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Life cycle greenhouse gas emissions of Electric Vehicles in China: Combining the vehicle cycle and fuel cycle

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ABSTRACT

Electric Vehicles (EVs) are known as the future vehicles that have the potential to provide environmental benefits all over the world. The Greenhouse Gas (GHG) emissions of EVs have already been estimated for each phase in the life cycle. However, the dedicated estimations in China are not complete enough to reveal the systematic impacts of real manufacturing technologies, driving cycle and recycling processes. This study has analyzed the GHG emissions of the Cradle-to-Gate (CTG) phase, Well-to-Wheel (WTW) phase and Grave-to-Cradle (GTC) phase for different vehicles in different time to figure out the key drivers and reduction opportunities, which are based on the well-selling A0-A class compact sedan model currently in China. The results indicate that the life cycle GHG emissions of an EV are about 41.0 t CO_2eq in 2015, 18% lower than those of an Internal Combustion Engine Vehicle (ICEV). This value will decrease to only 34.1 t CO_2eq in 2020 due to the reduction of GHG emission factor of electricity. Although the WTW phase is the largest contributor of GHG emissions for both vehicles, the proportions of each phase are quite different. The GHG emissions of the WTW phase of an EV are decreasing rapidly, but the CTG phase will not be improved at the same speed, which may become a barrier to fully take the environmental benefits of an EV. There are two major opportunities for reduction in the entire life cycle besides fuel economy development. One is EV recycling that can reduce the GHG emissions of the CTG phase by about a half. The other is the improvement of clean power grid that can further reduce the GHG emissions of the WTW phase.

1. Introduction

New Energy Vehicles (NEVs) are reforming the future transportation all over the world. Among all kinds of NEVs, Battery Electric Vehicles (BEVs), or called Electric Vehicles (EVs), are the most popular models seizing global attention. Under such trend, China has already made the plan for NEV development and aims to produce over 5 million NEVs by 2020 [1]. China is the largest vehicle manufacturer and has the largest vehicle market nowadays, accounting for nearly one third of the global vehicle production and sales [2]. The central government's plan has taken advantage of this market size and significantly improved NEV industry, especially EV industry, in China. The growth rate of EV production and sales remains higher than 30% since 2014 and the cumulative EV ownership has reached 1.5 million by the end of 2017, where over a half are passenger vehicles [3]. China has partially covered its ambition and is trying to continuously reform automotive industry. Since fuel combustion is a major source of national Greenhouse Gas (GHG) emissions [4], these trends seem to help China reach the 60–65% carbon emission reduction target made by the State Council in 2005 [5]. Under such circumstance, the real impacts of EVs must be revaluated to support the future regulations and policies, including the fuel economic standards, emission regulations and even subsidies.

In recent years, many scientists have evaluated the environmental impacts of EVs in different regions. In the U.S., the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by Argonne National

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Abbreviations

ANL	Argonne National Laboratory
ASR	After Shredding Residue
BatPaC	Battery Performance and Cost
BEV	Battery Electric Vehicle
BF-BOF	Blast Furnace – Basic Oxygen Furnace
CTG	Cradle-to-Gate
EAF	Electric Arc Furnace
EV	Electric Vehicle
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GTC	Grave-to-Cradle
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LFP	$LiFePO_4$
NEDC	New European Driving Cycle
NEV	New Energy Vehicle
NMC	$Li(NiCoMn)O_2$
WTW	Well-to-Wheel

Laboratory (ANL) has provided a comprehensive database on both GHG emissions and other pollutants for variable vehicles. Results indicate that EVs perform well in GHG emissions and even better in hazardous pollutants [6]. Orsi has estimated the energy consumption, CO_2 emissions and cost of passenger vehicles during Well-to-Wheel (WTW) phase and revealed the large advantage of EVs in the U.S [7]. Lewis conducted a complete Life Cycle Assessment (LCA) on electrified and lightweight vehicles in the U.S. Results indicated that EVs might solve the GHG emission problems in the future [8]. In Europe, the Ecoinvent database is commonly used for evaluation for both GHG and other emissions [9]. Hawkins has established a general LCA model for different kinds of passenger vehicles in Europe and provided estimations through this database. This study pointed out that the GHG emissions of EV manufacturing is quite considerable. At the same time, other impacts like human toxicity potential and mineral depletion potential had also been evaluated. EVs performed nearly 3 times better than ICEVs in these aspects [10]. Some other studies appeared after it, focusing on detailed vehicle assessments. Nanaki analyzed the environmental impacts of three kinds of vehicles in Greece and indicated the benefits of EVs. This study provided an evaluation on air pollutants and GHG emissions of them and pointed out that EVs perform the best in all scenarios [11]. Bauer paid attention to the environmental performance of vehicles in Europe under different technology scenarios in 2012 and 2030. The results indicated that EVs would bring much higher human toxicity potential and only a few benefits on GHG emissions because of high burdens from electricity in 2012 [12]. Tagliaferri carried out a similar study under different assumptions and predicted the future environmental impacts of EVs in England. This study has taken recycling rate into consideration and pointed out that the recycling rate could help make EVs a little more environmentally friendly [13]. In China, although some individual studies exist, no common database is available. Wang's study provided a reference evaluation of EVs in China and figured out the potential impacts. Although this study was written in 2013, the method used was quite valuable for new studies in China. This article was quite systematic and took geographic factors into consideration. It indicated that EVs could not reduce GHG emissions and would cause a large number of additional PM2.5 emissions in China due to the electricity mix. At the same time, EVs were much more expensive than ICEVs [14]. Huo has evaluated the air emissions of EVs in China in 2015, and provided comprehensive inventory data besides GHG emissions. These results revealed that EVs can reduce GHG emissions but increase the total and urban emissions of air pollutants like $PM_{2.5\text{-}10}$, SO_2, NO_x and CO in China. However, this situation can be controlled in the future [15]. In other regions, several studies exist focusing on the similar topic, they are also revelatory but not so important to this study.

Existing studies are valuable and complete enough to form a big image of EVs all over the world. However, further studies are necessary to eliminate the regional deviations and reveal the case in China. First, in the Cradle-to-Gate (CTG) phase, major GHG emissions are calculated through material consumption, energy consumption and emission factors, which vary significantly among different regions. For example, steel can be transformed through Blast Furnace – Basic Oxygen Furnace (BF-BOF) process or Electric Arc Furnace (EAF) process. The latter one is a kind of steel recycling technology and is much cleaner. The proportion of these two processes adopted in the U.S. are very different from it in China [16], leading to the different GHG emissions. It also happens to the power grid in China. Next, in the WTW phase, most of the studies adopted the New European Driving Cycle (NEDC) for analysis. This driving cycle is not suitable for all the regions, especially in crowded cities such as Beijing. Actually, the real driving cycle in Beijing is quite different from NEDC, causing about 35% more electricity consumption for EVs [17]. Finally, in the Grave-to-Cradle (GTC) phase, only a few studies have paid attention to the detailed technologies. Recycling technologies, especially battery recycling technologies, can significantly influence the environmental impacts. For example, in China, most enterprises adopt the hydrometallurgical process, while those in the U.S. adopt the pyrometallurgical process, causing the major difference [18]. In short, due to the regional distinction, the life cycle GHG emissions of EVs must be revaluated to reveal the real situation in China. The key point is to identify the technologies adopted by China and to make a more suitable driving cycle assumption.

With the target to fill such a gap, this study estimates the life cycle GHG emissions based on the real driving cycle, manufacturing processes and recycling technologies in China. In order to provide an updated evaluation model for the GHG emissions of EVs in China, as well as a reliable database, this study pays attention to the technical details in each phase and the EV model parameters. On the other hand, according to the industry reports, NEVs, especially EVs, are mainly sold in developed regions such as Beijing, Shanghai and Shenzhen, and the sales in these three regions accounts for about 40% of the total number in China [19]. Additionally, Beijing is very representative since it has the largest ownership and sales of EVs, so this study takes Beijing as a case for driving cycle analysis. On the other hand, this study will provide the comparable results for different years, which can reveal the trend of life cycle GHG emissions of EVs in China.

2. Methods and data

2.1. Vehicle model

According to the former researches, vehicle model specification is the basic assumption for analysis and significantly influences the results. Since this study aims to reveal the real situation in China, the vehicle model must match the EV market. In 2017–2018, the most popular EVs are A0-A class vehicles, which are compact sedans with about 1300–1500 kg as curb weight, accounting for over 90% of the EV sales in China [20]. The best-selling model is the BAIC EC-Series, which is mainly sold in Beijing and is also the world's third popular EV model [21]. Therefore, this study adopts the average parameters of these kinds of EV, as presented in Table 1. This vehicle model is a little larger than the BAIC EC-Series (about 1,100 kg, 20.3 kWh) and close to the former BAIC EV-Series (about 1,300 kg, 25.6 kWh). So some parameters like battery capacity are calculated linearly based on the curb weight and capacity of these two model series. The range of this kind of EV model is claimed about 200 km, with the electricity consumption on 13.5 kWh/100 km. However, this number may not reveal the real case in China since it can be a propaganda from EV manufacturers. This study adopts experimental results on these important areas. The deterioration of traction battery can also be a concern for GHG emissions of EVs, but it is another topic and this study does not quantify the impacts of it. The curb weight of this EV (without battery) is 1,300 kg and the battery weighs 188.7 kg, and the curb weight of an Internal Combustion Engine Vehicle (ICEV) is 1,400 kg. Steel and aluminum are the major materials for both vehicles. Cathode active material is the most important material for the battery, accounting for about 25% of the total weight. For the life time mileage, according to the official mileage assurance of these kinds of small EV models, such as BAIC EV/EC-series, they can drive about 120,000 to 150,000 km by the end of their life. Therefore, this study assumes that both ICEV and EV can drive 150,000 km as the baseline. In order to reveal the potential deviation caused by the lower mileage of EVs, this study will conduct a brief sensitivity analysis within a −30% interval according to the EV driving parameters in China.

EV models are likely to become larger in China in the future with the transformation of supporting policies. Several leading automotive enterprises have announced many new EV models with over 1600 kg as their curb weights. This trend will definitely influence the results in this study and it will be discussed as well.

Since the detailed mass distribution data are not available in China, this study imports them from the GREET model [6]. Although they are estimated through the tear-down data, dismantling reports, enterprise investigations and literature reviews in the U.S. [22], they are also suitable for Chinese vehicles after the modification of total weight [23] because of the similarity within the mass distribution. In order to provide comparative results, this study also employs the parameters of an ICEV from the GREET model in the same class with almost the same components except for the powertrain system.

Table 1
Vehicle model specification.

Vehicle type	ICEV	EV
Life time mileage (km)	150,000	150,000 (−30%)
Weight (without battery) (kg)	1400.0	1300.0
Steel	62.9%	65.5%
Cast iron	10.3%	2.0%
Wrought aluminum	1.9%	1.5%
Cast aluminum	4.5%	5.7%
Copper/Brass	1.9%	5.8%
Glass	3.0%	3.1%
Plastic	11.3%	11.9%
Rubber	2.2%	1.7%
Others	2.0%	2.8%
Battery type	Lead-acid (for ICEV)	NMC (for EV, traction)
Capacity (kWh)	/	27
Replacements during life time	2	0
Weight (battery) (kg)	16.3	188.7
Cathode active material	/	25.2%
Graphite/Carbon	/	15.7%
Binder	/	2.1%
Copper	/	11.7%
Wrought aluminum	/	23.9%
Electrolyte	/	10.6%
Lead	69.0%	/
Sulfuric acid	7.9%	/
Water	14.1%	/
Plastic	6.1%	1.7%
Others	2.9%	9.1%

The traction battery is another story. In China, Li-ion battery will dominate the market in the future. There are two kinds of Li-ion battery classified by their cathode active materials: $Li(NiCoMn)O_2$ (NMC) battery and $LiFePO_4$ (LFP) battery. Although NMC battery and LFP battery both have about 45% of the market share currently, NMC battery is more likely to be adopted by the future EVs because of the higher energy density [24]. In this study, the capacity of the traction battery is assumed to match the A0-A class (compact sedan with about 1300−1500 kg curb weight) EVs in China. The replacement of batteries is considered according to the official assurance of these kinds of small vehicle models, such as BAIC EV/EC-series and similar ICEVs. For NMC battery, there will be no replacement by the end of the EV life, but for lead-acid batteries used in ICEVs, there will be two times of replacement. These numbers are also adopted by GREET model and can reveal the situation in both China and the U.S [6]. The energy density and detailed mass distribution of the NMC battery are employed from the Battery Performance and Cost (BatPaC) model due to the lack of data in China [25].

2.2. Life cycle scope and assumption

As analyzed in the former sector, the entire life cycle includes CTG, WTW and GTC phases. Fig. 1 presents the details of each phase as well as the scopes of them. In order to reveal a complete life cycle, the entire scope is broad enough to cover all the GHG emission related processes. Both direct and indirect GHG emissions are included according to the Scope 3 [26]. The transportation of materials and components is also taken into consideration under the same assumption of GREET − a 9.3 t-load truck is used for transportation.

The CTG phase is the EV manufacturing phase, including both vehicle manufacturing and battery manufacturing. The process range from ore mining, material transformation, component manufacturing and assembly, vehicle assembly. The replacements of several certain components are considered in this phase as well. The EV manufacturing processes are similar between China and the U.S but some material production and transformation technologies are different, especially for steel and aluminum [27]. This study assumes a common process and adopts the dedicated data for each stage in China.

The WTW phase is the EV use phase. It is much more complicated due to the driving cycle. In China, as mentioned above, the official evaluation system adopts the NEDC assumption. However, it might not be scientific enough since it was developed according to the transportation in Europe [28]. Several studies appear recently to deal with it, especially for EVs. At present, certain instruments and analytical functions are necessary for tests, making it difficult to provide specific results for different regions [29]. This study adopts the results generated through thousands of real driving cycle data for different EVs in Beijing, whose energy consumption is 35% higher than that of NEDC [17]. This percentage is a little higher according to the study in the U.S. [30], but another study has also provided such results on energy consumption in 2014 in Beijing [31]. Furthermore, some driving pattern characteristics are similar in developed regions in China, indicating that the case in Beijing can partially represent a large number of EVs in China [32]. These assumptions are also applicable for ICEVs in Beijing and cause few deviations [33].

The GTC phase is the EV recycling phase. The beginning of EV recycling is dismantling, and it can be divided into vehicle recycling and battery recycling after that [34]. The vehicle recycling technology has nothing special and is commonly adopted by both EVs and ICEVs. The entire process includes shredding [35] and post-

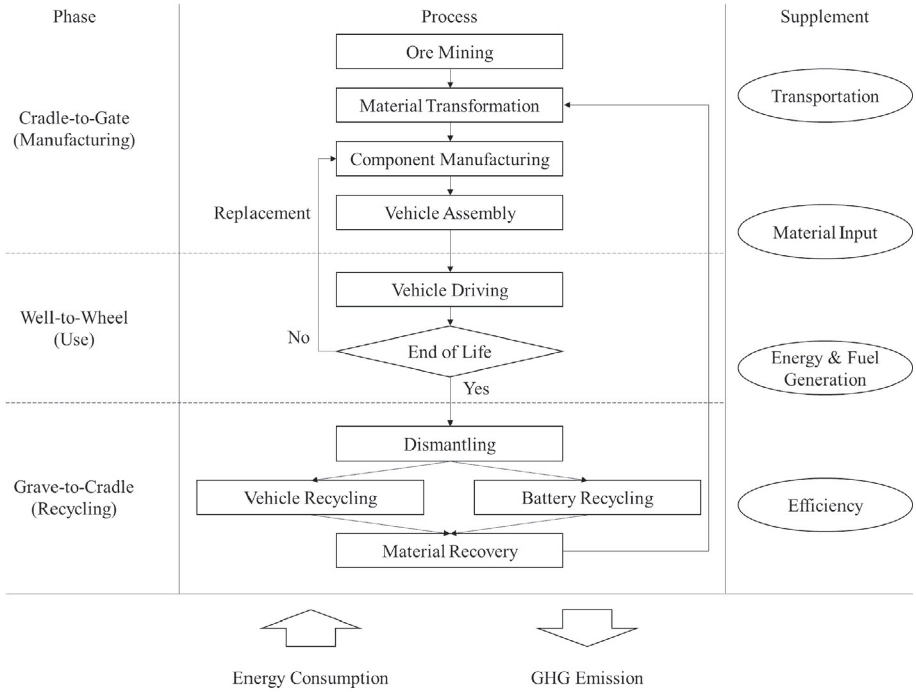

Fig. 1. Life cycle scope of EV.

shredding treatment [36]. According to the technology in China, only metal scraps are collected from the After Shredding Residue (ASR), while other materials are landfilled or burnt [37]. The battery recycling is quite different and this industry is growing. There are two major Li-ion battery recycling technologies worldwide: pyrometallurgical technology and hydrometallurgical technology. In the U.S leading enterprises such as Retriev (once named Toxico) prefer pyrometallurgical technology because the capacity is much larger. However, more and more enterprises in Europe, such as Recupyl and Euro Dieuze, are turning to hydrometallurgical technology because the cathode active materials such as cobalt and lithium can only be collected through it [38]. In China, only a few battery recycling enterprises exist and almost all the leading enterprises, such as Brunp [39], adopt the hydrometallurgical technology developed by Retriev in 1999 [40]. Therefore, this study assumes that the hydrometallurgical technology will be widely used in future China.

2.3. Calculation and data

According to the research scope, the life cycle GHG emissions can be calculated through equation (1)–(4).

$$E_{LC} = \left(E_A + \sum_i E_{M,i}\right) + E_D + \left(E_{VR} + E_{BR} + \sum_i E_{MR,i}\right) - E_S \quad (1)$$

In equation (1),

E_{LC} indicates the entire life cycle GHG emission,
E_A indicates the GHG emissions of component and vehicle assembly,
$E_{M,i}$ indicates the GHG emissions of the production and transformation of material i,
E_D indicates the GHG emissions of vehicle driving,
E_{VR} and E_{BR} respectively indicates the GHG emissions of vehicle and battery recycling (including dismantling),
$E_{MR,i}$ indicates the GHG emissions of the recovery of material i,
E_S indicated the reduction of GHG emissions when primary material is replaced by recovered material.

$$E_X = E_{DR} + \sum_j EC_{T,j} \times EF_{T,j} + \sum_i M_{M,i} \times \sum_j EC_{M,i,j} \times EF_j / EFC_j \quad (2)$$

In equation (2),

E_X represents the different "Es" mentioned in equation (1) except for E_D and E_S,
E_{DR} indicates the direct GHG emissions,
$EC_{T,j}$ and $EC_{M,i,j}$ respectively indicates the consumption of energy j for transportation and material i,
$M_{M,i}$ indicates the mass of material i,
EF_j indicates the life cycle GHG emissions factor of energy j,

EFC_j indicates the efficiency of energy j, including the line loss of electricity.

$$E_D = \sum_i MA \times FC_i \times EF_i / EFC_i \quad (3)$$

In equation (3),

MA indicates the life time mileage,
FC_i indicates the consumption of fuel i,
EF_i and EFC_i have already been noted.

$$E_S = \sum_i M_{MR,i} \times \sum_j EC_{MR,i,j} \times EF_j \quad (4)$$

In equation (4)

$M_{MR,i}$ indicates the mass of recovered material i,
$EC_{MR,i,j}$ indicates the consumption of energy j for primary material i,

EF_j has already been noted.

The essential data are presented in Table 2. First, GHG emissions of the CTG phase are revaluated based on a former study and the results are modified according to the vehicle parameters and emission factors [27]. For more details, GHG emissions from all the major materials accounting for about 80% of the total weight, such as steel and iron [41], aluminum [42], copper [43], cathode active material [27], are estimated according to the manufacturing technologies in China. For other materials with lower weight, the relevant data are imported from the U.S [44]. since they are not available in China. Secondly, GHG emissions of the WTW phase are calculated according to the fuel consumption. This study adopts the real driving data in Beijing [17]. Regarding the charge-discharge efficiency, this study considers about combination of different charging strategies and equipment. The efficiency highly depends on charging current during the process of EV charging, which can make the efficiency as low as 60% [45]. On average, for EV charging with Li-ion battery and charging pile, the efficiency can reach 85%–95% [46]. This study adopts the combined efficiency (charge and discharge) for EVs as about 90% [47]. The average line loss factor is adopted as 6.3% [48]. Finally, GHG emissions of the GTC phase are imported from a former study regarding the economic and environmental impacts of EV recycling in China with the same assumption on the recycling technologies [18]. In addition, as the recovered materials can take the place of primary materials during the CTG phase, the relevant environmental benefits are also included. The results have also been modified according to the vehicle parameters and emission factors.

The life cycle GHG emission factors of different fuels are considered as a combination of fuel generation and burning. The GHG emission factor of electricity in China varies by provinces. This study adopts the national weighted average value, not the value in Beijing because this study aims to provide general results and just the driving cycle in Beijing is considered as the representative for the country. This emission factor is relatively lower than the value adopted in many other studies because this one is estimated on the scenario in 2020 with the application of much renewable energy. Based on the provincial development plans, total capacity will be about 1965 GW in China in 2020, and the numbers for hydro, coal, natural gas, nuclear, wind, solar and other power will be 359, 1026, 110, 51, 244, 157 and 19 GW, respectively. This estimation indicates that coal-based electricity will only account for about half of the total capacity [49]. On the other hand, GHG emission factors for 2015 are also adopted to reveal the situation in recent years, which can help analyze the trends of life cycle GHG emission for both kinds of vehicles. The electricity generated from coal power accounted for about 68% of the total capacity in China in 2015, which made the GHG emission factor quite high [50]. The gasoline related emissions are estimated based on China's technologies [51] and burning emissions [52], which remain stable in recent years [53]. It has to be noted that the GHG emissions are identified as the emission of CO_2, CH_4 and N_2O, with the global warming potentials of 1, 25, 298 unit CO_2eq, respectively.

3. Results and discussion

3.1. Life cycle GHG emissions and sensitivity analysis

Based on the assumptions and scopes, the life cycle GHG emissions of an EV in China are presented in Table 3. In order to make it comparable, the same kind of results of an ICEV are also included. The entire life cycle GHG emissions of an EV are about 41.0 t CO_2eq, 18% lower than those of an ICEV, 50.0 t CO_2eq, in 2015. The GHG emissions of fuel consumption in the WTW phase cause the major difference. In 2020, this gap increases to 36% due to the large reduction of the GHG emission factor of electricity, which makes EV much cleaner in the WTW phase. In addition, if the recovered materials can be used for vehicle manufacturing, the life cycle GHG emissions of an EV can be reduced by about 17% in 2015 and 20% in 2020. This percentage will keep growing because recycling can help reduce the GHG emissions in the CTG phase by a certain proportion, and the CTG phase will account for a larger part of the life cycle GHG emissions due to the cleaner electricity.

With the technology development and policy transformation, EVs models are becoming larger as well as the energy density of batteries. However, they may not be linear correlated. Based on the NMC battery technology development plan, the density in 2020 will be nearly 2 times larger than it in 2015, from 180 to 300 Wh/kg. At the same time, the efficiency of battery system will also face

Table 2
Essential data for calculation and discussion.

Fuel consumption and GHG emissions	CTG		WTW		GTC	
	ICEV	EV	ICEV	EV	ICEV	EV
Fuel consumption (kJ/100 km/kg)						
Electricity	Not applicable		/	46	Not applicable	
Gasoline			136	/		
Charging efficiency			/	90.0%		
Line loss factor			/	6.3%		
In 2015						
GHG emission (kg-CO_2eq)	10,486	12,984	Further calculation		1777	2407
Vehicle (without battery)	10,486	9819			1777	1714
Traction Battery (NMC)	/	3165			/	693
Recycling benefits (kg-CO_2eq)	Not applicable		Not applicable		−5255	−6960
Factor (kg-CO_2eq/MJ)						
Electricity	203					
Gasoline	91					
In 2020						
GHG emission (kg-CO_2eq)	9744	11,996	Further calculation		1486	2056
Vehicle (without battery)	9744	9025			1486	1390
Traction Battery (NMC)	/	2971			/	666
Recycling benefits (kg-CO_2eq)	Not applicable		Not applicable		−4924	−6634
Factor (kg-CO_2eq/MJ)						
Electricity	159					
Gasoline	91					

Table 3
Life cycle GHG emissions of an EV and ICEV.

GHG emissions (kg-CO_2eq)	CTG		WTW		GTC	
	ICEV	EV	ICEV	EV	ICEV	EV
In 2015						
Vehicle (without battery)	10,486	9819	37,722	25,593	1777	1714
Traction battery	/	3165			/	693
Subtotal	10,486	12,984	37,722	25,593	1777	2407
Total (ICEV)	49,985					
With recycling benefits	44,730					
Total (EV)	40,983					
With recycling benefits	34,023					
In 2020						
Vehicle (without battery)	9744	9025	37,722	20,062	1486	1390
Traction battery	/	2971			/	666
Subtotal	9744	11,996	37,722	20,062	1486	2056
Total (ICEV)	48,952					
With recycling benefits	44,028					
Total (EV)	34,113					
With recycling benefits	27,479					

rapid growth with the technology route of high Si anode, 811 (Ni:Co:Mn = 8:1:1) cathode and low-organic liquid electrolyte (gradually all-solid electrolyte) Li-ion battery [54]. This level is higher than the worldwide expectation from a study in 2018, which calculates the potential of high Si anode and high Ni cathode Li-ion battery [55]. Therefore, the target of China may be hard to achieve, but it can a good reference for this study.

The structure of life cycle GHG emissions of EVs will face several changes, with larger proportion of GHG emissions in the CTG and GTC phases. In detail, GHG emissions from the WTW phase will increase a little due to the larger curb weight but also be countered by higher efficiency of battery management systems. CTG phase will become a more important role in terms of GHG emissions because the curb weight growth will directly cause the larger GHG emissions. Advanced battery manufacturing are also likely to make it more GHG emission intensive. Accordingly, the GHG emission benefits from GTC phase will also become larger.

Fig. 2 presents the breakdown of life cycle GHG emissions. Clearly, the contribution of each phase is quite different for these two vehicles. In 2015, The CTG, WTW and GTC phases respectively account for about 32%, 62% and 6% of the life cycle GHG emissions of an EV in China. These numbers for an ICEV are about 21%, 75% and 4%. With the development of the power grid, these percentages change differently for two vehicles. In 2020, the GHG emissions of three phases account for 35%, 59% and 6% for an EV, while they are 18%, 79% and 3% for an ICEV. EVs can significantly benefit from the power grid improvement, which makes the GHG emissions of the CTG phase account for a larger proportion in the future.

Take the variable mileage into consideration, as mentioned in section 2.1, EVs are more likely to have lower mileage than ICEVs. If the life time mileage of the reference EV decreases by 15% or 30%, the GHG emissions of the WTW phase will also decrease by 15% or 30% and the life cycle GHG emissions will decrease by 9.4% or 18.8% in 2015, and 8.8% or 17.6% in 2020. At the same time, the proportions of the GHG emissions of each phase will turn to 35%, 59%, 6% or 39%, 54%, 7% in 2015 and 38%, 55%, 7% or 43%, 50%, 7% in 2020, respectively. Therefore, if the life time mileage of an EV is lower than expected, the environmental advantage will be further strengthened at a considerable level. This additional benefit is becoming lower with the decrease of the share of the WTW phase. However, the impacts of the CTG phase will be magnified, which makes it even more important to figure out the reduction opportunities of the GHG emissions in this phase.

Figs. 3–5 presents the details of the GHG emissions of each phase. This study aims to figure out the contributors of life cycle GHG emissions so it is extremely important to identify the emission sources. On the basis of such analysis, the potential route for GHG emission reduction can also be identified and evaluated.

First, the exact GHG emissions of the CTG phase of an EV are about 13.0 t CO_2eq, 24% larger than those of an ICEV in 2015. This difference is largely caused by the additional GHG emissions of traction battery manufacturing. In fact, the traction battery manufacturing emits about 3.2 t CO_2eq. This situation remains the same in 2020. Although the GHG emissions of the CTG phase of an EV will decrease to 12.0 t CO_2eq, the traction battery will still be a large problem and causes 3.0 t CO_2eq emissions. In comparison, this number for an ICEV will be only about 9.7 t CO_2eq. Unfortunately, this gap cannot be fundamentally reduced with the development of power grid if the battery manufacturing technique does not change. The reduction opportunities for the GHG emissions of this phase will be even more important as this phase causes 35% of the life cycle GHG emissions for an EV in 2020. Furthermore, these GHG emissions come out before EV driving, so they are not avoidable through driving or charging improvements. It will become a large limit for China to get full environmental benefits from EVs.

Secondly, the WTW phase accounts for the largest part of GHG emissions, about 25.6 t CO_2eq for an EV and 37.7 t CO_2eq for an ICEV in 2015. These emissions are highly related to the driving cycle and power generation. As this study adopts the real driving cycle in Beijing, the energy consumption is about 35% higher than it of NEDC. However, the driving cycle is not easy to improve because it is determined by the entire transportation. Take EV driving as an example, Due to the crowded transportation in Beijing, the mean velocity is about 23.96 km/h, 27% lower than it of NEDC, and the standard deviation of velocity is also much lower. At the same time, the mean positive acceleration is about 0.41 m/s^2, 18% lower than it of NEDC [17]. These numbers indicate that people are driving and accelerating slowly in Beijing, both in urban and suburban areas, which causes the higher energy consumption. It is reasonable that other major cities, such as Shanghai and Shenzhen, are under the similar situation. On the other hand, the improvement of power grid provides significant benefits for EVs in this phase. In 2020, the GHG emissions of the WTW phase of an EV decrease to 20.1 t CO_2eq, while the value for an ICEV does not change. Clearly, this reduction is caused by the reduction of the GHG emission factor of electricity, which decreases by about 22% from 2015 to 2020. With the gradual application of renewable and nuclear energy, the emission factor will face continuous decrease in the future. Therefore, the WTW phase will be more and more efficient to fully exploit the advantage of EVs.

Finally, although the GHG emissions of the GTC phase are quite few, it is an important phase because the recovered materials can take the place of primary materials, especially for steel, aluminum and cathode active materials. The exact GHG emissions of this phase are about 1.8 t CO_2eq for an ICEV and 1.7 t CO_2eq for an EV in 2015. These numbers decrease to 1.5 t CO2eq and 1.4 t CO_2eq respectively in 2020. However, if all the recovered steel, aluminum and cathode active materials can be applied for manufacturing, the potential reduction of GHG emissions is 5.3 t CO_2eq for an ICEV and 7.0 t CO_2eq for an EV in 2015. In other words, if the recovered materials are used for vehicle manufacturing in 2015, the GHG emissions of the CTG phase can be reduced by about a half for both an ICEV and an EV. The life cycle GHG emissions can be reduced by 11% for an ICEV and 17% for an EV accordingly. Although the potential reduction of GHG emissions decreases a little to 4.9 t CO_2eq for an ICEV and 6.6 t CO_2eq for an EV in 2020 because of the reduction of GHG emissions of primary material manufacturing, the environmental benefits are still large enough to deal with the high GHG emissions in the CTG phase. Furthermore, recycling is

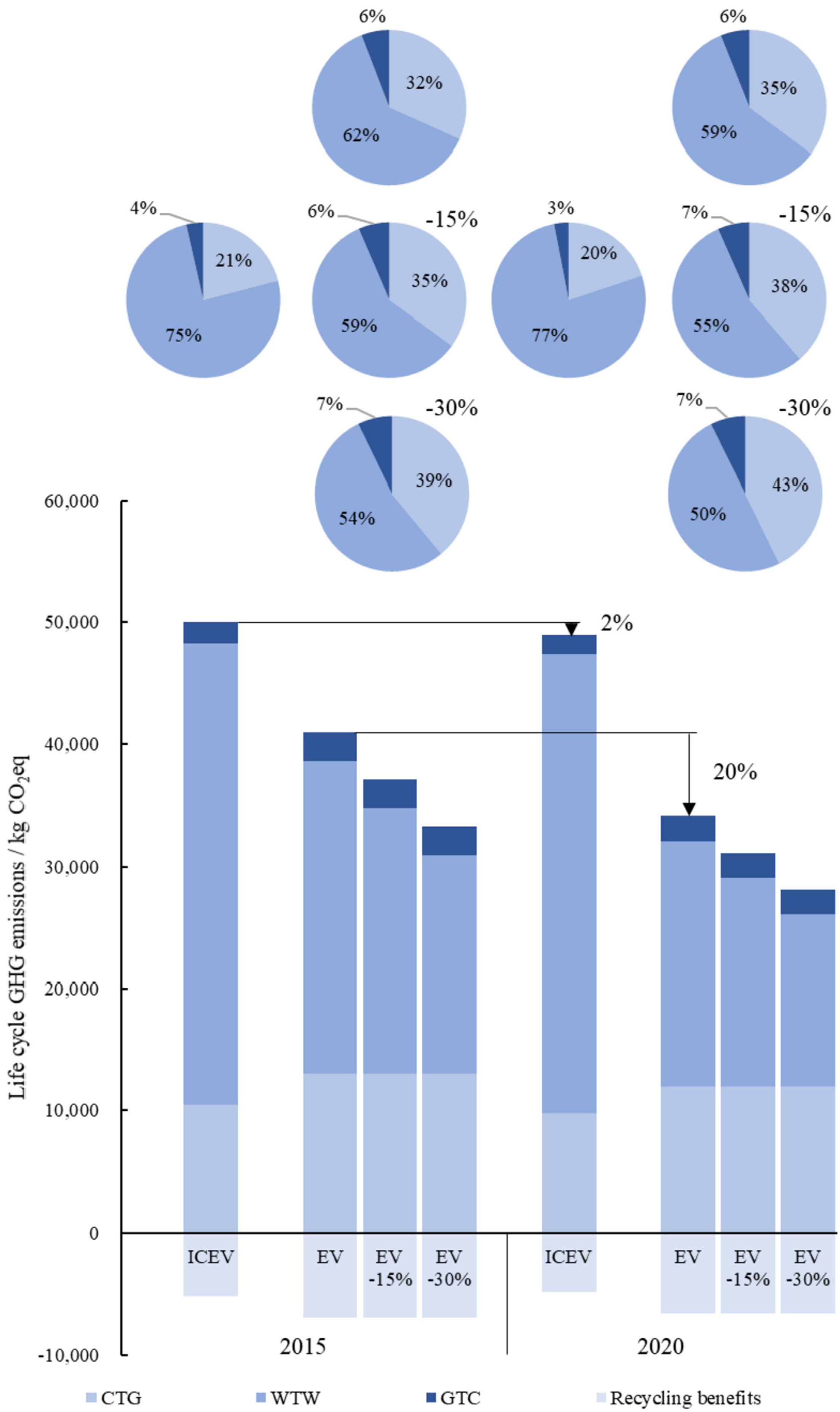

Fig. 2. Life cycle GHG emissions of an ICEV and an EV in 2015 and 2020.

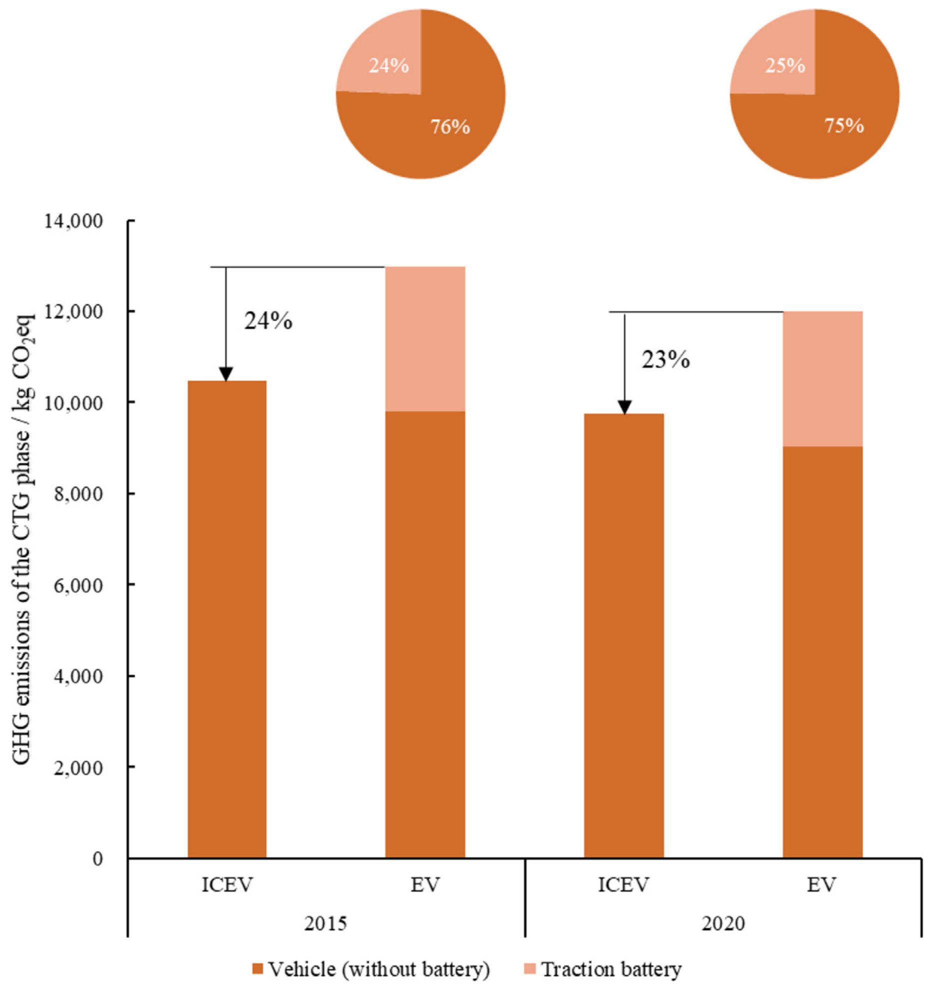

Fig. 3. GHG emissions of the CTG phase.

extremely more important for EVs as the traction battery recycling is more beneficial than the vehicle recycling itself. Since the cathode active material for NMC battery causes huge GHG emissions, the potential reduction is 6.8 kg CO_2eq per kilogram of traction battery recycling, about 3 times larger than that of vehicle (without battery) recycling [18].

In short, the characteristics of GHG emissions vary among different vehicles. In the CTG phase, EVs have a large problem on the battery manufacturing which causes the high GHG emissions. It will be a barrier to deep dig the environmental benefits of EVs. In the WTW phase, although it is the largest GHG emission source for both kinds of vehicles, it is clear that this phase contributes to a larger proportion for an ICEV than an EV. This difference is becoming more and more obvious in these years. Therefore, specialized method should be developed to deal with the problems of EVs. Another characteristic is that EVs can benefit more from recycling than ICEVs. As analyzed above, EV recycling is an opportunity to help control the life cycle GHG emissions of EVs. It will be even more beneficial in the future with the development of recycling technologies since the battery recycling industry is still in the primary stage in China.

3.2. Reduction opportunities

In order to make sure that the environmental benefits of EVs can be fully taken, this study aims to analyze the reduction opportunities in each phase and consider the facilitating methods. Actually, the government has already promulgated several fuel economy policies for both ICEVs, which will reduce the life cycle GHG emissions. According to the fuel consumption limits for passenger cars, the average gasoline consumption per 100 km will be reduced by about 30% from 2015 to 2020 [56]. This improvement can directly reduce GHG emissions of the WTW phase and has great impact on the entire life cycle. The electricity consumption for EVs has not been limited by the government yet, but it is also likely to decrease in order to maintain competitive against ICEVs. These impacts will be greater for ICEVs than EVs due to their huge GHG emissions of the WTW phase, and may also be the greatest opportunity for ICEVs.

In the future, other opportunities lie inside the vehicle cycle as well as the relevant industries. For example, in order to reduce the GHG emissions of the WTW phase of an EV, only improving the efficiency of EV driving is not enough, the emission factor is also very influential and it is determined by the power grid. Therefore, these study divides them into two parts and evaluates them individually.

From the internal point of view, the key opportunity is to enhance EV recycling and use recovered materials instead of primary materials. The potential environmental benefits of EV recycling has already been estimated in the sections above. According to the EV manufacturing and sales in recent years, there will be nearly 1 million end-of-life EVs that should be recycled in 2025 [57]. The

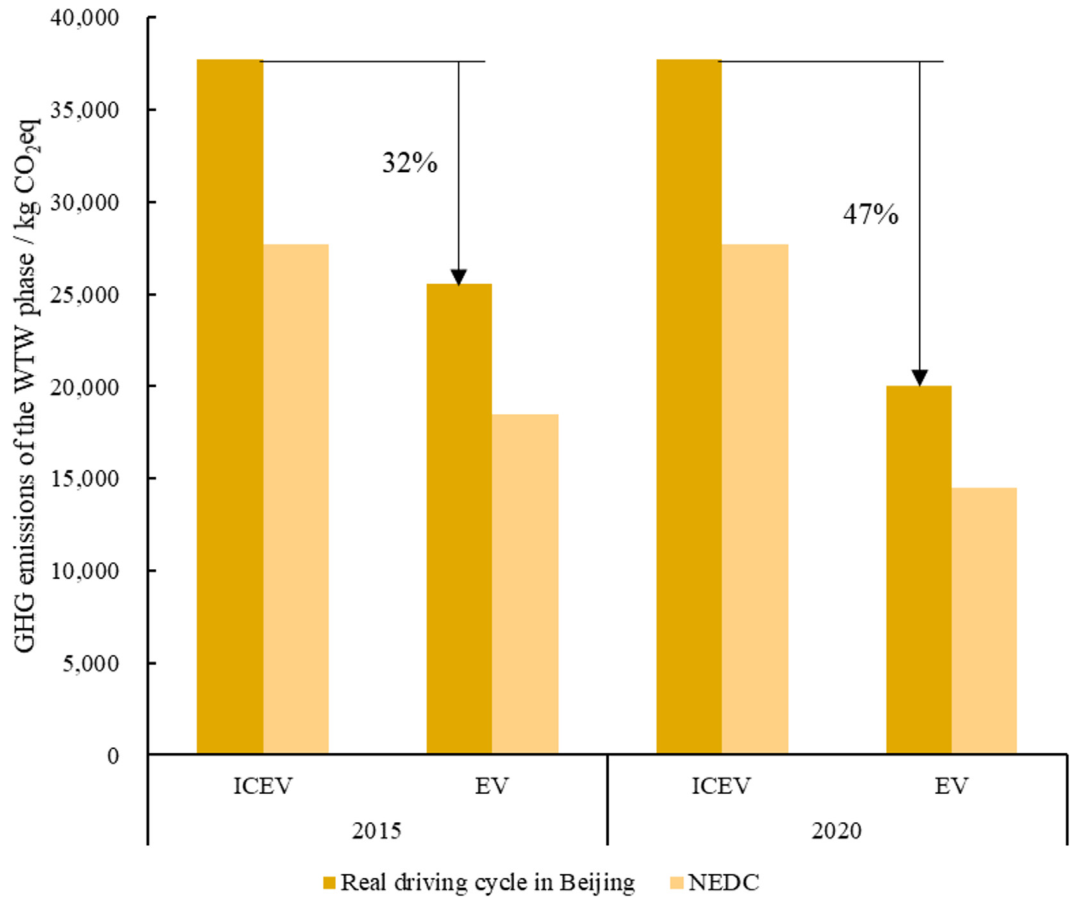

Fig. 4. GHG emissions of the WTW phase.

volume will be larger and it is definitely sustainable. In fact, Chinese government has already paid much attention to EV recycling. Vehicle recycling regulations and standards have been gradually promulgated since 2001, but most of them do not involve traction battery recycling. These regulations are quite similar to the European Directive 2000/53/EC standard, aiming to make sure end-of-life vehicles can be properly treated above a certain rate [58]. In 2018, the first traction battery recycling regulation was issued by the central government of China, and it has been put into force since August 2018 [59]. This regulation has clearly identified the responsibility of each player in the traction battery recycling chain. The manufacturer will be punished if their batteries are not recycled. Under such circumstance, new EVs will face strict recycling standards and be put into a specific process at the end of their life. The recovered materials will be applied into EV manufacturing and partially take the place of primary materials. This reduction opportunity is extremely important because it can help deal with the barrier caused by the GHG emissions of the CTG phase of EVs.

From the external point of view, the key opportunity is the improvement of power grid. In China, wind and solar energy have the potential to reduce the GHG emission factor of electricity. In late 2017, China has announced a national cap-and-trade system, which introduced a price on carbon for the electric utility sector. As a result, the installations of wind and solar will grow substantially. In addition, China aims to increase the share of non-fossil energy to 20% by 2030 [60]. This is why the emission factor may decrease significantly from 2015 to 2020. However, there are still some challenges for the power grid, especially the load balancing problem. The traditional power grid can treat the load variations by dispatching thermal units and hydropower, but with the penetration of renewable energy, it will be more and more difficult. This problem will become even worse because EV charging will be a huge burden for the power grid [61]. Therefore, this reduction opportunity is hard to reach, but it is the only way to fundamentally reduce the GHG emissions in the WTW phase for EVs. In other words, without the clean electricity, EVs may not have the real life cycle environmental benefits.

Comprehensively speaking, these two opportunities have completely covered three phases in the life cycle. EV recycling can substantially solve the GHG emissions problem in the CTG phase and deal with the potential pollution caused by the end-of-life batteries in the GTC phase. The improvement of clean electricity is the base to ensure that EVs are environmentally friendly as it is the key factor to determine the GHG emissions in the WTW phase. These two opportunities are independent and can be taken at the same time. They have indicated the trend to further enhance the benefits of EVs.

4. Conclusion

EVs are identified as “zero-emission” vehicles and facing rapid growth all over the world, especially in China. The central government of China has issued a series of supporting policies to promote EV industry since 2012, including subsidies, fuel consumption regulations and dual credit regulation. However, the real environmental impacts of EVs have not been studied completely in China. This study aims to provide a systematic evaluation of the life cycle GHG emissions of an EV in China based on real manufacturing

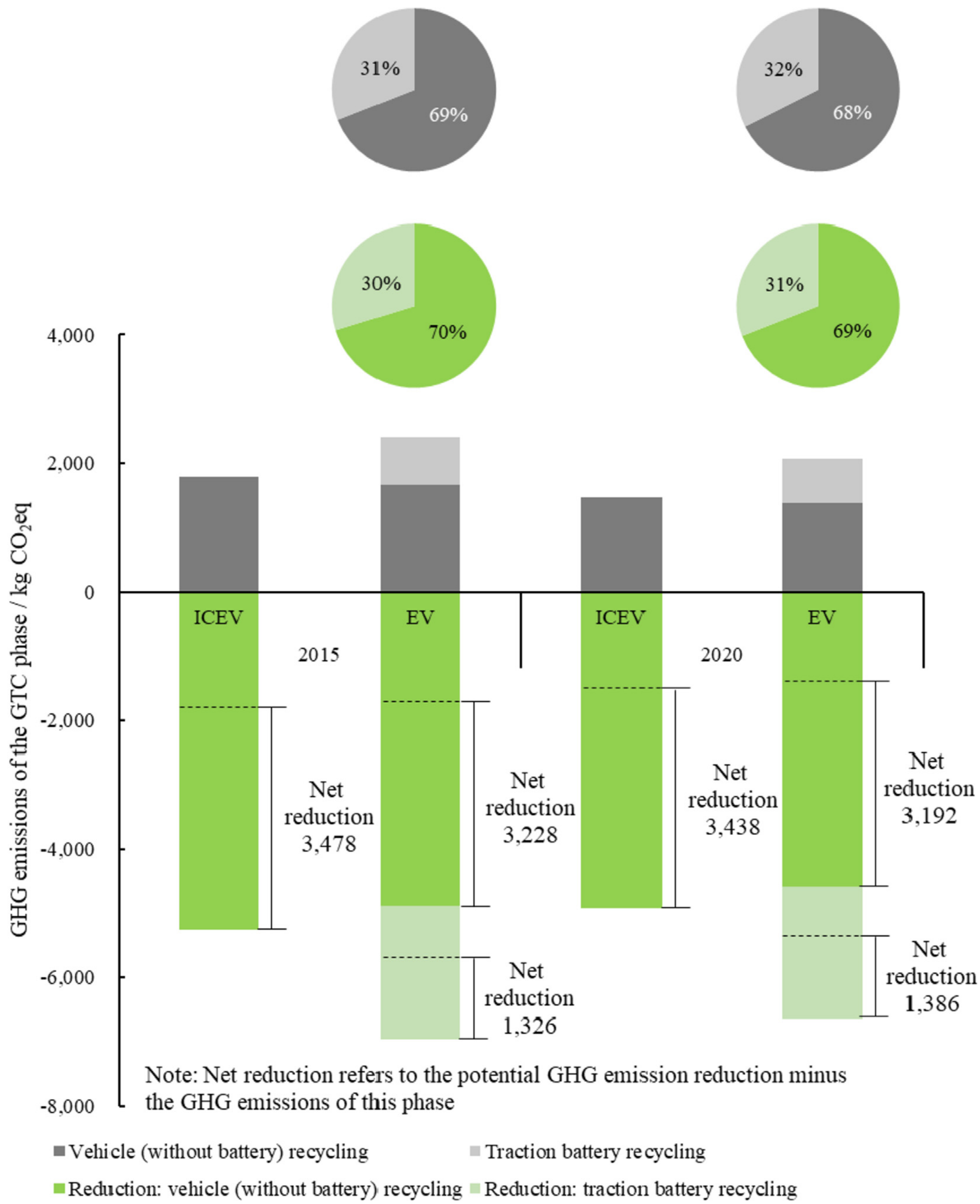

Fig. 5. GHG emissions of the GTC phase and potential reduction.

technologies, real driving cycle and real recycling process. The energy structure is also considered.

Under the key assumptions, this study adopts an A0-A class compact sedan model for analysis, which can represent the best-selling EV models recently in China. The life cycle GHG emissions of an EV in China were about 41.0 t CO_2eq in 2015 and it would decrease to 34.1 t CO_2eq in 2020. These emissions were about 50.0 t CO_2eq for an ICEV in 2015 and it would only decrease to about 49.0 t CO_2eq in 2020. The major contributor of GHG emissions is the WTW phase, accounting for about 59–62% of the life cycle GHG emissions of an EV and 75–79% of an ICEV. This is why the gap of GHG emissions between EVs and ICEVs is becoming wider with the improvement of clean power grid. The GHG emissions of the other two phases are relatively stable, especially the CTG phase, which will become a barrier to take complete environmental benefits from EVs in China. At the same time, if EV models become larger with high energy density batteries, the CTG and GTC phase will become more intensive in terms of GHG emissions.

There are two major opportunities to reduce the life cycle GHG emissions of EVs. One is to improve the EV recycling industry. If the end-of-life EV can be properly recycled and all the recovered materials can be used instead of primary materials in the CTG phase, the life cycle GHG emissions of an EV can be reduced by about 17%. ICEVs can also benefit a lot from recycling. The other opportunity is the improvement of clean power grid. If renewable energy can be applied as planned, the GHG emissions factor of electricity will be further reduced. The GHG emissions in the WTW phase of EVs will then face heavy reduction, such as the estimation in this study, from 25.6 t CO_2eq in 2015 to 20.0 t CO_2eq in 2020.

There are still some limitations in this study. For example, the vehicle parameters may change with the consumer preference in the future. EVs may become lighter and the fuel consumption will decrease. On the other hand, this study has provided a reasonable evaluation on the GHG emissions, but the cost effectiveness should also be considered for further studies.

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