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Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China ☆

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HIGHLIGHTS

- Cradle-to-gate greenhouse gas emissions of internal combustion engine and battery electric vehicles are compared.
- Greenhouse gas emissions of battery electric vehicles are 50% higher than internal combustion engine vehicles.
- Traction battery production causes about 20% greenhouse gas emissions increase.
- 10% variations of curb weight, electricity and Li-ion battery production affect the results by 7%, 4% and 2%.
- Manufacturing technique improvement, vehicle recycling and energy structure optimization are major mitigation opportunities.

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ABSTRACT

Electric drive vehicles are equipped with totally different propulsion systems compared with conventional vehicles, for which the energy consumption and cradle-to-gate greenhouse gas emissions associated with vehicle production could substantially change. In this study, the life cycle energy consumption and greenhouse gas emissions of vehicle production are compared between battery electric and internal combustion engine vehicles in China's context. The results reveal that the energy consumption and greenhouse gas emissions of a battery electric vehicle production range from 92.4 to 94.3 GJ and 15.0 to 15.2 t CO_2eq, which are about 50% higher than those of an internal combustion engine vehicle, 63.5 GJ and 10.0 t CO_2eq. This substantial change can be mainly attributed to the production of traction batteries, the essential components for battery electric vehicles. Moreover, the larger weight and different weight distribution of materials used in battery electric vehicles also contribute to the larger environmental impact. This situation can be improved through the development of new traction battery production techniques, vehicle recycling and a low-carbon energy structure.

1. Introduction

Electric Drive Vehicles (EDVs) are considered to be environmentally-friendly and have attracted much attention worldwide, and Battery Electric Vehicles (BEVs) are the most popular vehicles among all kinds of EDVs. In China, the country with the world's largest automotive market, the government is determined to develop BEV industry and produced over 250 thousand BEVs in 2015, and the annual growth rate was 420% [1]. In addition, according to the production plan, the cumulative output of BEVs in China will reach 5 million in 2020, meaning that BEVs will gradually replace Internal Combustion Engine Vehicles (ICEVs) [2]. Under such circumstances, the proportion of different kinds of vehicles produced worldwide will face significant changes in the coming years [3], which will influence the evaluation methods

Abbreviations: ANL, Argonne National Laboratory; ASCM, Automotive System Cost Model; BEV, battery electric vehicle; BF-BOF, Blast Furnace-Basic Oxygen Furnace; BFG, Blast Furnace Gas; CAAM, China Association of Automobile Manufacturers; COG, Coke Oven Gas; CTG, cradle-to-gate; EAF, Electric Arc Furnace; EDV, electric drive vehicle; ELV, End-of-Life Vehicle; GDP, Gross Domestic Product; GHG, greenhouse gas; GREET, Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model; HEV, Hybrid Electric Vehicle; HVAC, heating, ventilating and air conditioning; ICEV, internal combustion engine vehicle; IEA, International Energy Agency; INDCs, Intended Nationally Determined Contributions; IPCC, Intergovernmental Panel on Climate Change; LCA, life cycle assessment; LFP, $LiFePO_4$; NMC, $Li(NiCoMn)O_2$; NBSC, National Bureau of Statistics of China; NDRC, National Development and Reform Commission; OICA, Organisation Internationale des Constructeurs d'Automobiles; WTW, Well-to-Wheel.

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and results of the energy consumption and environmental impact associated with future vehicles, especially in China.

In recent years, many scholars have carried out research on this subject and provided several important results. However, many of them paid more attention to the use phase, which is also called the Well-to-Wheel (WTW) stage. Lewis (2014) evaluated the life cycle environmental benefits of vehicle electrification and weight reduction, which was mainly based on the fuel combustion during the use phase [4]. Yuan (2015) estimated the energy consumption and WTW CO_2 emissions of BEV range in China. It was indicated that short driving range and low speeds could help reduce the environmental impact [5]. Zeng (2016) paid attention to the WTW GHG emissions of conventional motor vehicles in China, pointing out that low-carbon policies in road transportation was necessary [6]. Oris (2016) provided the estimation results about the environmental impact of vehicles in five different countries, revealing that BEVs were the potential alternatives which can help reduce fuel consumption and emissions in the transport sector [7]. Bicer (2016) conducted research on the emissions from vehicles using different fuels, such as hydrogen, methanol and electricity. Hydrogen driven vehicles were proved to be more environmentally-friendly [8]. Onn (2017) compared the WTW emissions of several kinds of vehicles on the Malaysian electricity mix. The results indicated that Hybrid Electric Vehicles (HEVs) were promised to be cleaner for developing countries [9].

Although the use phase is dominant when considering the life cycle environmental impact, the production phase is an important supplement and has caused wide concern due to the great environmental impact of traction battery production. Hawkins (2013) established a complete Life Cycle Assessment (LCA) model for vehicles, including production, use, disposal and recycling. The author pointed out that although the energy consumption and emissions from the use phase generally accounted for the majority, the influence of the production phase is significant [10]. Sharma (2013) qualified the performance of BEVs on Greenhouse Gas (GHG) emissions under the Australian driving conditions [11]. The vehicle production phase was studied by decomposing the vehicles into several major parts. Wang (2013) estimated the life cycle emissions of different vehicles in China and pointed out that the performance of BEVs was not ideal with China's generation mix and manufacturing techniques [12]. Nanaki (2013) paid attention to both vehicle production and use phases of vehicles in Greece. It proved that the source of electricity could greatly affect the benefits of BEVs [13]. Tagliaferria (2016) calculated the total environmental burdens of BEVs under the technology system of Europe, finding that BEV production was the major impediment to performance [14].

Existing studies have provided an important conclusion that BEV production was not exactly perceived in many countries, and the situation must be improved to avoid a negative influence. In fact, with the rapid growth of the automotive industry, global vehicle production reached 90.8 million in 2015 [15] and contributed about 5.6 billion tons of CO_2 emissions to the total level of the manufacturing sector, which accounted for over one third of the energy-related CO_2 emissions [16]. When it comes to China's case, the government announced in the Intended Nationally Determined Contributions (INDCs) in 2015 that the national CO_2 emissions would reach a peak before 2030 and the CO_2 emissions per unit of Gross Domestic Product (GDP) were expected to decrease by 60–65% compared to the number in 2005 [17]. The development of BEVs has been prioritized to help achieve the target and BEV production has already become one of the major concerns.

On the other hand, the environmental impact of vehicle production vary greatly owing to discrepancies in manufacturing techniques. Although several referential results have provided by former research, they are far from perfect due to the huge regional differences. Since nobody has anticipated the rapid growth of electric drive vehicles in China, the country with relatively weak manufacturing base and coal based energy structure, most of the former studies were based on the manufacturing process in developed countries and paid little attention to China's case. Only a few studies have mentioned the situation in China with little detailed analysis concentrated on the production phase.

To delve into this subject, this study places emphasis on energy consumption and GHG emissions from vehicle production, especially for BEV production in China, a promising country with the world's largest vehicle output. In order to describe the situation comprehensively, this study employs a Cradle-to-Gate (CTG) framework, in which all the processes, including material production, energy transformation, components production and assembly, are considered. Furthermore, a China-specific database consisting of the relevant data from representative enterprises and a wide range of literature studies is established. This study aims to provide important results on energy consumption and GHG emissions associated with each component, material and energy source throughout the entire vehicle production process in China, which is an important reference for the government to make decisions. Furthermore, the results can help find out major reduction opportunities in the future.

2. Methods

2.1. Assumptions and system boundary

A complete CTG system has been employed in this study, including material production and transformation, component manufacturing, battery and other attachment production, assembling and replacements. According to the enterprise investigation and literature review, most of the materials and energy consumed during vehicle production are produced in China. Only a few ores, such as lithium ores, are imported from other countries because China does not have enough resources, and this situation causes minor environmental impact. Therefore, this study assumes that all the vehicle production processes occur in China. Table 1 presents the components in ICEVs and BEVs. Fig. 1 presents the stages considered and the calculation logic of the energy consumption and GHG emissions of the entire process. The distribution, use and disposal of vehicles are not included in the system as this study aims to explore the environmental impact of vehicle produc-

Table 1
Components in ICEVs and BEVs.

ICEV	BEV
Common components	
Body: including body-in-white, interior, exterior, and glass	
Chassis (without battery)	
Respective components	
Powertrain system	
Engine unit	Powertrain thermal system
Engine fuel storage system	Powertrain electrical system
Powertrain thermal system	...
Exhaust systemEmission control electronics	
Powertrain electrical system	
...	
Transmission system	
Automatic transmission	Continuously variable transmission
Torque converter	Single-ratio gearbox
...	...
Traction motor	
/	Traction motor
Electronic controller	
/	Electronic controller

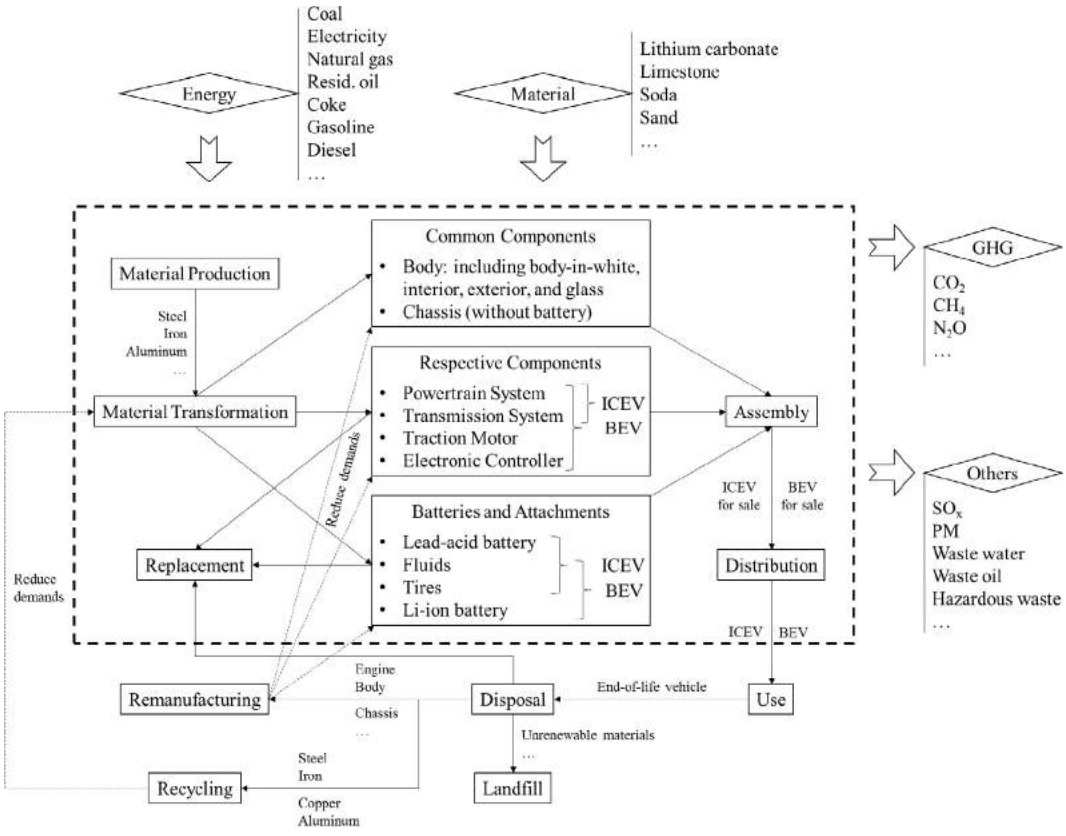

Fig. 1. Vehicle production model and boundary defined.

tion. The negligible energy consumption and GHG emissions caused by few materials used in auxiliary, such as kaolin, are not calculated.

For more details, material production and transformation refer to the entire process from ore mining and extraction to shaping. The components and attachments are divided into three parts: common components represent the general components of ICEVs and BEVs, such as the body and chassis; respective components represent the different systems between ICEVs and BEVs, such as the automatic transmission for an ICEV and the continuously variable transmission for a BEV; batteries and attachments represent the extra supplements of ICEVs and BEVs. Assembly not only includes the gathering of essential components, but also takes pre-techniques such as stamping, welding and painting into consideration. Distribution is the transport process for both ICEVs and BEVs. Replacement refers to the production, transport and assembly of the components should be replaced during the vehicle's life time, such as tires and batteries. In addition, transportation of materials and components should be considered. According to the investigated enterprises, the factories are always built close to the suppliers to reduce transportation costs. Therefore, the standard 9.3 t-load trucks are most commonly used to cover the distance of about 100 km. Otherwise, other transportations are more efficient in some special cases. For instance, China is not able to mine and process a mass of lithium ores, and most of lithium products are imported from Chile. Under such circumstances, ships are more likely to be used for transportation. However, such circumstances are quite rare when considering the entire vehicle production process. In order to evaluate the major effect of transportation, this study assumes that manufacturers use the standard 9.3 t-load trucks, and the distance to cover is about 100 km. Error exists due to the various transportations adopted by different manufacturers to cover different distances, but it is not significant according to our investigations and other reliable model assumptions [18].

When it comes to the energy consumption and GHG emissions, all the energy related processes are taken into consideration, as well as both direct emissions and indirect emissions under the definition of Scope 3 [19]. In short, GHG emissions are estimated based on the manufacturing techniques, which determine the materials, energy input and non-combustion GHG emissions. Additionally, the emissions associated with materials and energy are estimated throughout their entire life cycles, including extraction, processing and consumption.

2.2. Vehicle specifications

As mentioned above, over 250,000 BEVs have been produced in China during 2015, but this is small-scale in comparison to China's over 24 million vehicles production [1]. Meanwhile, the annual growth rate of BEVs was nearly 100 times larger than the growth rate of ICEVs [20]. Therefore, in order to provide the most representative result now and in the future, standard mid-size ICEVs and BEVs with conventional materials are chosen as the reference vehicles in this study, as presented in Table 2. The reference vehicles have similar common components and different propulsion technologies, which are similar in dynamic and endurance performances.

As the weight distributions of the same vehicles are similar worldwide and China's context is unclear, this study employs the general parameters from the Automotive System Cost Model (ASCM) established by Oak Ridge National Laboratory [21]. Some additional parameters, such as the weight distribution of attachments and fluids, are imported from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) established by Argonne National Laboratory (ANL) [22]. In detail,

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Table 2
Material composition for the reference vehicles.

ICEV without batteries, tires and fluids (kg)		BEV without batteries, tires and fluids (kg)	
Total	1292	Total	1692
(a) Major parts			
Steel	805	Steel	1123
Cast iron	141	Cast iron	34
Wrought aluminum	28	Wrought aluminum	18
Cast aluminum	60	Cast aluminum	93
Copper	24	Copper	79
Magnesium	0	Magnesium	0
Glass	37	Glass	59
Average plastic	144	Average plastic	205
Rubber	29	Rubber	30
Others	24	Others	51
Sources	[21,22]		

NMC battery (kg)		LFP battery (kg)		Others (kg)	
Total	171	Total	228	Lead-acid battery	15(2)
(b) Batteries and others					
Active material	48	Active material	56	Polypropylene	1
Graphite/carbon	0	Graphite/carbon	0	Lead	11
Binder	0	Binder	0	Sulfuric acid	1
Copper	0	Copper	0	Fiberglass	0
Wrought aluminum	31	Wrought aluminum	35	Water	2
Electrolyte: $LiPF_6$	0	Electrolyte: $LiPF_6$	0	Others	0
Ethylene Carbonate	4	Ethylene Carbonate	5	**Tires**	**36(3)**
Dimethyl Carbonate	19	Dimethyl Carbonate	28	Steel	12
Polypropylene	34	Polypropylene	47	Rubber	24
Polyethylene	0	Polyethylene	0	**Fluids**	**26**
Polyethylene terephthalate	3	Polyethylene terephthalate	6	Brake fluid	1(3)
Steel	9	Steel	18	Transmission fluid	1(1)
Thermal insulation	9	Thermal insulation	18	Windshield fluid	3(19)
Coolant: Glycol	3	Coolant: Glycol	4	Adhesives	14
Electronic Parts	1	Electronic Parts	1	Powertrain coolant	7(3)
Sources	[24]			[22]	

Notes:
(a) Numbers in the parentheses denote the replacing times during the vehicle's life time (omit zero).
(b) Tires for both kinds of vehicles are defined as standard radial tires.
(c) External loss, such as the depreciation of facilities for assembly, are not considered.

the total weight has been adjusted based on the average case in MY2010 of the Autonomie model, and most of the parameters are estimated through enterprise investigations, literature reviews and dismantling reports. The weight distribution of most components is included, as well as various reliable advanced technologies. For instance, the specifications of battery in BEVs are considered based on the development of traction battery industry in China. According to the industry research, $LiFePO_4$ (LFP) batteries shared about 52% of the entire market in China in 2015. While the number for $Li(NiCoMn)O_2$ (NMC) batteries is 39%, and other kinds of batteries haven't formed scale [23]. Therefore, LFP and NMC batteries are both chosen as the objects and have formed a bifurcation in this study. When it comes to battery specification, due to the lack of clear technical standards in China, this study utilizes the parameters provided by the Battery Performance and Cost (BatPaC) model [24], which are normalized through existing literatures and reports.

2.3. Mathematical formulation

The energy consumption and GHG emissions of all the vehicles and different components can be calculated through Eqs. (1)–(6).

$$EC = \sum_i \sum_j EC_{Si,j} \tag{1}$$

$$GE = \sum_i GE_{NCi} + \sum_i \sum_j GE_{Si,j} \tag{2}$$

where EC denotes the total life cycle energy consumption per ICEV/BEV (MJ); $EC_{Si,j}$ denotes the consumption of energy j during the stage i per ICEV/BEV (MJ); GE denotes the total life cycle GHG emissions per ICEV/BEV (kg CO_2eq); GE_{NCi} denotes the non-combustion GHG emissions during stage i per ICEV/BEV (kg CO_2eq); $GE_{Si,j}$ denotes the GHG emissions of energy j consumed during the stage i per ICEV/BEV (kg CO_2eq);

$$EC_{Si,j} = \sum_k m_k EC_{i,j,k} \tag{3}$$

$$GE_{NCi} = \sum_k m_k (GE_{mi,k} + \sum_p M_p GE_{Mi,p}) \tag{4}$$

$$GE_{Si,j} = \sum_k m_k GE_{i,j,k} \tag{5}$$

where m_k denotes the weight of material k per ICEV/BEV (t); M_p denotes the weight of material p input per ICEV/BEV (t); $EC_{i,j,k}$ denotes the consumption of energy j associated with every t of material k during the stage i (MJ/t); $GE_{mi,k}$ denotes the non-combustion GHG emissions associated with every t of material k during the stage i (kg CO_2eq/t); $GE_{Mi,k}$ denotes the GHG emissions associated with the input of material p (e.g. kaolin) for every t of material k during the stage i (kg CO_2eq/t); $GE_{i,j,k}$ denotes the GHG emissions of energy j consumed for every t of material k during the stage i (kg CO_2eq/t);

$$GE_{i,j,k} = EF_j EC_{i,j,k} \tag{6}$$

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

2.4. Data

2.4.1. Material production and transformation for components production

Table 3 presents energy consumption from the production and transformation of materials used in vehicles without batteries, tires and fluids. As mentioned in Table 1, although an ICEV or BEV (without batteries, tires and fluids) is made up of various different materials, and several certain materials such as steel, iron, aluminum, copper and plastic account for over 90% by weight. Therefore, this study focuses on these materials and analyzes their cradle-to-gate energy consumption and GHG emissions in details. For the other materials, due to the lack of reliable data in China, the reference results from GREET [18], Keoleian et al. [25], Burnham et al. [26] and Brown [27] are imported.

The steel production and transformation defined in this study comprises iron ore extraction, ore processing, coke production, sintering, iron-making, steel-making and steel transformation. The Blast Furnace-Basic Oxygen Furnace (BF-BOF) technique and the Electric Arc Furnace (EAF) technique are chosen as the iron-making and steel-making methods according to the proportion [28]. Subsequent steps such as casting, rolling and cutting are also included followed by transformation techniques including stamping and machining to prepare the steel for component production. Most of the data is derived from one of the biggest steel factories in China [29], while the coke production is considered based on the reports of Chinese coke producers [21]. The data for steel transformation is imported from GREET [18].

The iron used in vehicles is mostly for the engine, indicating that the transformation process consists of iron casting, forging and machining. The pre-treatment process of casting iron is similar with steel, including ore extraction and processing. The additional data is gathered from GREET.

The aluminum is divided into two parts: cast aluminum and wrought aluminum, which is distinguished by the processing methods. Before transformation, the process includes bauxite mining, anode and alumina production, smelting and lastly producing the ingots. The data related to aluminum production is based on the estimation of primary aluminum production in China [30], while the other data is gathered from GREET.

The copper is used mainly for wire drawing in vehicles, which only requires simple processing methods. In other words, most of the energy consumption and GHG emissions of copper production are created during primary production processes such as smelting and refining. In addition, compared with steel, aluminum and iron, copper content is minor in the vehicles. Therefore, this study only considers the specific energy consumption of copper. The energy consumption is estimated based on the manufacturing techniques in China [31].

Average plastic includes all kinds of plastic used in vehicles, such as polypropylene, polyethylene, acrylonitrile-butadienestyrene, and polyvinyl chloride Since the Chinese chemical plants have not reported reliable data, this study employs the data from GREET instead.

Table 4 is the supplement to Table 2, which is focused on the materials used in batteries and other attachments. Fluids are not included because they are considered as materials input and discussed in Section 2.4.3.

The active material is the most important part for Li-ion batteries. This causes a huge amount of energy consumption and GHG emissions. Since the Li-ion battery industry is still in a preliminary stage and is growing fast in China, detailed data is not obtainable and the total value is used instead, which is from one of China's major battery plants [32]. The total energy consumption and GHG emissions of the active material are 125,306 MJ/t, 1866 kg-CO_2eq/t for the NMC battery, and 113,017 MJ/t, 1641 kg-CO_2eq/t for the LFP battery.

Other materials refer to a series of supplementary materials to support the battery operation, including graphite/carbon, binder, copper, aluminum, electrolyte, plastic, steel, coolant, thermal insulation and electronic parts. Some of them, such as steel, aluminum, copper and plastic, have been analyzed above. Others are estimated based on the common production techniques [33].

Rubber is the key material of tires, and tire industry is well developed in China. In this study, the whole process from exploitation to tire shaping is taken into consideration. And the data is employed from a general radial tire plant in China [34].

2.4.2. Components and vehicle assembly

The assembling process has been divided into six parts: paint production [35] and painting [36], Heating, Ventilation and Air Conditioning (HVAC) and lighting, material handling, heating, air compressing and welding [37]. The battery assembly is considered based on China's situation [38]. Table 5 presents the detailed energy consumption of them.

2.4.3. GHG emission factors

GHG emissions are identified as the combination of CO_2, CH_4 and N_2O emissions in this study, while they are converted into CO_2 equivalent (CO_2eq), and the global warming potentials are 1, 25 and 298. This study estimates the GHG emissions through energy and material consumption. Therefore, the life cycle emission factors of different kinds of energy are important to insure reliable results, as presented by Table 6.

The life cycle GHG emissions associated with energy are from production and combustion stages. In detail, the GHG emissions from the production of coal, natural gas, residual oil, gasoline, die-

Table 3
Energy consumption of the production and transformation of materials used in vehicles (without batteries, tires and fluids).

Energy consumption (MJ/t)	Steel	Iron	Aluminum		Copper	Average plastic
			Wrought	Cast		
Total	45,571	9299	68,161	73,771	26,225	25,534
Coal	21,300	0	47,802	50,426	4387	433
Electricity	2001	692	14,660	15,368	5460	1492
Natural gas	8277	5742	5699	7977	0	19,784
Coke	12,117	2639	0	0	0	0
Residual oil	253	194	0	0	6812	3566
Gasoline	3	2	0	0	0	62
Diesel	39	30	0	0	9566	1,97
BFG	1087	0	0	0	0	0
COG	494	0	0	0	0	0
Sources	[18,29,43]	[18]	[18,30]		[31]	[18]

Table 4
Energy consumption of the production and transformation of materials used in batteries and other attachments.

Energy consumption (MJ/t)	Active material		Other materials		Rubber
	NMC	LFP	NMC	LFP	
Total	125,306	113,017	59,514	52,464	40,051
Coal	/	/	11,992	12,067	0
Electricity	/	/	40,630	32,871	751
Natural gas	/	/	4408	4753	21,639
Coke	/	/	173	187	0
Residual oil	/	/	1188	1369	17,661
Gasoline	/	/	1	1	0
Diesel	/	/	1098	1191	0
BFG	/	/	17	17	0
COG	/	/	7	8	0
Sources	[32]		[33]		[34]

Table 5
Energy consumption of components and vehicle assembly.

Energy consumption (MJ per vehicle)	Painting	HVAC and lighting	Material handling	Heating	Air compressing	Welding	Battery assembly		
							NMC	LFP	Lead-acid
Total	2727	290	60	3143	80	120	257	257	40
Coal	0	0	0	0	0	0	0	0	0
Electricity	302	290	60	0	80	120	162	162	15
Natural gas	2425	0	0	3143	0	0	95	95	25
Sources	[35–37]						[38]		

Table 6
Life cycle GHG emission factors.

Life cycle GHG emission factors (g-CO_2eq/MJ, g-CO_2eq/kWh)	Production	Combustion	Total	Sources
Coal	2.4	95.1	97.5	[39,40,44]
Electricity	834.5	/	834.5	[41,42]
Natural gas	8.6	56.2	64.8	[39,40,44]
Coke	/	107.5	107.5	[43,44]
Residual oil	14.0	77.7	91.7	[39,40,44]
Gasoline	18.1	69.6	87.7	[39,40,44]
Diesel	16.3	74.4	90.7	[39,40,44]
BFG	/	260.1	260.1	[44]
COG	/	44.5	44.5	[44]

Note:
(a) Blast Furnace Gas (BFG) and Coke Oven Gas (COG) are the by-products of coke production, indicating that the emission factors are included in the factor of coke production.
(b) Supplies used during the material production process, such as limestone, steam and oxygen, are calculated in terms of the energy (listed above) used based on the GREET model.

sel are estimated based on China's circumstance [39] and the data is imported from SinoCenter database [40]. The GHG emission factor of electricity is considered more carefully. Since China is a big country, the provincial emission factors vary among a wide range. Meanwhile, vehicle production is related to various industries throughout the country, which makes it unreasonable to use the factor in one certain region. Therefore, this study estimates the provincial average GHG emission factor through the provincial grid emission factors [41] and the weighted average generating capacity [42]. As mentioned above, the emission factor of coke production is imported from the reports of Chinese coke producers [43]. When it comes to the energy combustion, this study assumes that the combustion modes in China conform to the international standard. Therefore, the emission factors are imported from the Intergovernmental Panel on Climate Change (IPCC) guidelines [44].

3. Results and analysis

3.1. Overview

Fig. 2 presents the detailed energy consumption and GHG emissions of each component, material and energy source. It has been revealed that the total energy consumption and GHG emissions of a BEV with an NMC/LFP battery are 92,392 MJ, 15,005 kg CO_2-eq/94,341 MJ, 15,174 kg CO_2eq, which is 45%, 50%/48%, 52% greater than the level of an ICEV, 63,515 MJ, 9985 kg CO_2eq, respectively. In order to concisely highlight the core sectors, several sectors accounting for only a little proportion are not labeled in this figure. In short, the larger energy consumption and GHG emissions of BEVs are mainly caused by certain sectors, such as the Li-ion batteries, and steel.

3.2. Energy consumption and GHG emissions of each component

Fig. 3 presents the detailed energy consumption and GHG emissions of each component.

Clearly, energy consumption and GHG emissions of the body (including the body-in-white, interior, exterior and glass) and chassis (without battery) are 21,577 MJ, 2810 kg CO_2eq and 13,051 MJ, 1710 kg CO_2eq for an ICEV; 34,250 MJ, 4460 kg CO_2eq and 20,648 MJ, 2706 kg CO_2eq for a BEV with an NMC/LFP battery, the number is quite large for the reference vehicles. Li-ion batteries in the BEV cause huge amounts of additional energy consumption and GHG emissions. In actuality, the values for an NMC/LFP battery

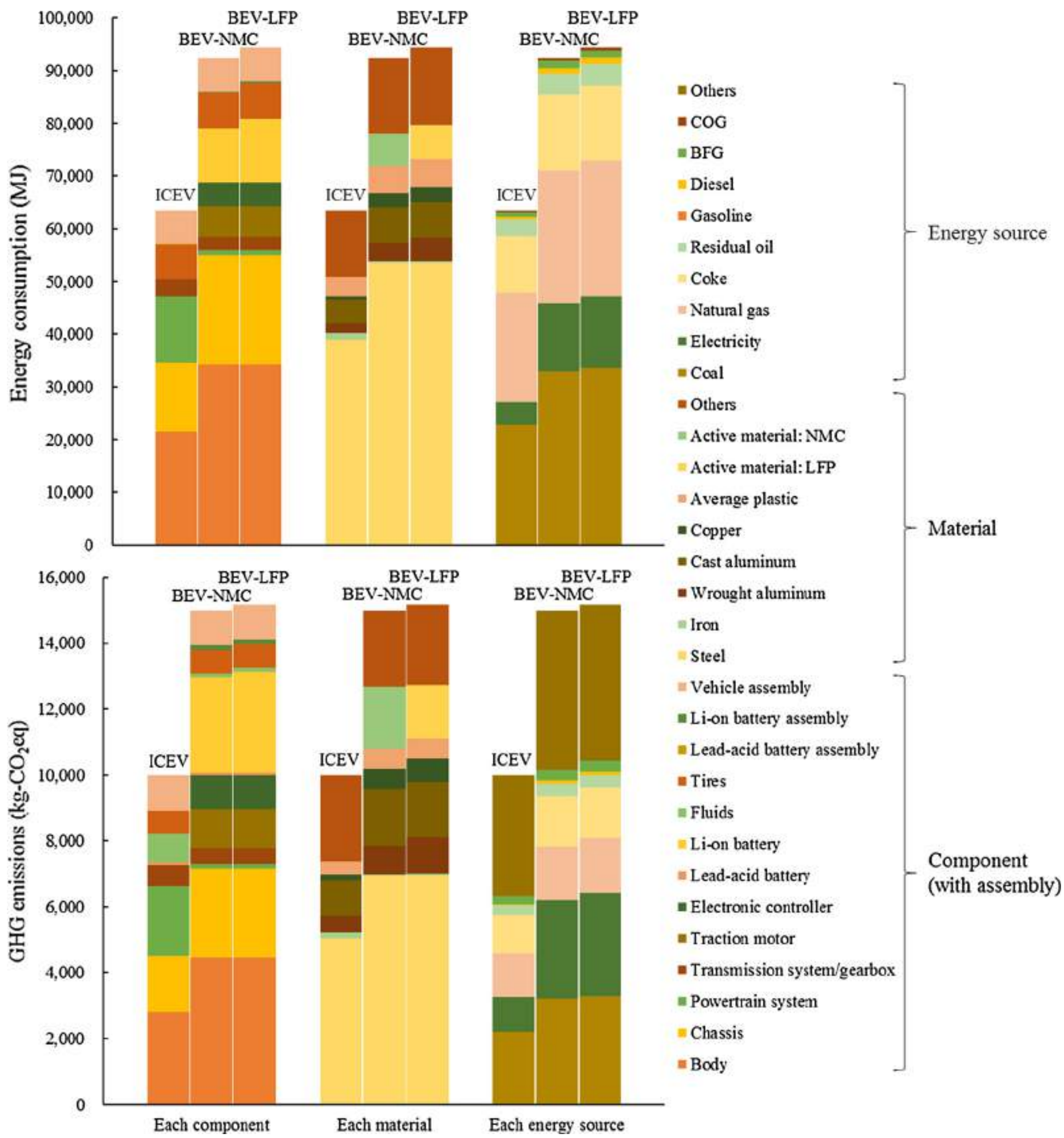

Fig. 2. Total energy consumption and GHG emissions.

are 10,117 MJ, 2896 kg CO_2eq/12,066 MJ, 3066 kg CO_2eq, which is determined that BEV production consumes more energy and emits more GHG. Furthermore, the energy consumption and GHG emissions of several other components of a BEV are also larger than those of an ICEV due to the larger weight.

3.3. Energy consumption and GHG emissions of each material

Fig. 4 presents the detailed energy consumption and GHG emissions of each material.

When it comes to the materials, steel appears to be dominant due to the vast consumption in both ICEVs and BEVs. The energy consumption and GHG emissions of steel are 38,881 MJ, 5048 kg CO_2eq for an ICEV, 53,498 MJ, 6946 kg CO_2eq for a BEV with an NMC battery, and 53,549 MJ, 6952 kg CO_2eq for a BEV with an LFP battery, accounting for the largest proportion. Aluminum is also an important material as it is used in several light-weight components. It is worth mentioning that the active materials used in an NMC/LFP battery result in 6,016/6334 MJ energy consumption and 1,866/1641 kg CO_2eq GHG emissions, and the preliminary production techniques in China are responsible for such large values.

3.4. Energy consumption and GHG emissions of each energy source

Fig. 5 presents the detailed energy consumption and GHG emissions of each energy source. The GHG emissions from 'Others' are relatively high due to various non-combustion emissions embedded in this sector. However, this section aims to analyze the energy consumption and GHG emissions from different kinds of energy, the 'Others' sector is not analyzed in details.

Based on the steel production techniques in China, huge amounts of coal and coke are consumed during the BF-BOF process, which leads to high GHG emissions associated with coal and coke. Natural gas and electricity are widely used for the production of various materials, as well as component/vehicle assembly. It has been revealed that the GHG emissions of electricity consumption account for a larger proportion than the electricity consumption itself does, indicating that the GHG emission factor of electricity is more significant than the average level among all kinds of energy in China.

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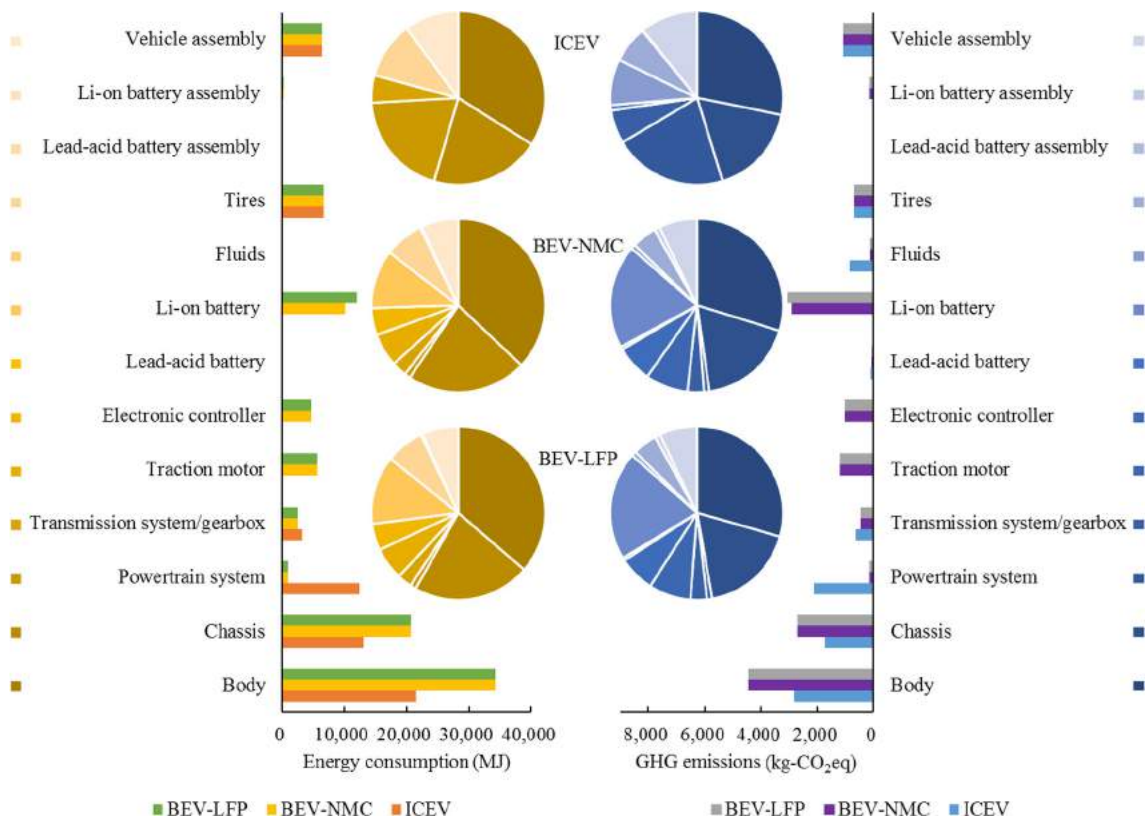

Fig. 3. Energy consumption and GHG emissions of each component.

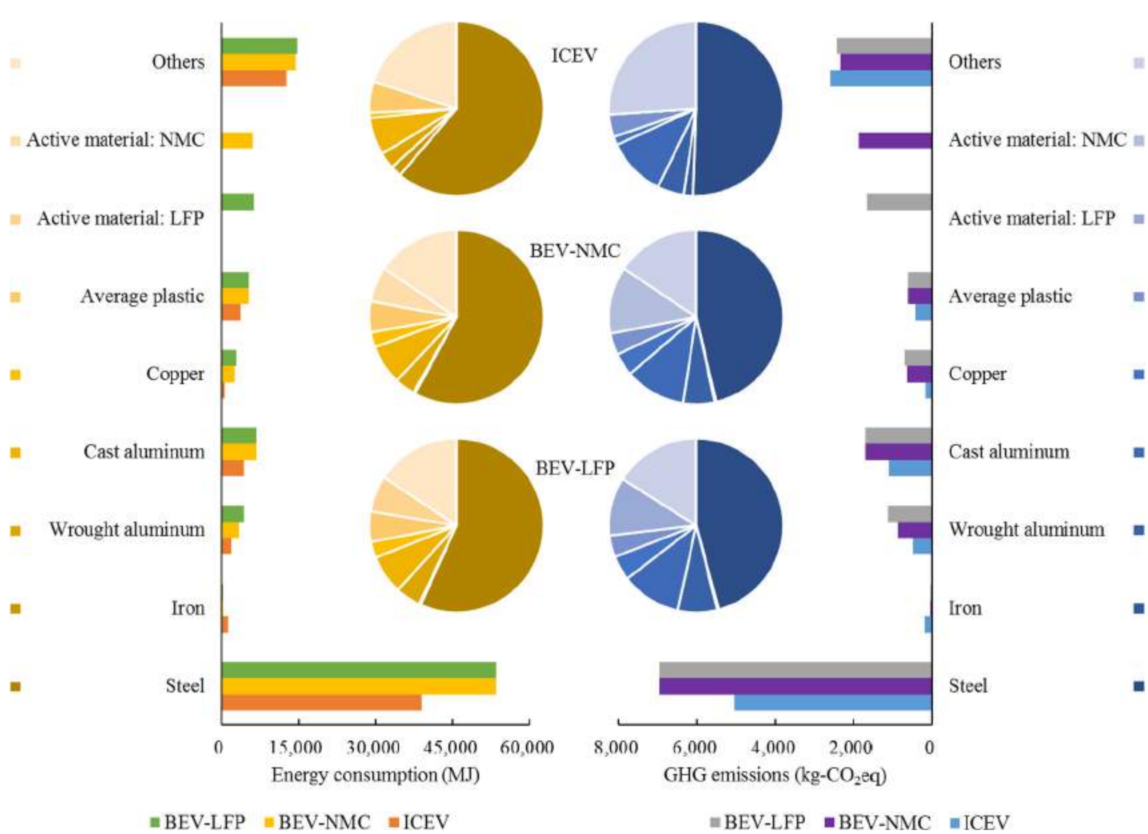

Fig. 4. Energy consumption and GHG emissions of each material.

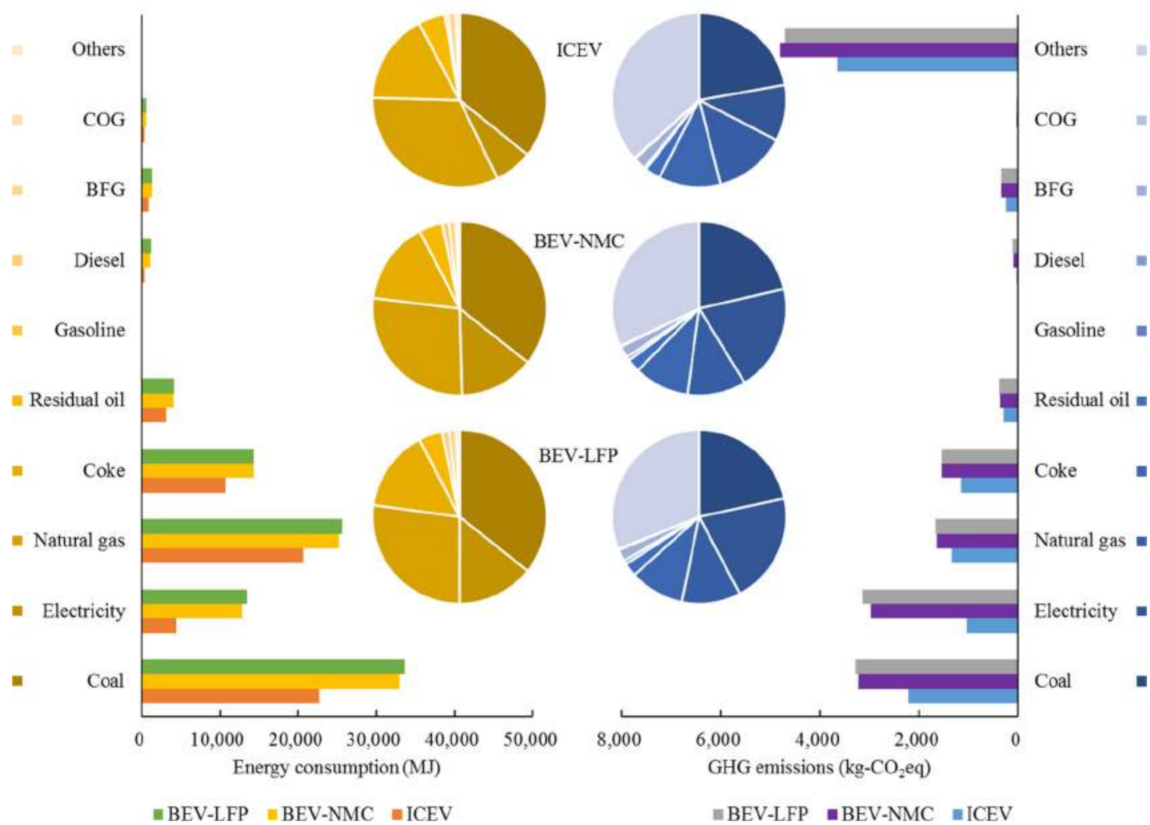

Fig. 5. Energy consumption and GHG emissions of each energy source.

3.5. Sensitivity analysis

According to the importance and technical trends of BEVs in China, three major sectors are analyzed in this section: curb weight; GHG emission factor of electricity production; energy consumption and GHG emissions of Li-ion battery production. Fig. 6 presents the results of analysis.

As mentioned in Section 2.2, the vehicle specifications are estimated based on enterprise investigations, literature reviews and dismantling reports. Errors exist due to the diversity of vehicles. In order to reflect the effect on results, this study calculated the energy consumption and GHG emissions when the curb weight is 10% heavier or lighter. As a result, the energy consumption of an ICEV, BEV-NMC and BEV-LFP are influenced by 8.0%, 7.5% and 7.3%, and the levels for GHG emissions are 7.3%, 6.7% and 6.6%.

On the other hand, a huge amount of electricity is consumed during vehicle production, and the GHG emission factor of electricity production is relatively large due to the coal-based grid mix in China. This study analyzes the effects by assuming a 10% larger or smaller GHG emission factor. Apparently, the energy consumption remains the same, and GHG emissions of an ICEV, BEV-NMC and BEV-LFP are influenced by 3.7%, 3.8% and 3.9%.

Furthermore, the Li-ion battery industry is in a preliminary stage in China, and very few studies were focused on the energy consumption and GHG emissions of the batteries, as well as the production standards. Therefore, this study considers the errors caused by Li-ion battery production. Parameter 0.9 and 1.1 are used to multiply the energy consumption and GHG emissions of an NMC/LFP battery production. Considering the total energy consumption and GHG emissions of a BEV with NMC/LFP battery, the decrements are 1.1%, 2.0%/1.3%, 2.0%, respectively. Due to the large uncertainty of the Li-ion battery production techniques, care must be taken when estimating the energy consumption and GHG emissions associated with batteries.

4. Discussion

4.1. Comparative simulation results

Several former research studies have provided benchmarks for the energy consumption or GHG emissions of ICEVs or BEVs. Argonne National Laboratory estimated the level in the U.S. and revealed that the GHG emissions of an ICEV are 7052 kg CO_2eq, and the number for an equivalent BEV with NMC/LFP battery was 9,450/9222 kg CO_2eq [18], which were significantly lower than the values in China. The more advanced Li-ion battery production techniques and matured vehicle recycling industry were the dominating reasons. Alternatively, the situation in Europe was quite different. Hawkins estimated the GHG emissions of mid-size ICEV and BEV production based on the Ecoinvent v2.2 database, and the results revealed that the GHG emissions of a BEV with an NMC/LFP battery were 13/14 t CO_2eq, while an equivalent ICEV only emitted 6.5 t CO_2eq [10]. In Australia, the situation was even worse because of the large GHG emission factor of electricity. A B-class BEV produced in Australia would create about 13 t CO_2eq, and the number for an equivalent ICEV was about 8 t CO_2eq [11]. When it came to the situation in China, Wang evaluated the environmental impact of a B-class BEV produced in China. The author pointed out that about 10.2 t CO_2eq would be created if 40% of the materials used in the vehicle were recycled materials. The number was relatively small due to the large proportion of recycled materials [12].

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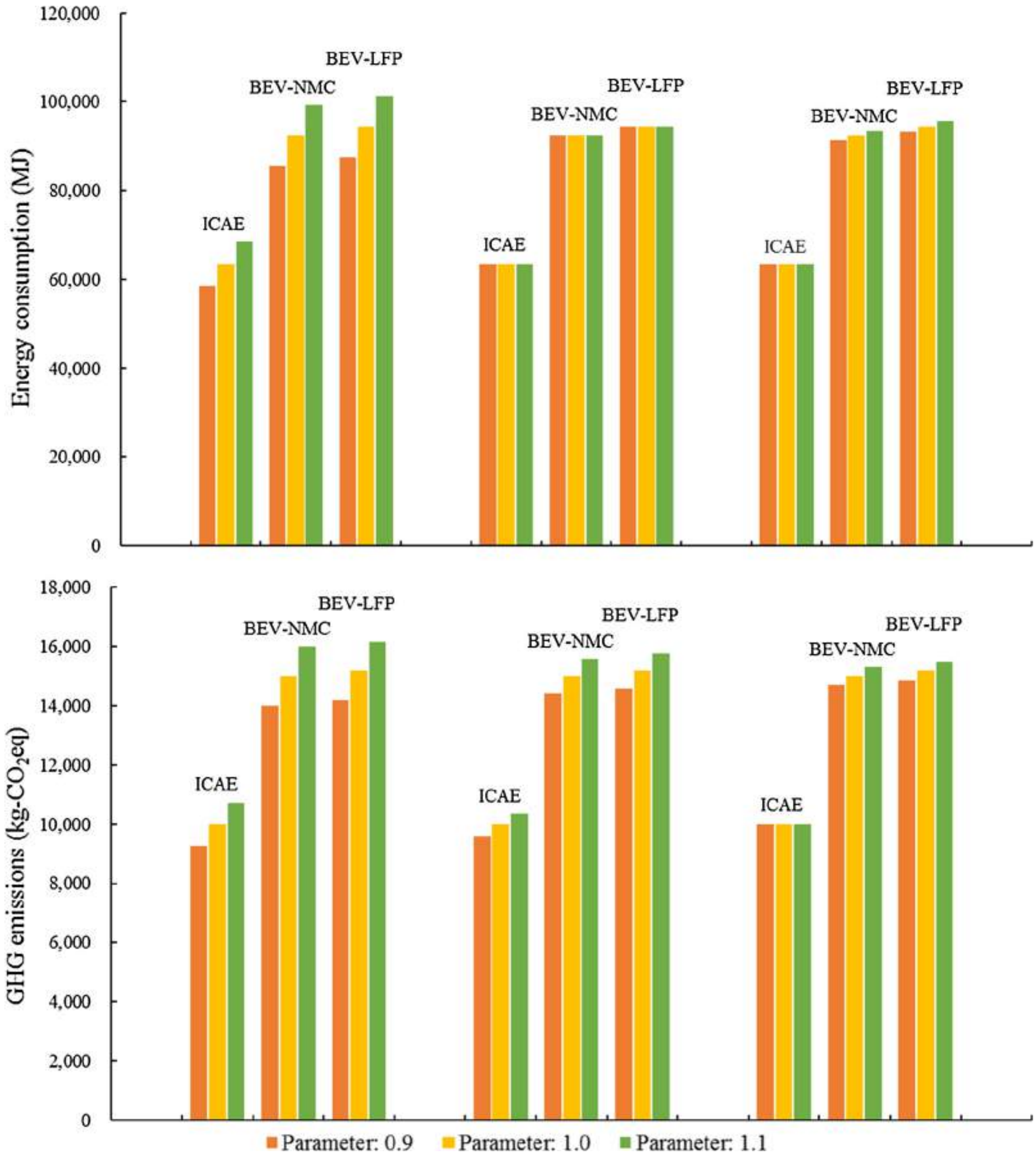

Fig. 6. Energy consumption and GHG emissions when (a) curb weight, (b) GHG emission factor of electricity production, (c) energy consumption and GHG emissions of Li-ion battery production are multiplied by sensitivity parameters.

In short, the results vary in a wide range among different regions due to the variable production techniques and auxiliary industries. However, all the reference results have showed that the environmental impact of BEV production is much worse than it of ICEV production, which matches the results in this study.

4.2. Mitigation opportunities

BEVs are designed to obtain more environmental benefits, but the energy consumption and GHG emissions of BEV production are much larger than those of ICEV production in China. According to the results in this study, several mitigation opportunities can be expected:

(a) From a component point of view, Li-ion battery production techniques have a large room for improvement. The U.S. has cleaner production techniques for Li-ion batteries, which only lead to about 1.1 t CO_2eq GHG emissions for NCM/LFP battery production [18], one third of the level in China. Furthermore, the manufacturing techniques of other parts can be improved as well. For example, if the best available technologies are adopted by the steel production, the energy consumption can be reduced from 45.6 GJ/t to 21.0 GJ/t [18], which can save up to 30% of the total energy consumed during vehicle production.

In order to improve the situation, Chinese government should pay more attention to integrate or outlaw the scattered midget plants and promote leading plants to research and develop more advanced products. There is no doubt that the products from midget plants are cheaper and have lower performance. They are profitable but inhibit the motivation to develop advanced products. In recent years, China has already introduced a series of policies to rule the manufacturing industry, but the regulatory power remains to be enhanced.

(b) From a material point of view, the vehicle recycling industry ought to be developed in China. The energy consumption and GHG emissions of several materials production, such as steel, aluminum and active materials, are quite large.

Although not all the materials in the vehicles can be recycled. This circumstance can be effectively improved by using recycled materials. However, the recycled steel only accounts for 11% of the total steel consumption in China, while the proportion is 56% in the EU, 70% in the U.S. and 90% in Turkey [45]. For example, 3.1 t CO_2eq GHG emissions can be reduced by recycling an 1145 kg ICEV in China, implying a similar reduction rate for the BEVs without batteries [46]. In addition, considering the situation in the U. S., the reduction rate of the energy consumption and GHG emissions of the Li-ion battery production is up to 48% by battery recycling [47].

In order to gain environmental benefits from vehicle recycling, a series of measures should be taken. First, an efficient law and regulation system is necessary. Globally, vehicle recycling has attracted much attention and is well managed in many developed countries. In the U.S., driven by the profits and strict regulations, over 95% of the End-of-Life Vehicles (ELVs) are taken into recycling by specific enterprises, and about 80% of the materials can be recovered [48]. In the EU, all the European Member States are forced by the European Directive 2000/53/EC to guarantee the 85% recycling rate for ELVs, and 95% of the materials should be recovered [49]. In Japan, a series of regulations focused on ELV management have been put into application since 2005. Unofficial leagues, which consist of vehicle manufacturers, recycling enterprises and non-profit organizations, play important roles in the vehicle recycling industry. Forced by the government and leagues, the recycling rate of ELVs reached 95% in 2015 [50]. In China, although detailed regulations have been introduced since 2001, a large number of ELVs are still managed illegally. The disorderly market and weak regulatory power make formal recycling enterprises hardly survive [51]. Taking the cases in developed countries as references, Chinese government should define the responsibilities of each participant in the vehicle recycling industry. For example, vehicle manufacturers in the U.S. and EU are responsible for the vehicle recycling, and they will be seriously punished if ELVs are not recycled appropriately. Chinese government is trying to establish a similar system, but it may take a long time to form the regulatory power.

Secondly, market mechanism can help establish the vehicle recycling industry. In fact, vehicle recycling, especially Li-ion battery recycling, is profitable. For example, as mentioned in the former section, China is poor at lithium ore mining and processing, and most of the lithium products are imported from Chile, which partly results in the high cost of Li-ion production. Li-ion battery recycling is an efficient way to provide lithium products, such as the NMC material [47], which is the meaningful for both manufacturers and recycling enterprises. Actually, the leading vehicle recycling enterprises, such as Brunp Recycling, are growing rapidly in recent years. Chinese government can take advantage of the market mechanism to support formal enterprises.

Finally, China should pay attention to develop effective vehicle recycling techniques. A complete vehicle recycling process in developed countries is made up of three major stages: dismantling, shredding and post-shredding-treatments [52]. However, most domestic vehicle recycling enterprises in China are still in a preliminary stage, in which only basic techniques are adopted to recycle steel, iron scraps and rubber at low rates [46]. These enterprises have weak research and development power and little motivation to improve themselves, which do not contribute to the vehicle recycling industry in China. Therefore, the government can improve the standards for vehicle recycling enterprises and support the leading ones to develop advanced techniques. Furthermore, the Li-ion battery recycling techniques are different from normal vehicle recycling techniques. The most widely adopted technique is the hydrometallurgical process, which has been optimized by Retriev Technologies, one of the leading battery recycling enterprises in North America [53]. In China, the battery recycling industry is developed in only a few years and there are not many enterprises. The leading battery recycling enterprises have already been able to carry out the advanced hydrometallurgical process [54]. The government can support these enterprises and set relatively high standards for battery recycling enterprises to guarantee the orderly market.

(c) From an energy point of view, China is paying attention to optimizing the energy structure and reducing the emission factors of the grid mix. For example, the application of solar power, nuclear power and wind power is bound to reduce the emission factor of electricity, 835 g CO_2eq/kWh in China, which is much higher than that in the U.S., 609 g CO_2eq/kWh [18]. Therefore, the GHG emissions of vehicle production can be reduced indirectly.

On the other hand, as mentioned above, the GHG emission factor of electricity varies significantly among different provinces. Chinese government can consider supporting the manufacturing plants carrying out energy intensive processes in the provinces with low emission factors. For instance, GHG emissions of primary aluminum production vary from 8.2 (Qinghai) to 21.7 (Inner Mongolia) t-CO_2eq/t-ingot due to the huge amount of electricity consumed during the production process and the large disparity between the factors in Qinghai and Inner Mongolia [30]. In fact, the government aims to reduce the industrial pollution and has introduced policies to support the factories built in the northwest, causing that China's industrial center is gradually moving from northeast China to northwest China [55].

5. Conclusions

In order to reflect the environmental impact when ICEVs are replaced with BEVs in China, the country with the largest BEV output and automotive market worldwide, this study estimates the CTG energy consumption and GHG emissions of vehicles, which is an important phase during the vehicle life cycle. Standard mid-size passenger ICEV and BEV with NMC/LFP batteries are chosen as the reference vehicles. The total energy consumption and GHG emissions are 63,515 MJ, 9985 kg CO_2eq for an ICEV, 92,392 MJ, 15,005 kg CO_2eq for a BEV with an NMC battery and 94,341 MJ, 15,174 kg CO_2eq for an EV with an LFP battery. Comparatively speaking, the values for an EV are about 50% higher than those for an ICEV. The results are analyzed from each component, material and energy source points of view. Considering the components, Li-ion batteries incur nearly 13% of total energy consumption and 20% of total GHG emissions of BEV production. From a material point of view, steel, aluminum and active materials lead to about 60%, 10% and 7% of total energy consumption and 50%, 17% and 11% of total GHG emissions respectively. When it comes to energy sources, coal, coke, electricity and natural gas account for about 36%, 16%, 10% and 30% of total energy consumption.

Aiming to find out the mitigation opportunities, this study analyzes three major methods. First, manufacturing techniques, especially energy intensive processes, can be improved to reduce the energy consumption and then the GHG emissions. For example, a Li-ion battery produced in the U.S. only creates one third of the GHG emissions of it produced in China. Secondly, vehicle recycling is an efficient way to reduce the material consumption, which indirectly reduce the energy consumption and GHG emissions. If all the vehicle materials can be recycled to produce new vehicles, about 30% of the energy consumption and GHG emissions can be saved.

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Finally, the energy structure in China is being improved gradually. The fossil fuels are replaced with renewable and clean energy such as solar power, which helps reduce the GHG emission factor of electricity to approach the level in developed countries. This will reduce the GHG emissions of vehicle production as well.

Errors exist due to the uncertain curb weight, GHG emission factor of electricity production and Li-ion battery production technique. Therefore, sensitivity analysis is carried out to evaluate the effect of these three sectors. As a result, when the curb weight, GHG emission factor of electricity production, or energy consumption and GHG emissions of Li-ion battery production are changed by 10%, the results are changed by about 7%, 4% or 2%, respectively. Due to the rapid growth of vehicle industry in China, care must be taken before drawing conclusions in the future.

Despite the important results provided by this study, further research studies are required to obtain more precise estimations. For example, the vehicle specifications and other technological parameters are unclear in China, causing a certain amount of error. On the other hand, due to the rapid growth of vehicle industry in China, a regularly updated database containing the vehicle specifications, manufacturing parameters, emission factors and energy efficiency should be established.

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