag{6}$$

Where,

M_k denotes the weight of part k (vehicle without battery and tires, NMC battery, tires) (t);

$EC_{k,j}$ denotes the consumption of energy j per t of part k recycling (MJ/t);

$N_{k,l}$ denotes the consumption of material l input per t of part k recycling (t/t);

$EC_{k,l}$ denotes the life cycle energy consumption per t of material l production (MJ/t);

$GE_{k,l}$ denotes the life cycle GHG emissions per t of material l production (kg CO_2eq/t);

$GE_{k,NC}$ denotes the non-combustion GHG emissions per t of part k recycling (kg CO_2eq/t).

3.3. Data

3.3.1. Recycling stages

As listed in Table 2, based on the LCA model in this study, this section presents the energy/material consumption, non-combustion GHG emissions and products per t of end-of-life EV input in different stages, including vehicle dismantling, vehicle (without batteries and tires) recycling, battery recycling and tire recycling. These stages are classified into three major parts. Replacements and landfill are considered for all the stages mentioned.

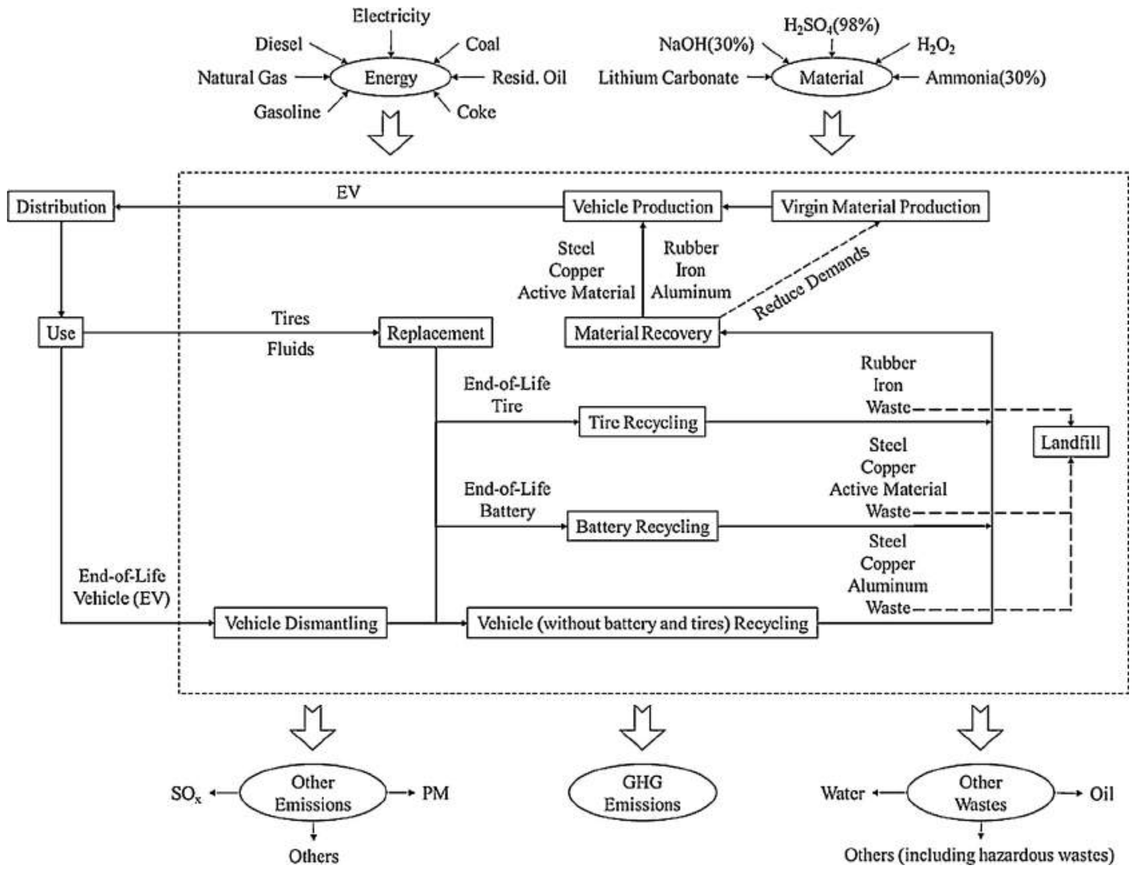

Fig. 4. LCA model employed and system boundary.

Table 2
Energy/material consumption, non-combustion GHG emissions and scrap production of different stages.

Energy/material consumption, non-combustion GHG emissions and scrap production		Vehicle recycling	Battery recycling	Tire recycling
Energy consumption (MJ/t)	Coal	0.0	0.0	2,143.1
	Electricity	77.6	2,329.3	800.0
	Diesel	790.0	0.0	0.0
	Natural gas	0.0	5,018.8	0.0
Material consumption (kg/t)	Magnetite	6.5	0.0	0.0
	Salted solution	1.6	0.0	0.0
	H_2SO_4 (98%)	0.0	1,100.0	0.0
	NaOH (30%)	0.0	2,180.0	0.0
	$NH_3{\cdot}H_2O$ (28%)	0.0	110.0	0.0
	Li_2CO_3	0.0	120.0	0.0
Non-combustion GHG emissions (kg CO_2eq/t)		0.0	67.3	170.9
Scrap production (kg/t)	Steel	647.7	180.0	0.0
	Iron	0.0	0.0	230.0
	Aluminum	41.3	0.0	0.0
	Rubber	0.0	0.0	670.0
	Copper	31.0	100.0	0.0
	NMC	0.0	250.0	0.0
Sources		Belboom et al. (2016), Li et al. (2016); Enterprise investigation	Georgi-Maschler et al. (2012), Ordoñez et al. (2016), Xie et al. (2015); Enterprise investigation	Li et al. (2010)

Vehicle recycling includes the whole process from dismantling to the recycling of vehicles without batteries and tires, and the replacements of several components are considered. Batteries and tires are sent to the specific recycling processes after dismantling, while all the other components are recycled in this step. Data in this part are normalized based on the industrial data from Comet Traitement SA in Belgium while several post shredding treatments are not carried out due to the expectation for China in 2025. For

Table 3
Energy consumption, non-combustion GHG emissions and recovery rate of material recovery.

Energy consumption and recovery rate		Steel	Iron	Aluminum	Rubber	Copper
Virgin	Coal	16,309.6	0.0	45,551.5	0.0	4,374.4
	Electricity	1,309.7	405.8	13,740.0	99.1	4,983.0
	Natural gas	3,208.9	204.9	0.0	17,660.8	0.0
	Coke	9,278.3	0.0	0.0	0.0	0.0
	Resid. oil	193.5	193.5	0.0	17,661.0	5,927.5
	Gasoline	2.2	2.2	0.0	0.0	0.0
	Diesel	29.9	29.9	0.0	0.0	9,565.7
	Blast furnace gas	2,421.9	0.0	0.0	0.0	0.0
	Coke oven gas	1,101.6	0.0	0.0	0.0	0.0
Recovery	Coal	0.0	98.8	0.0	/	/
	Electricity	1,764.0	0.0	208.2	/	/
	Natural gas	3,432.9	0.0	5,294.9	/	/
	Coke	179.2	0.0	0.0	/	/
	Resid. oil	0.0	0.0	0.0	/	/
	Gasoline	0.0	0.0	0.0	/	/
	Diesel	0.0	1,312.3	0.0	/	/
	Blast furnace gas	0.0	0.0	0.0	/	/
	Coke oven gas	0.0	0.0	0.0	/	/
Recovery rate		95.9%	100.0%	96.8%	40.0%	77.6%
Sources		ANL (2016), Weng (2009), Jing et al. (2014); Enterprise investigation	ANL (2016)	Hao et al. (2015); Enterprise investigation	Burnham et al. (2006)	Zeng et al., 2012; Brahmst, 2006

Note:.
1. The recovery processes of rubber and copper are included in the recycling processes mentioned in 2.3, 2.4, and the recovery rates are calculated based on the final products of such processes.

Table 4
Life cycle GHG emissions of energy and material input.

Life cycle GHG emission factors	GHG emissions from production	GHG emissions from combustion	Sources
Energy (g CO_2eq/MJ, g CO_2eq/kWh)			
Coal	2.4	95.1	Chen (2014), IPCC (2006)
Electricity	834.5	/	NBSC (2016), Ma et al. (2014)
Natural gas	8.6	56.2	Chen (2014), IPCC (2006)
Coke	24.1	107.5	Weng (2009), IPCC (2006)
Resid. oil	14.0	77.7	Chen (2014), IPCC (2006)
Gasoline	18.1	69.6	Chen (2014), IPCC (2006)
Diesel	16.3	74.4	Chen (2014), IPCC (2006)
Blast furnace gas	Included in coke	260.1	IPCC (2006)
Coke oven gas	production	44.5	IPCC (2006)
Material (g CO_2eq/kg)			
H_2SO_4 (98%)	276.3	/	Yuan and Wang (2012)
NaOH (30%)	477.0	/	Hong et al. (2014)
$NH_3{\cdot}H_2O$ (28%)	621.0	/	Makhlouf et al. (2015)
Li_2CO_3	1251.3	/	Dunn et al. (2012)

Note: 1. Blast furnace gas and coke oven gas are by-products of coke, whose emissions factors are included in coke production.

Table 5
Energy consumption and products of each stage.

Energy consumption and products	Vehicle recycling	Battery recycling	Tire recycling	Material recovery	Total
Energy consumption (MJ)	13,145.8	2,583.6	784.8	/	16,514.2
Recycling process	1,808.7	2,278.7	729.1	/	4,816.5
Material recovery	11,337.1	304.9	55.7	11,697.7	11,697.6
Products (kg)					
Steel	1,095.6	30.6	0.0	1,079.8	/
Iron	0.0	0.0	33.4	33.4	/
Copper	52.4	17.0	0.0	53.9	/
Aluminum	69.8	0.0	0.0	67.6	/
Rubber	0.0	0.0	97.2	38.9	/
NMC	0.0	42.5	0.0	42.5	/
Status	**Scrap**	**Scrap**	**Scrap**	**Products**	/

instance, the expected vehicle recycling process doesn't include plastic recovery and energy regeneration, which requires the top techniques in developed countries and is unlikely to be introduced to China in a few years.

Battery recycling is one of the processes after vehicle dismantling, and the replacements during life time are considered. The data are from one of the top battery recycling enterprise in China, while several materials such as P507 extraction agent, kerosene, HCl and Na_2CO_3 are not included due to the immaterial amount. In addition, the recovery of NMC is performed at the end of battery recycling process, meaning that such products can be used by NMC battery producers without secondary processing.

Tire recycling is also one of the processes after vehicle dismantling, while the replacements during life time are considered as well. The data are estimated based on the developed dynamic devulcanization techniques in China, which is expected to dominate in the tire recycling industry in 2025 due to the high quality and yield rate. Meanwhile, the devulcanized rubber will be further processed to get styrene butadiene rubber as the final product.

3.3.2. Material recovery and virgin material production

When it comes to the reduction of energy consumption and non-combustion GHG emissions when virgin materials are replaced by recovered materials, all the related data are listed in Table 3, including the consumption of different energy both for virginal production and recovery.

It is worth mentioning that since the EVs to be recycled in 2025 are produced currently, all the data related to virgin materials are based on the current situation in China, while the advanced recovery processes in developed countries are applied to material recovery. Furthermore, the consumption of diesel is considered in the vehicle recycling stage, under the assumption that 9.3 t-load trucks are used to cover the average distance (ANL, 2016).

Data related to virgin steel are from one of the biggest steel plants in China, which employs the Blast Furnace-Basic Oxygen Furnace (BF-BOF) process consisting of all the stages from iron ore mining to steel production. Steel recovery is an Electric Arc Furnace (EAF) process with much less energy input than BF-BOF, while the data are from GREET provided by ANL.

Iron scraps can be straightly input to produce cast iron. Therefore, the recovery process represents only the transport of iron scraps.

Regional average energy consumption and non-combustion GHG emissions from the production of virgin aluminum in China are imported, including all the stages from bauxite mining to primary ingot casting. And the aluminum recovery consists of two stages: scrap preparation and secondary ingot casting, while the related data are from GREET.

As a developed technique all over the world, rubber production in China is not quite different from it in the U.S., therefore this study imports relevant data from GREET. The additional GHG emissions caused by the regulations and facilities in China will be discussed later.

Energy consumption of copper production is estimated according to the techniques employed in China, which consumes a huge amount of coal and electricity.

When it comes to NMC which is not listed in Table 3 due to the lack of standard detailed energy consumption in China, the life cycle energy consumption and GHG emissions per t of NMC production are 125,362.4 MJ (ANL, 2016) and 1,866.2 kg (Wang, 2012), and the recovery of NMC is considered in the battery recycling process.

3.3.3. GHG emission factors

GHG emissions are defined as the emissions of CO_2, CH_4 and N_2O while they are multiplied by the convert coefficient 1, 25 and 298 in this study (IPCC, 2014). And the other GHG emissions are not taken into consideration due to the little amount, such as CFC, NO, SF_6, etc. In addition, a widely used combustion mode is assumed based on GREET when considering the CH_4 and N_2O emissions. As this study estimates the life cycle GHG emissions through energy and material consumption, the emission factors listed in Table 4 are important to ensure the reliability of the results.

All of the energy production is estimated on the basis of China's situation. For more details, the emission factors of coal, natural gas, resid. oil, gasoline and diesel production are from the SinoCenter database established by Beijing University of Technology, while electricity and coke production is calculated through the regional average value in China. In addition, the emission factors of combustion are provided by IPCC (2006). In short, the emission factors of energy production are all calculated on the Chinese case, while the values for combustion are global and imported from IPCC.

When it comes to the materials, life cycle GHG emission factors of H_2SO_4 (98%), NaOH (30%), $NH_3{\cdot}H_2O$ (28%) and H_2O_2 are from a wide range of literature focused on the situation in China. However, since the lithium industry in China has not been developed yet and Chile is world's biggest lithium exporter with the top techniques, this study employed the GHG emission factor calculated under Chile's situation.

4. Results and discussion

4.1. Results

The calculation results of energy consumption per end-of-life EV in China of the detailed vehicle recycling process and material recovery are presented in Table 5. It can be found that the total energy consumption of recycling is 16.5 GJ, and the vehicle recycling process consumes over 79% of the total energy.

According to the techniques expected, most of the materials can be recycled as scraps and put into material recovery. Steel accounts for about 82% by weight, while NMC is the most valuable product in spite of its little weight.

The final results about the reduction of energy consumption and GHG emissions per end-of-life EV which are calculated through Eqs. (1)–(6) are presented in Table 6. In short, the total reduction of energy consumption and GHG emissions are 32.1 GJ and 5.1 t CO_2eq per end-of-life EV.

4.2. Discussion

Fig. 5 presents the detailed reduction of energy consumption and GHG emissions per end-of-life EV. According to our former studies, the life cycle GHG emissions from the production of an EV with NMC battery are about 14.9 t CO_2eq (Qiao et al., 2016), implying that the number for an EV with recycling is only 9.8 t. That is to say, about 34% of the total GHG emissions from EV production can be reduced by recycling.

As benchmarks, reduction of GHG emissions from an 1145 kg Internal Combustion Engine Vehicle (ICEV) recycling is about 3.1 t CO_2eq (Li et al., 2016), proving that similar reduction rates exist among EV (without batteries and tires) and ICEV. When it comes to battery recycling, the reduction rate of energy consumption and GHG emissions of an $LiMn_2O_2$ battery through recycling is up to 48% (Dunn et al., 2012), a little higher than the rate of NMC battery.

Considering the impacts on the whole life cycle of an EV, this study estimates the reduction rate of life cycle GHG emissions by recycling. When powered by the coal-based electricity like the situation in China, GHG emissions of production phase and use phase of an EV account for about 29% and 70%, and the proportions for an ICEV are about 17% and 83% (Hawkins et al., 2013). Under this circumstance, about 10% of the life cycle GHG emissions of an EV can be reduced by recycling, which is much higher than the level of an ICEV, about 4%.

Considering the energy consumption and GHG emissions from the recycling and material recovery processes shown in Fig. 6,

Table 6
Reduction of energy consumption and GHG emissions.

Reduction	Vehicle recycling	Battery recycling	Tire recycling	Total
Energy consumption (MJ)	40,583.5	6,649.0	1,405.8	48,638.4
Steel	35,563.9	993.3	0.0	36,557.2
Iron	0.0	0.0	27.9	27.9
Copper	1,011.0	327.8	0.0	1,338.8
Aluminum	4,008.7	0.0	0.0	4,008.7
Rubber	0.0	0.0	1,377.9	1,377.9
NMC	0.0	5,327.9	0.0	5,327.9
Comprehensive reduction	27,437.7	4,065.4	621.0	32,124.2
GHG emissions (kg CO_2eq)	6,138.8	1,865.7	123.2	8,127.6
Steel	4,819.3	134.6	0.0	4,954.0
Iron	0.0	0.0	12.4	12.4
Copper	243.9	79.1	0.0	323.0
Aluminum	1,075.5	0.0	0.0	1,075.5
Rubber	0.0	0.0	110.7	110.7
NMC	0.0	1,652.0	0.0	1,652.0
Comprehensive reduction	**3,989.6**	**1,150.3**	**−35.6**	**5,104.4**

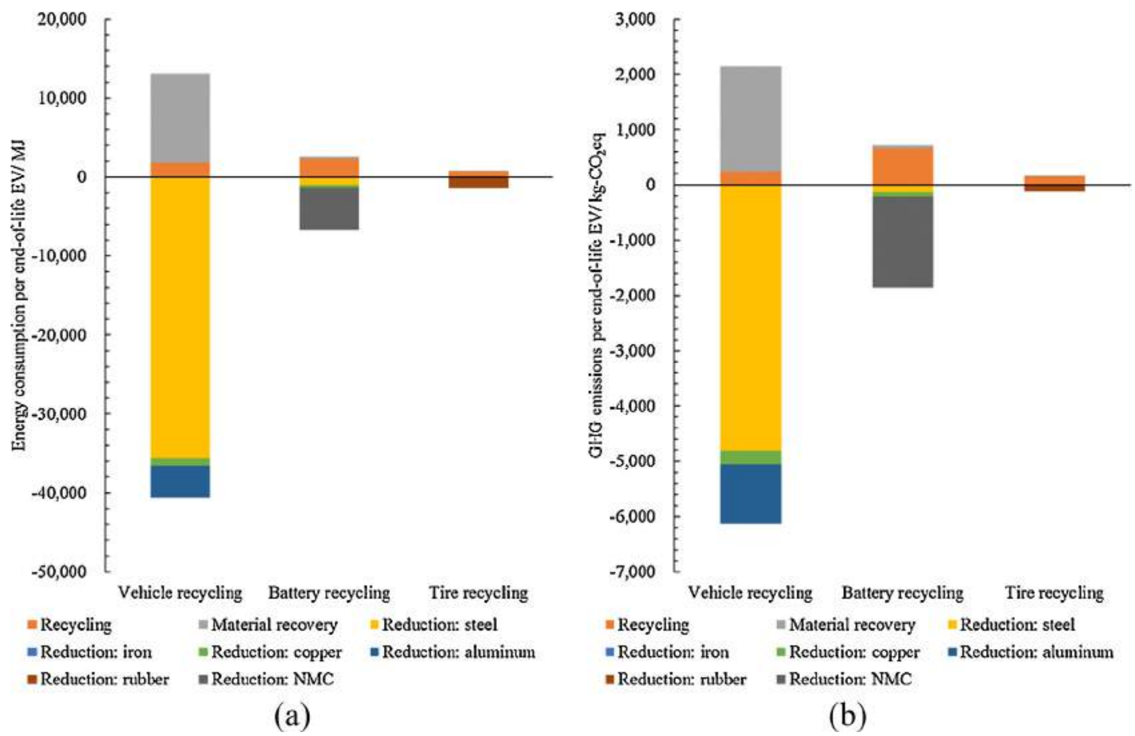

Fig. 5. Reduction of a) energy consumption and b) GHG emissions per end-of-life EV.

vehicle recycling accounts for about 80% of the total energy consumption and 71% of the total GHG emissions because of the large number of scraps to be recovered. About 86% of the total energy consumption is caused by material recovery and the number for GHG emissions is about 89%. However, the situation is quite different for batteries and tires. For instance, since most of the materials, including NMC, are recovered during the recycling process of an NMC battery, about 88% of the energy consumption and 93% of the GHG emissions are from battery recycling.

Despite the huge energy consumption and GHG emissions, vehicle recycling is the most important stage with 27.4 GJ and 4.0 t CO_2eq reduction as shown in Fig. 7, accounting for over 85% and 78% of the total level separately. The huge amount of recovered steel consumed in the vehicles is the major reason.

From another point of view, although the NMC battery only shares about 9% of the whole EV by weight, 4.1 GJ and 1.2 t CO_2eq can be reduced by its recycling, accounting for about 13% and 23% of the total reduction, which is largely influenced by NMC recovery. Considering the 2,896.3 kg CO_2eq emissions from NMC battery production (Qiao et al., 2016), the reduction rate is about 40%, higher than the rate of vehicle recycling. Due to the little weight and normal materials of tires, the reduction is relatively small when recycled.

As the input of the system in this study is based on the industrial data of certain techniques, several errors may happen due to the variable techniques employed by different enterprises in China. At the same time, additional GHG emissions are sure to be caused in several stages, such as vehicle recycling and rubber production, in China due to the backward emission processing technology and lack of regulations. Even so, the results can provide an important reference for the government and enterprises to make decisions.

In short, energy consumption and GHG emissions can be significantly reduced by vehicle recycling due to the large weight. In addition, the techniques are already developed in several countries and can be taken as examples for China. Furthermore, in spite of the little weight of battery, the reduction is quite huge due to

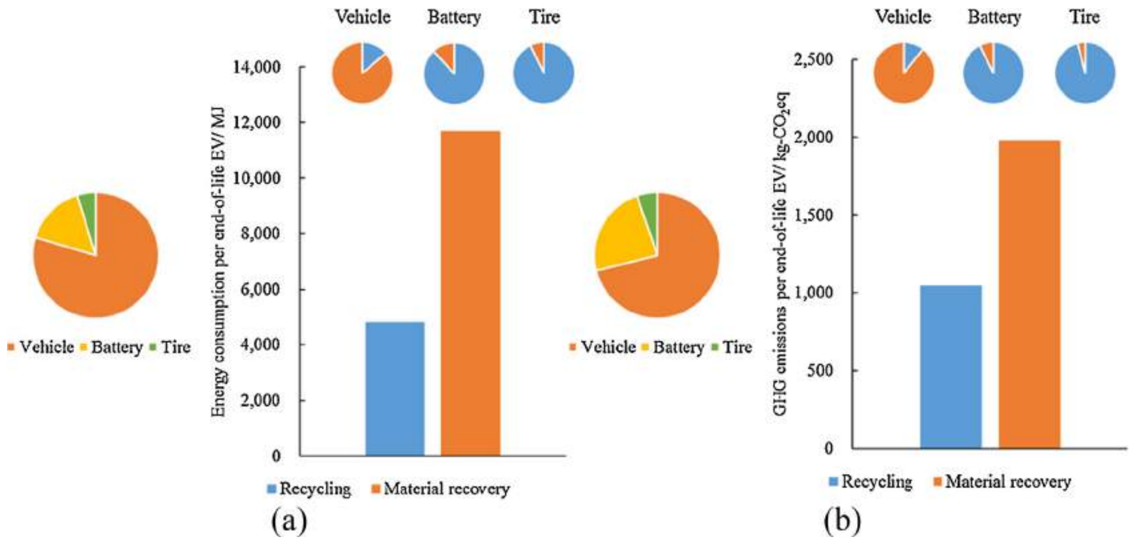

Fig. 6. Composition for a) energy consumption and b) GHG emissions per end-of-life EV.

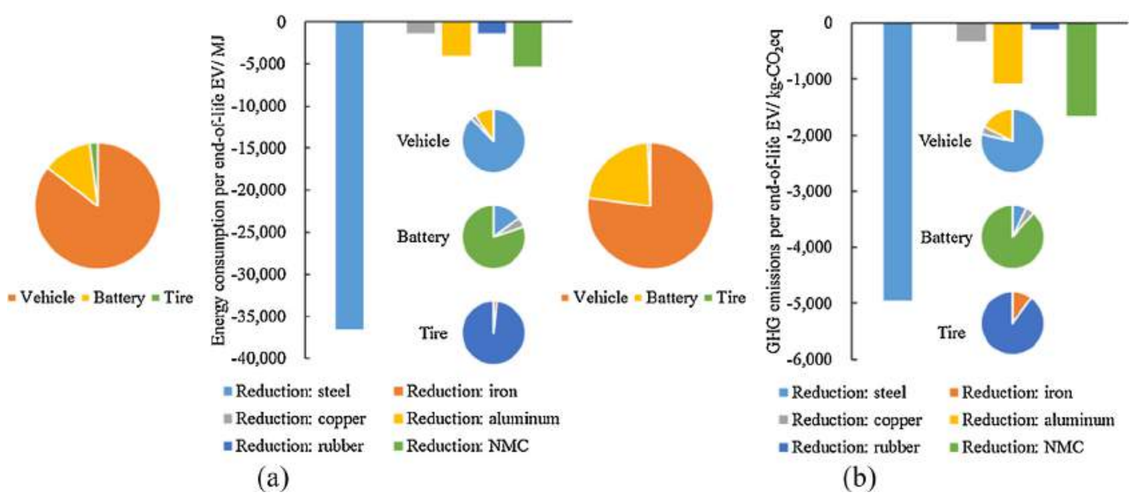

Fig. 7. Composition for reduction of a) energy consumption and b) GHG emissions per end-of-life EV.

the recovery of NMC. However, since efficient battery recycling techniques haven't been fully developed yet in any country, the techniques employed in this study are based on the top techniques currently. Therefore, more attention should be paid to developing battery recycling process.

4.3. Uncertainty analysis

Since the assumption of this study is the situation in 2025 China, uncertainty exists due to the unpredictable growth of techniques. This section aims to provide quantitative analysis about the uncertainty caused by future techniques. And several fixed factors are not calculated. For example, the material composition of EVs may change a lot due to the lightweight trend, and most of the steel may be replaced by aluminum, which will lead to quite different results. Actually, as calculated above, the reduction of energy consumption and GHG emissions per t of aluminum recycling are much larger than those of steel recycling, indicating that the EV recycling can provide even more environmental benefits if the lightweight trend keeps going on. However, this kind of uncertainty is not calculated because this study assumes that the EVs recycled in 2025 are produced almost currently, which would not influenced by the future lightweight techniques. Therefore, two aspects about the future recycling techniques and emission factors are considered in this study: 1) energy consumption and products of unexpected recycling and recovery techniques; 2) lower GHG emission factors of fuel production due to the ongoing development.

Fig. 8 presents the variation of reduction while the energy consumption of recycling and recovery processes are multiplied by the parameters a) 0.8, 1.2 or the amount of products are multiplied by the parameters b) 0.8, 0.9 (considering that relatively high scrap production rates are imported in this study, the parameters are smaller than 1.0). It has been revealed that with the growing of energy consumption of recycling and recovery processes, the final reduction is decreasing due to the fixed reduction through replacements of virgin materials as they are being produced currently. On the other hand, although energy consumption and GHG emissions from recycling and recovery processes are increasing with the growth of the recycling products, the final reduction is larger when more virgin materials can be replaced.

Fig. 9 presents the reduction of GHG emissions while the emission factors of fuel production are multiplied by the parameters 0.8, 0.9. The influence is not large due to the small emission factors of fuel production except electricity. However, not much electricity is used during the recycling and recovery process. From another point of view, no changes happen to the reduction of energy consumption

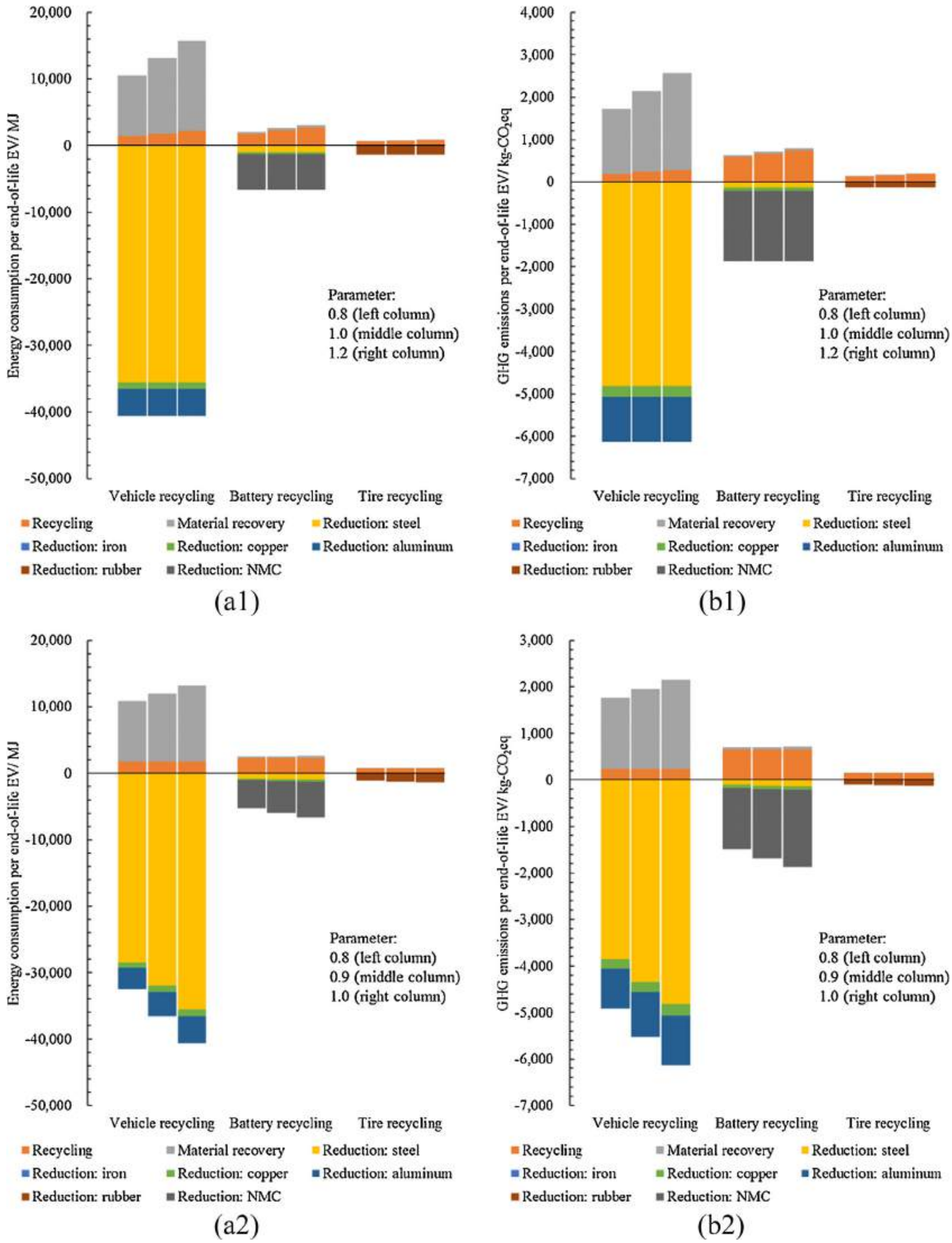

Fig. 8. Variation of reduction of a) energy consumption, b) GHG emissions while 1) energy consumption of recycling and recovery processes, 2) products of recycling are multiplied by parameters.

and GHG emissions through the replacements of virgin materials as they are produced currently with the current emission factors. Therefore, the final reduction increases slowly with the decrease of emission factors.

5. Conclusion

This study has estimated the reduction of energy consumption and GHG emissions if an EV is recycled in 2025 China. Uncertainties are taken into consideration due to the unpredictable techniques in the future. The results indicate that the total reduction per end-of-life EV is 32.1 GJ and 5.1 t CO_2eq, about 34% of the life cycle GHG emissions from EV production in China. Considering the whole life cycle, about 10% of the GHG emissions can be reduced by recycling, while the number for an ICEV is only about 4%. In China, due to the weak manufacturing industry and coal-based energy structure, EV recycling must be developed to obtain more environmental benefits. Several measures can be taken to ensure the

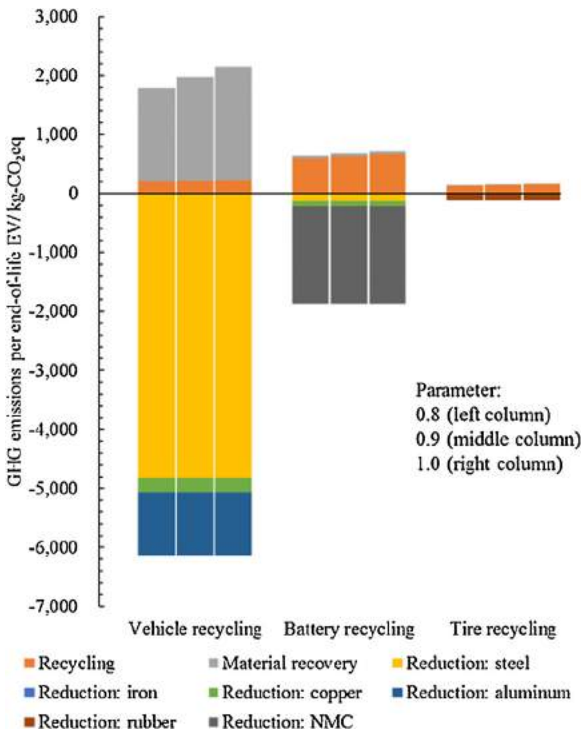

Fig. 9. Variation of reduction of GHG emissions while emission factors of energy are multiplied by parameters.

development: first of all, vehicle (without batteries and tires) recycling is currently the most important stage and has been maturely developed in advanced countries, China can employ the techniques with matched regulations; secondly, more attention should be paid to battery recycling in the future as it has huge potential benefits; finally, infrastructures may become one of the obstacles for China to develop clean recycling techniques.

Since the EVs to be recycle in 2025 China are produced currently, the results will not be influenced by the future production techniques such as lightweight and new type batteries. But due to the unpredictable recycling techniques and emission factors, the results will change within a certain range. For instance, the reduction decreases if the techniques in 2025 are below the level expected in this study, in other words, having more energy consumption during recycling and recovery processes and having fewer products.

Despite the important results provided by this study, several vacancies remain to be covered by further studies. As a primary industry, battery recycling will embrace a rapid growth in the coming few years, meaning that the techniques will change to a great extent. From another point of view, the pilot use of end-of-life battery is not taken into consideration in this study because of the unclear plan in China. In short, although the technique expected in this study is reasonable from the current point of view, it may change significantly.

Acknowledgements

This study is sponsored by the National Natural Science Foundation of China (71403142, 71690241, 71572093), Beijing Natural Science Foundation (9162008), State Key Laboratory of Automotive Safety and Energy (ZZ2016-024).

References

Argonne National Laboratory (ANL), 2016. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (Accessed October 2016) https://greet.es.anl.gov/.

Bauer, C., Hofer, J., Althaus, H.J., Duce, A.D., Simons, A., 2015. The environmental performance of current and future passenger vehicles: life cycle assessment based on a novel scenario analysis framework. Appl. Energy 157, 871–883.

Belboom, S., Lewis, G., Bareel, P., Leonard, A., 2016. Life cycle assessment of hybrid vehicles recycling: comparison of three business lines of dismantling. Waste Manage. 50, 184–193.

Brahmst, E., 2006. Copper in End-of-Life Vehicle Recycling. The center for Automotive Research, Ann Arbor, Michigan.

Burnham, A., Wang, M., Wu, Y., 2006. Development and Applications of GREET 2.7—the Transportation Vehicle-cycle Model. Argonne National Laboratory.

Burnham, A., 2012. Updated Vehicle Specifications in the GREET Vehicle-Cycle Model. Argonne National Laboratory.

China Association of Automobile Manufacturers (CAAM), 2016. China automotive industry yearbook 2015, Beijing.

China Association of Automobile Manufacturers (CAAM), 2016b. The Development of Chinese Automobile Industry Annual Report. Social Sciences Academic Press.

Chen, Y., 2014. A Study on Life Cycle Ecological Benefits Assessment of Automotive Parts (unpublished Publicly). Hunan University, pp. 42–48, Ph.D. Academic Dissertation.

Cheng, Y., Cheng, J., Lin, C., 2012. Operational characteristics and performance evaluation of the ELV recycling industry in Taiwan. Resour. Conserv. Recycl. 65, 29–35.

Chinese Government, 2015. Enhanced actions on climate change: China's Intended Nationally Determined Contributions (INDCs) (Accessed September 2016) https://www.sdpc.gov.cn/xwzx/xwfb/201506/t20150630_710204.html.

Chinese State Council, 2012. Energy saving and new energy vehicles development plan 2012-2020 (Accessed June 2016) http://www.gov.cn/zwgk/2012-07/09/content_2179032.htm.

Chinese State Council, 2015. Made in China 2025 (Accessed October 2016) http://www.gov.cn/gongbao/content/2015/content_2873744.htm.

Cossu, R., Lai, T., 2015. Automotive shredder residue (ASR) management: An overview. Waste Manage. 45, 143–151.

Das S., 2004. A comparative assessment of alternative powertrains and body-in-white materials for advanced technology vehicles. SAE Technical Paper. 01-0573.

Diener, D., Tillman, A., 2015. Component end-of-life management: exploring opportunities and related benefits of remanufacturing and functional recycling. Resources Conserv. Recycl. 102, 80–93.

Dunn, J.B., Gaines, L., Sullivan, J., Wang, M.Q., 2012. Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive Lithium-Ion batteries. Environ. Sci. Technol. 46 (22), 12704–12710.

Duval, D., MacLean, H.L., 2007. The role of product information in automotive plastics recycling: a financial and life cycle assessment. J. Clean. Prod. 15 (11), 1158–1168.

Espinosa, D.C.R., Bernardes, A.M., Tenório, J.A.S., 2004. An overview on the current processes for the recycling of batteries. J. Power Sources 135 (1), 311–319.

Gaines, L., 2014. The future of automotive lithium-ion battery recycling: charting a sustainable course. Sustainable Mater.Technol. 1, 2–7.

Georgi-Maschler, T., Friedrich, B., Weyhe, R., Heegn, H., Rutz, M.V., 2012. Development of a recycling process for Li-ion batteries. J. Power Sources 207, 173–182.

Gerrard, J., Kandlikar, M., 2007. Is European end-of-life vehicle legislation living up to expectations? Assessing the impact of the ELV Directive on 'green' innovation and vehicle recovery. J. Clean. Prod. 15 (1), 17–27.

Halabi, E.E., Third, M., Doolan, M., 2015. Machine-based dismantling of end of life vehicles: a life cycle perspective. Procedia CIRP 29, 651–655.

Hao, H., Geng, Y., Hang, W., 2015. GHG emissions from primary aluminum production in China: regional disparity and policy implications. Appl. Energy 166, 264–272.

Hawkins, T.R., Singh, B., Majeau-Bettez, G., Stromman, A.H., 2013. Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. 17 (1), 53–64.

Hong, J., Chen, W., Wang, Y., Xu, C., Xu, X., 2014. Life cycle assessment of caustic soda production: a case study in China. J. Clean. Prod. 66, 113–120.

Hu, S., Wen, Z., 2015. Why does the informal sector of end-of-life vehicle treatment thrive? A case study of China and lessons for developing countries in motorization process. Resources Conserv. Recycl. 95, 91–99.

Intergovernmental Panel on Climate Change (IPCC), 2006. IPCC guidelines for national greenhouse gas inventories (Accessed March 2016) http://www.ipcc-nggip.iges.or.jp/public/2006gl.

Intergovernmental Panel on Climate Change (IPCC), 2014. Climate change 2013: the physical science basis.58–59 (Accessed Jan 2017) http://www.ipcc.ch/report/ar5/.

Jing, R., Cheng, J., Gan, V., Woon, K., Irene, M., 2014. Comparison of greenhouse gas emission accounting methods for steel production in China. J. Clean. Prod. 83, 165–172.

Kumar, V., Sutherland, J.W., 2009. Development and assessment of strategies to ensure economic sustainability of the U.S automotive recovery infrastructure. Resources Conserv. Recycl. 53 (8), 470–477.

Li, X., Xu, H., Gao, Y., Tao, Y., 2010. Comparison of end-of-life tire treatment technologies: a Chinese case study. Waste Manage. 30 (11), 2235–2246.

Li, W., Bai, H., Yin, J., Xu, H., 2016. Life cycle assessment of end-of-life vehicle recycling processes in China——take Corolla taxis for example. J. Clean. Prod. 117, 176–187.

Ma, C., Li, S., Ge, Q., 2014. Greenhouse gas emission factors for grid electricity for Chinese provinces. Resources Sci. 36 (5), 1005–1012.

Makhlouf, A., Serradj, T., Cheniti, H., 2015. Life cycle impact assessment of ammonia production in Algeria: a comparison with previous studies; Comparative life cycle assessment of various ammonia production methods. Environ. Impact Assess. Rev. 50, 35–41.

National Bureau of Statistics of China (NBSC), 2016. Annual Provincial Power Generation. Beijing, China. http://data.stats.gov.cn/easyquery.htm?cn=C01.(Accessed May 2016).

Nanaki, E.A., Koroneos, C.J., 2013. Comparative economic and environmental analysis of conventional, hybrid and electric vehicles-the case study of greece. J. Clean. Prod. 53, 261–266.

Nelson, P.A., Gallagher, K.G., Bloom, I., Dees, D.W., 2011. Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles. Argonne National Laboratory.

Organisation Internationale des Constructeurs d'Automobiles (OICA), 2016. Global Vehicle Production (Accessed March 2016) http://www.oica.net/.

Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., Nagasaka, T., 2015. Toward the efficient recycling of alloying elements from end of life vehicle steel scrap. Resources Conserv. Recycl. 100, 11–20.

Ordoñez, J., Gago, E.J., Girard, A., 2016. Processes and technologies for the recycling and recovery of spent lithium-ion batteries. Renew. Sustain. Energy Rev. 60, 195–205.

Qiao, Q., Zhao, F., Liu, Z., Jiang, S., Hao, H., 2016. Comparative study on life cycle CO2 emissions from the production of electric and conventional vehicles in China. In: 8th International Conference on Applied Energy, Beijing, P.R. China, Oct 8–10.

Richa, K., Babbitt, C., Gaustad, G., Wang, X., 2014. A future perspective on lithium-ion battery waste flows from electric vehicles. Resour. Conserv. Recycl. 83, 63–76.

Sakai, S., Yoshida, H., Hiratsuka, J., Vandecasteele, C., Kohmeyer, R., Rotter, V.S., 2014. An international comparative study of end-of-life vehicle (ELV) recycling systems. J. Mater. Cycles Waste Manage. 16 (1), 1–20.

Santini, A., Morselli, L., Passarini, F., Vassura, I., Carlo, S.D., Bonino, F., 2011. End-of-life vehicles management: italian material and energy recovery efficiency. Waste Manage. 31 (3), 489–494.

Scrosati, B., Garche, J., Sun, Y., 2015. Advances in Battery Technologies for Electric Vehicles. Woodhead Publishing, pp. 503–516.

Sharma, R., Manzie, C., Bessede, M., Crawford, R.H., Brear, M.J., 2013. Conventional, hybrid and electric vehicles for Australian driving conditions: part 2: life cycle CO_2-e emissions. Transp. Res. C: Emerg. Technol. 28, 63–73.

Simon, B., Ziemann, S., Weila, M., 2015. Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: focus on Europe. Resources Conserv. Recycl. 104, 300–310.

Smith, V.M., Keoleian, G.A., 2004. The value of remanufactured engines life-cycle environmental and economic perspectives. J. Ind. Ecol. 8 (1–2), 193–221.

Tagliaferria, C., Evangelistia, S., Acconciab, F., Domenechc, T., Ekinsc, P., Barlettab, D., Lettieri, P., 2016. Life cycle assessment of future electric and hybrid vehicles: a cradle-to-grave systems engineering approach. Chem. Eng. Res. Des. 112, 298–309.

Vermeulen, I., Caneghem, J.V., Block, C., Baeyens, J., Vandecasteele, C., 2011. Automotive shredder residue (ASR): reviewing its production from End-of-Life Vehicles (ELVs) and its recycling, energy or chemicals' valorization. J. Hazard. Mater. 190 (1), 8–27.

Wang, D., Zamel, N., Jiao, K., Zhou, Y., Yu, S., Du, Q., 2013. Life cycle analysis of internal combustion engine, electric and fuel cell vehicles for China. Energy 59, 402–412.

Wang, Q., 2012. Cathodes Materials of Lithium Ion Battery Comparative Analysis Based on Life Cycle Assessment. M.S. Academic Dissertation, South China University of Technology, pp. 35–36.

Weng, X., 2009. Research about the problems exist in the statistics of comprehensive energy consumption per unit product of coke in China. Metall. Econ. Manage. 4, 22–26.

Xie, Y., Yu, H., Ou, Y., Li, C., 2015. Environmental impact assessment of recycling waste traction battery. Inorg. Chem. Ind. 47 (4), 43–46.

Yuan, X., Wang, B., 2012. Life cycle assessment of sulfuric acid production through combination of pyrite and ferrous scrap. J. Sci. Technol. 6, 132–134 (in Chinese).

Zeng, G., Yang, J., Song, X., Lv, B., 2012. Energy consumption and carbon emissions scenario analysis of pyrometallurgical copper based on LCA. China Popul. Resources Environ. 22 (4), 46–50.

Zhao, Q., Chen, M., 2011. A comparison of ELV recycling system in China and Japan and China's strategies. Resources Conserv. Recycl. 57, 15–21.

Zhao, F., Chen, Y., Hao, H., Liu, Z., 2016. The problem analysis and countermeasures of recycling automotive products in China. Sci. Technol. Manage. Res. 36 (11), 116–120.