Life Cycle Cost and GHG Emission Benefits of Electric Vehicles in China

Qinyu Qiao[1,2], Fuquan Zhao[1,2], Zongwei Liu[1,2], Han Hao[1,2]*, Xin He[3], Steven Victor Przesmitzki[3], Amer. Ahmad. Amer[4]

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

[2] Tsinghua Automotive Strategy Research Institute, Tsinghua University, Beijing 100084, China

[3] Aramco Services Company: Aramco Research Center, Detroit 46535, US

[4] Research and Development Center, Saudi Aramco, Dhahran, 31311, Saudi Arabia

* Correspondence: hao@tsinghua.edu.cn

Abstract: The penetration rate of Electric Vehicles (EVs) is continuously growing in China. Since EV is considered as an environment-friendly vehicle with lower cost of operation, many studies have paid attention to the Life Cycle Cost (LCC) and Greenhouse Gas (GHG) emission evaluation on EVs. This study aims to expand the scope and provide comprehensive results for LCC and GHG emission comparison between ICEV and EV under different driving cycles, which refer to the driving patterns and parameters such as velocity and acceleration changed by years. The charging infrastructure and battery pilot use have also been involved in the evaluation. Results show that the LCC of an EV is about 9% higher than that of an ICEV under the driving cycle in Beijing in 2020. At the same time, the life cycle GHG emissions of an EV are about 29% lower than those of an ICEV. If the lifetime mileage is not as long as expected, the gap of LCC would be larger and the gap of GHG emissions would be smaller. Recycling is very effective in reducing the GHG emissions but does not work for LCC reduction. Battery pilot use has large potentials on LCC reduction but it still needs time to realize. In this scenario without battery pilot use, the cost effectiveness of an EV is about 4 kg CO_2eq/$.

Keywords: Life Cycle Analysis, Cost Effectiveness, Recycling, Driving Cycle Update

Abbreviations

ANL	Argonne National Laboratory
ASR	After Shredding Residue
CTG	Cradle-to-Gate
ELV	End-of-Life Vehicle
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
LCC	Life Cycle Cost
MIIT	Ministry of Industry and Information Technology
NEDC	New European Driving Cycle
NEV	New Energy Vehicle
NMC	$Li(NiCoMn)O_2$
PHEV	Plug-in Hybrid Electric Vehicle
TCO	Total Cost of Ownership
WLTP	World-wide harmonized Light duty Test Procedure
WTW	Well-to-Wheel

1. **Introduction**

Driven by the government, New Energy Vehicles (NEVs), such as Electric Vehicles (EVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Fuel Cell Vehicles (FCVs), are becoming the major shift for private transportation in China. According to the development plan, over 5 million NEVs would be produced cumulatively by 2020, and most of them would be EVs [1]. This indicates that the penetration rate of NEVs would grow rapidly in China given its recent total vehicle production growth rate [2]. In order to enhance the consumer preference towards EVs, Chinese government has granted a series of policies including subsidies at the first step, and tax benefits together with infrastructure construction at the second step [3]. For example, 7,400 charging stations and 2.5 million charging piles (small charging facilities designed for EVs, generally located in parking lots) are expected to be installed in developed areas such as Beijing, Shanghai, Tianjin, Hebei and Guangdong before 2020 to meet the projected needs of 2.66 million EVs. In Beijing, the government plans to cover 100% of available residential parking lots, 25% of office parking lots, 20% of school parking lots and 15% of hospital parking lots by charging piles by 2020 [4]. These supports worked well in the past 5 years. The average growth rate of EVs in China has remained higher than 30% since 2014 and most of them are passenger vehicles [5]. Therefore, the economic and environmental impacts of EVs would be more and more important in the transportation sector for China, which must be comprehensively evaluated for policy making in the next step.

Life Cycle Cost (LCC) of EV has already been studied from many different degrees worldwide. Rusich (2015) has estimated the Total Cost of Ownership (TCO) and social lifecycle cost of different vehicles including EVs in Italy in 2013. This study points out that the cost of ownership for EV is higher than ICEV, but its social cost is lower [6]. Wu (2015) compared TCO between EV and ICEV and pointed out that TCO of EV would be lower with longer distance and smaller vehicles. EVs are likely to be more cost competitive by 2025 [7]. Palmer (2018) conducted a similar assessment but between different countries, which pointed out that the cost of EV compared to ICEV was being reduced year by year in all countries [8]. Diao (2016) has evaluated the cost of EVs under intangible cost of traffic policies in China. Results showed that EVs are not cost competitive in the tangible sector, but they had great advantages if intangible sector, such as driving and purchasing restriction policy, was considered [9]. Morrison (2018) compared the cost competitiveness between EV and FCV to explore their market potentials. This study pointed out that EV would be cheaper than FCV before 2030, and then FCV would be more cost competitive [10]. He (2017) estimated the LCC for EVs in China from the consumer's point of view. This study defined a critical price, just like a breakeven point for consumers to choose EV instead of ICEV, which is a good method for cost analysis [11]. Delmas (2017) calculated the cost of carbon by EVs in California, which would be $288 per year for a household in suburban areas of California [12].

However, only a few of them have paid attention to the cost of charging infrastructures and battery pilot use, which are very different from gas stations for Internal Combustion Engine Vehicles (ICEVs). Zhang (2018) conducted a review on cost of public charging infrastructures. This study pointed out that several factors, such as charging price, location and subsidy, should be emphasized when evaluating the cost of infrastructures [13]. Ou (2018) has calculated the cost impacts from parking and charging for PHEVs in China. Results showed that the cost ranged from $2,399 to $10,802 from 2015 to 2050 [14]. Lee (2018) discussed about the cost of charging infrastructures by different levels in the U.S. and pointed out that the fixed cost of residential charging can be higher than $1,354 [15].

On the other hand, the Greenhouse Gas (GHG) emission benefits of EVs have been discussed through the life cycle point of view by many scholars. Argonne National Laboratory (ANL) has developed the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model under supports from the Department of Energy in the US. Its database contains energy consumption and GHG emission data for different kinds of vehicle and fuel, which has covered all the processes in the vehicle life cycle. It has shown that EVs perform better than ICEVs on GHG emissions in the U.S. [16]. At the same time, Ecoinvent is another database for the similar purpose for vehicles in Europe [17]. Based on these two databases, many scholars have already made a series of interesting studies. Hawkins (2013) has established a complete Life Cycle Assessment (LCA) model for EVs in Europe and pointed out that EVs performed much better than ICEVs in both GHG emissions and human toxicity potential [18]. This study was a pioneer for the environmental benefit analysis on EVs. Soon after it, Lewis (2014) has evaluated the GHG emissions of diverse powertrain vehicles in the U.S. [19] Bauer (2015) has conducted a study on LCA of EVs in different technology scenarios. This study brought a different opinion that EVs had only a few benefits on GHG emissions due to the high burdens from electricity in 2012 [20]. In China, although there is no common database like GREET or Ecoinvent, scholars have carried out great researches on each stage of EV's life cycle. Wang (2013) has conducted LCA on EVs, FCVs and ICEVs in 2013 and established an early-stage model for EV's GHG emission analysis in China. This study was valuable for following researches [21]. Qiao (2019) has combined the fuel cycle and vehicle cycle to compare the GHG emissions from EVs with ICEVs and paid much attention on the recycling stage. Results showed that if well recycled, EVs would have great GHG emission benefits against ICEVs in China [22]. These valuable results would be great benchmarks for this study.

Existing studies have already done well in both two parts, but there is still a gap to completely reveal the situation in China. For example, some studies focusing on the GHG emissions adopt a B-class vehicle as reference, but others focusing on the cost may adopt an A-class one. It is very hard for third parties to compare their results. At the same time, only a few studies have paid attention to the impacts of driving cycle, which may become a major issue in China due to the new policy that new EVs should take World-wide harmonized Light duty Test Procedure (WLTP) instead of New European Driving Cycle (NEDC) for testing in the future [23]. Furthermore, most of the studies have not considered the impacts from charging infrastructures. Unlike gas stations, the average number of EVs served by one charging pile can be very small, especially in residential areas. This study aims to provide a comprehensive evaluation on both cost and environmental benefits of EVs in China, as well as cost effectiveness analysis on GHG emissions. From the cost point of view, this study considers not only the cost of vehicle, fuel and recycling, but also the average cost of charging infrastructures for EVs. The revenue of recycling has been subtracted in the cost of manufacturing. Battery pilot use was also analyzed, which means that some end-of-life batteries would be used by low-speed EVs and then energy storage before recycling. From the environmental point of view, in order to reveal the situation in China, this study adopts all the manufacturing and recycling data in China, and analyzes two kinds of driving cycle. In short, this study evaluates both cost and GHG emission benefits of EVs in China for the whole life cycle. These results could be helpful for future decision making.

2. Methods and data

2.1 Calculation

As shown in Fig. 1, this study divides the whole life cycle into three stages. Cradle-to-Gate (CTG) represents the manufacturing stage from material generating to vehicle sales, which also includes the transport and storage of components and vehicles. Well-to-Wheel (WTW) represents the usage stage including fuel generating and consumption, repairment, and the infrastructure construction cost for EV. Repairment is also included in the usage stage, and engine/transmission repairments are the major contributor in this stage. Grave-to-Cradle (GTC) represents the recycling stage including battery pilot use, vehicle and battery recycling, and material recovery.

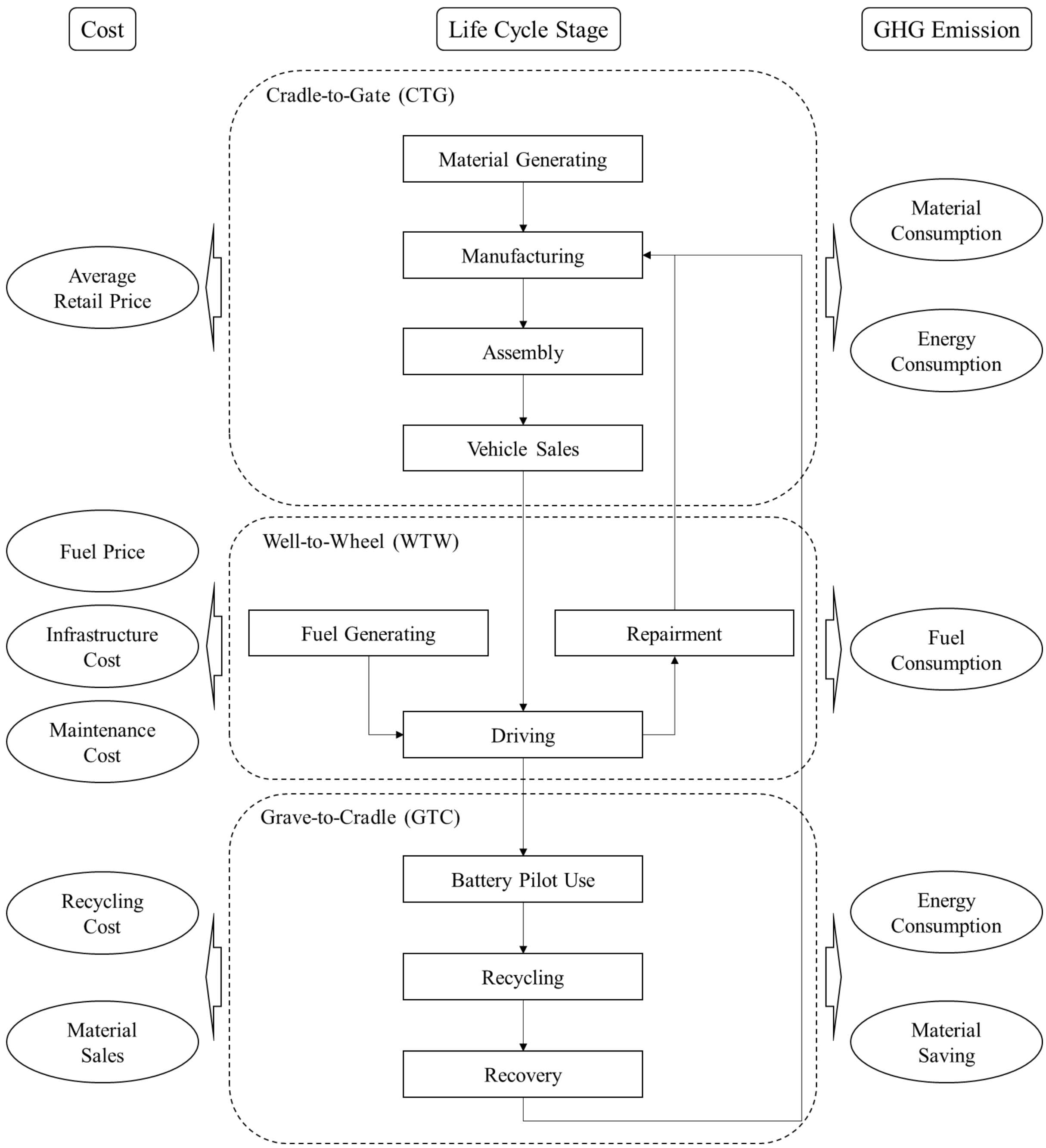

Fig. 1 Scope and calculation system

In order to make EV and ICEV comparison, this study adopts three-step calculation method. These equations are developed based on the typical LCA logic and simplified according to the technology processes, especially material production processes, in China.

First, equations (1) and (2) calculate the life cycle cost and GHG emissions respectively.

$$\mathrm{TC} = \left(\sum_i \mathrm{C_i} - \mathrm{MS}\right) + \mathrm{C_e} - \mathrm{CSP} \qquad (1)$$

$$\mathrm{TE} = \sum_i \mathrm{E_i} - \mathrm{ES} \qquad (2)$$

TC represents the LCC of different vehicles,

where $\mathrm{C_i}$ is the cost in stage i,

$\mathrm{C_e}$ is the external cost such as the charging infrastructure cost per vehicle,

MS is the cost saving from material recovery.

CSP is the cost saving from pilot use.

TE represents the life cycle GHG emissions of different vehicles,

where $\mathrm{E_i}$ is the GHG emissions in stage i,

ES is the GHG emissions saved through the usage of recovered materials.

Secondly, equation (3) and (4) are the details of cost and GHG emission calculation for different stages.

$$\mathrm{C_i} = \left(\sum_j \mathrm{FC_j} \times \mathrm{FP_j}/\mathrm{FE_j} + \sum \mathrm{C_O}\right) + \sum \mathrm{C_p} + \sum \mathrm{C_T} \qquad (3)$$

$$\mathrm{E_i} = \sum_j \mathrm{EC_j} \times \mathrm{EF_j}/\mathrm{EFC_j} + \sum_k \mathrm{MC_k} + \mathrm{E_T} \qquad (4)$$

Where

$\mathrm{FC_j}$ is the consumption of fuel j,

$\mathrm{FP_j}$ is the price of fuel j,

$\mathrm{FE_j}$ is the efficiency of fuel j, including the charging loss and line loss of electricity,

$\mathrm{C_O}$ is the cost of operation, including tax, maintenance and repairment cost,

C_p is the direct price paid, including the vehicle and battery price, which has covered the material cost,

C_T is the technical cost, such as the cost of recycling and recovery process.

EC_j is the consumption of energy j,

EF_j is the GHG emission factor of energy j,

EFC_j is the efficiency of energy , similar with FE_j,

MC_k is the life cycle emission from the consumption of material k,

E_T is the technical GHG emission, such as the emission from recycling process.

Finally, equation (5)-(6) are the calculation for the saving parts.

$$MS = \sum_l MM_l \times P_l \quad (5)$$

$$ES = \sum_l MM_l \times (EM_{V,l} - EM_{S,l}) \quad (6)$$

Where

MM_l is the mass of recovered material l,

P_l is the price of recovered material l,

$EM_{V,l}$ and $EM_{S,l}$ are the life cycle emission of virgin material l and secondary material l (recovered), respectively.

2.2 Data

According to equation (1)-(6), supporting data are listed in Table 1-2. In Table 1, the reference vehicle chosen in this study is an A-class EV with a 27 kWh $Li(NiCoMn)O_2$ (NMC) battery, which is currently the best-selling model in China [24]. For example, BAIC EC series (about 1,100kg, 20.3kWh), EV series (about 1,300kg, 25.6kWh), Chery eQ (about 1,400kg, 30.6kWh) and JAC iEV6E (about 1,400kg, 34.9kWh) are among the best-selling models in China during 2018-2019, and they have similar parameters with those adopted in this study, as well as in GREET. According to the development plan, the energy density of NMC battery is supposed to be larger in the future, but it has not been put into mass production so far [25]. So, this study adopts a relatively conservative assumption, and the impacts of future high-density battery will be discussed in the coming chapters. The ICEV for comparison is chosen as most of its components are the same as the reference EV, except for the engine and transmission. The reference vehicles chosen in this study are a little smaller than those in the GREET model [26] since EVs sold in China are smaller than those in the U.S. [27], but the mass distribution of different materials is imported from it. This difference would probably lead to lower life cycle GHG emissions in China than in the US. The life cycle mileage and maintenance characteristics are adopted according to the driving behaviors [18] and traffic policies in China [9]. However, recent studies show that lifetime mileage would be an important factor for comparison [28]. Therefore, this study takes a low-mileage scenario into consideration, which is 60% of normal mileage. This scenario can reveal the impact from mileage deviation, but does not lead to the real mileage an EV would drive.

Table 1 Vehicle and battery parameter

	EV	ICEV	Source
Vehicle			
Weight without battery (kg)	1,300	1,400	[24], [29]

Mileage (km) - normal	200,000	200,000	[16], [18], [30]
Mileage (km) – low	120,000	120,000	By assumption
Lifetime (year)	10	10	[9], [31]
Repair times per 10,000 km	2	2	[9], [32]
Battery			
Type	NMC	/	[25], [26]
Weight (kg)	189	/	[26]
Capacity (kWh)	27	/	[26]
Replacement per lifetime	0	/	[26]
Other attachments			
Tires (in total, kg)	36	36	
Fluids (in total, kg)	25	42	

In Table 2, the vehicle prices are adopted according to the average price of vehicles sold in China. For example, the price of an A-class Geely Emgrand with internal combustion engine is about $16,700, while the price of a same model with traction battery and motor is about $28,700. The prices of other large A-class EVs such as BYD Qin, Rowel and Lynk range from $27,000 to $33,000. The maintenance cost is decided by the traffic policies [9]. In China, ICEV owners should pay about $55 as the ownership tax every year, and take the quality inspection periodically, which would cost about $50 for each time. The GHG emissions of manufacturing are imported from a former study [22] and the results have been modified according to the vehicle parameters.

The fuel cost and GHG emissions depend on fuel consumption and fuel price, while fuel consumption depends on the driving cycle. Since NEDC [33] would be no longer adopted for vehicle testing by Ministry of Industry and Information Technology (MIIT), and WLTP would be adopted instead, this study adopts two driving cycle for analysis [23]. However, the tested data for WLTP are not available so far due to the policy implement time, this study uses the real driving cycle in Beijing as a representative of WLTP based on their similarity [34]. According to WLTP, an A-class vehicle should take the level 3 testing cycle (Power-Weight Ratio>34kW/t), which contains four-level speed scenarios in 30 minutes and 23.3km. The average speed is about 40km/h. Under Beijing driving cycle, detailed data such as speed, acceleration and fuel consumption are tested through thousands of real driving experiments in both urban and suburban areas by two studies, and the results have been modified according to the vehicle weight difference [34], [35]. The speed scenarios are similar with WLTP, but the average speed is lower due to the crowded traffic in Beijing, about 30km/h. On the other hand, for the situation in 2020, ICEV's fuel consumption should be reduced according to policies, so this study adopts the fuel consumption limit from the policy for ICEV since vehicle manufacturers are likely to only just meet this requirement [36]. EVs do not have to meet such requirements. Furthermore, the charging efficiency [37] and line loss for electricity [38] have also been taken into consideration. Fuel prices are imported according to the government standards, and the charging price might vary among different provinces and places. This study takes Beijing as a reference, which is normally higher than the national average.

The life cycle GHG emission factors of different materials, energy and fuels are necessary as well. This study aims to provide results in both 2015 and 2020 to reveal the trend of GHG emissions, so the factor of electricity in 2020 has been involved according to the provincial power grid development plan, which is estimated under the same scope of the factor in 2015 [39]. This factor is a weighted average value of all the provinces in China by their power generation. Deviation exists in these two factors due to the different data sources in different years, but they could be taken for reference. Other GHG emission factors are imported based on the generating process in China.

It is worth notice that the cost of charging infrastructure for EVs is considerable, while its life cycle GHG emissions only account for an ignorable small percentage [40]. Unlike the ratio of ICEV to gas station, the EV-pile ratio is much smaller [41], meaning that the impacts of charging piles should be taken into consideration for EV evaluation. However, the cost of charging piles in China is not available due to the variety of land cost in different cities. This study adopts the cost of residential charging piles in the U.S., which has the similar parameters with those in Beijing [15].

The recycling cost and GHG emissions are estimated according to the recycling technologies. Vehicle resale cost has also been involved in this part. Vehicle recycling is quite mature all over the world, which consists of dismantling, shredding and post-shredding treatment [42]. However, most of the post-shredding treatment methods are not applied in China, so this study imports technology data on dismantling and shredding from an End-of-Life Vehicle (ELV) recycling company in Jiangxi province [43]. Battery recycling is more complicated. There are two NMC battery recycling technologies, pyrometallurgical and hydrometallurgical processes. In China, most leading enterprises choose to adopt hydrometallurgical which can get more recovered materials [44]. This technology was developed by Retriev, which consisted of base soak, sinking and sintering. Cost data are adopted from the relative technical reports [45], and GHG emission data are adopted from a leading battery recycling enterprise in China [44]. Pilot use is an efficient method to take use of end-of-life batteries besides recycling. In China, pilot use aims to adapt end-of-life batteries to low-speed vehicles and then energy storage [46], but the penetration rate is not promising. The benefit of pilot use is adopted from the estimation by key players in this field.

In the end, all of the cost data should be converted into the same currency in the same year to keep comparability. This study takes the average inflation rate, average exchange rate, and current price level ratio of PPP conversion factor (GDP) to market exchange rate [47] into consideration. All the final results would be in the unit of 2018 U.S. dollars.

Table 2 Data for calculation

	EV-NMC	ICEV	Source
Manufacturing			
Retail price ($)	30,000	20,000	[9], [48]
GHG emissions (kg CO_2eq)	11,996	9,744	[22]

Usage			
Maintenance cost			
Vehicle ownership tax ($/year)	0	55	[9]
Engine/Transmission repairment cost ($/time)	0	50	[9]
Driving cost - NEDC			
Fuel consumption (kWh or L/100km) in 2015	14.20	6.36	[34], [36]
Fuel consumption (kWh or L/100km) in 2020	14.20	5.00	[36]
Driving cost - Driving cycle in Beijing			
Fuel consumption (kWh or L/100km)	19.64	8.64	[34]
Fuel consumption (kWh or L/100km) in 2020	19.64	6.80	[34]
Fuel price			
Electricity for EV ($/kWh)	0.214	/	[49], [50], [51]
#92 Gasoline for ICEV ($/L)	/	1.07	[52]
Efficiency			
Charging efficiency	90%		[31], [37]

Line loss	6%	6%	[38]
Recycling			
Recycling cost ($)	1418.2	202.9	[53]
Recycling revenue ($)	1840.1	530.4	[53]
2015 GHG emission reduction (kg CO_2eq)	4553.3	3477.6	[53]
Pilot use benefits per battery			
Benefits from low-speed EV ($/kWh)	64.3	/	[54]
Benefits from energy storage ($/kWh)	94.2	/	[55]
Infrastructure cost			
Vehicle-infrastructure ratio	2	/	[4]
Construction cost ($/unit)	1,354	/	[15]
Maintenance cost ($/year)	0	/	[15]
Lifetime (year)	5	/	[15]
GHG emission factor			
Electricity in 2015 (kg CO_2eq/kWh)	732		[56]
Electricity in 2020 (kg CO_2eq/kWh)	574		[39]
Gasoline (kg CO_2eq/MJ)	91		[57]
Natural gas (kg CO_2eq/MJ)	67		[58]
H_2SO_4 (98%) (kg CO_2eq/t)	276		[59]

NaOH (30%) (kg CO_2eq/t)	477	[60]
Currency conversion		
Average inflation rate (China 2000-2018)	2.2%	[47]
Average inflation rate (U.S. 2000-2018)	2.4%	[47]
Price level ratio (in China)	0.523	[61]
Exchange rate CNY to USD	7.0	[47]

Note: Calorific value adopted in this study: gasoline 43.07MJ/kg, diesel 42.552MJ/kg, natural gas 35.554MJ/m^3, electricity 3.6MJ/kWh.

3. Results and discussion

3.1 Cost and GHG emission evaluation

Based on the data above, all the results are listed in Table 3. For example, the GHG emission of EV usage under the driving cycle in Beijing can be calculated through equation (4). The value 34,124 kg CO_2eq equals to 19.64 (fuel consumption rate)×200,000 (total mileage)/100 (exchange) × 732 (emission factor of electricity)/0.9 (charging efficiency)/0.94 (line loss). Other results can also be calculated through equation (1)-(6).

In short, The LCC of EV with NMC battery in China is about $39,935 under the driving cycle in Beijing, almost the same as that of ICEV in 2015. With the reduction of ICEV's fuel consumption, the LCC of ICEV under real driving cycle in Beijing would decrease to

$36,723 in 2020, 8% lower than that of EV. This gap would be larger under NEDC, about 7% in 2015 and 12% in 2020. Furthermore, the LCC under the driving cycle in Beijing and NEDC would be higher than it under NEDC, about 7% for EV and 11% for ICEV in 2020. Under the low-mileage situation, the LCC gap between EV and ICEV would increase to 18-22% in 2020, meaning that EV would be relatively more expensive if the mileage is not long as expected.

The life cycle GHG emissions of EV are about 42,554 kg CO_2eq in 2015 and 34,167 kg CO_2eq in 2020 under the driving cycle in Beijing. These numbers are 27% and 29% lower than those of ICEV in 2015 and 2020, respectively. Under NEDC, these gaps become 25% and 28%. Under the low-mileage situation, these gaps become smaller but still over 20%.

Table 3 Cost and GHG emission evaluation results

	EV-NMC		ICEV	
	2015	2020	2015	2020
LCC - total				
Driving cycle in Beijing ($)	39,935	39,935	39,681	36,723
Low mileage	36,334	36,334	32,697	30,923
NEDC ($)	37,441	37,441	35,060	32,885
Low mileage	34,837	34,837	29,925	28,620
LCC - details				
Manufacturing	30,000	30,000	20,000	20,000

Usage – driving cycle in Beijing	10,357	10,357	20,009	17,051
Low mileage	6,756	6,756	13,025	11,251
Fuel	9,003	9,003	17,459	14,501
Fuel – low mileage	5,402	5,402	10,475	8,701
Tax and engine/transmission repairment	/	/	2,550	2,550
Infrastructure	1,354	1,354	/	/
Usage – NEDC	7,863	7,863	15,387	13,212
Low mileage	5,259	5,259	10,252	8,947
Fuel	6,509	6,509	12,837	10,662
Fuel – low mileage	3,905	3,905	7,702	6,397
Maintenance	/	/	2,550	2,550
Infrastructure	1,354	1,354	/	/
Recycling	1,418	1,418	203	203
Pilot use (100%) benefit from low-speed vehicle	-1,735	-1,735	/	/
Pilot use (100%) benefit from energy storage	-2,543	-2,543	/	/
Revenue	-1,840	-1,840	-530	-530
GHG emission - total				
Driving cycle in Beijing (kg CO_2eq)	42,554	34,167	57,304	48,081

Low mileage	28,904	24,299	37,186	31,371
NEDC (kg CO_2eq)	33,101	26,756	43,991	37,023
Low mileage	22,401	19,020	29,198	24,737
GHG emission - details				
Manufacturing (include repairment)	12,984	11,996	10,486	9,744
Usage – driving cycle in Beijing	34,124	24,670	50,296	41,774
Low mileage	20,474	14,802	30,178	25,064
Usage – NEDC	26,749	19,339	36,982	30,716
Low mileage	16,049	11,603	22,189	18,430
Recycling	2,407	2,056	1,777	1,486
Reduction through recovered material	-6,960	-6,634	-5,255	-4,924

Fig. 2 shows the cost and GHG emission comparison between EV and ICEV under different driving cycles in different years. Given the lower cost of electricity than gasoline, EV's cost of usage is only about half of that of ICEV in 2015 with the same mileage. This gap become smaller in 2020, about 39-41%, due to the reduction of ICEV's fuel consumption. It would also be smaller under the low-mileage situation. However, since the average retail price of EV is higher, the LCC of EV is higher than ICEV, especially in 2020. Recycling slightly reduces LCC for both vehicles.

It is clear that EV has advantage in the life cycle GHG emissions, especially in the future due to the penetration of green energy. GHG emissions of the usage stage are only 24,670 kg CO_2eq for EV under driving cycle in Beijing in 2020, about 41% less than those for ICEV though ICEV's fuel consumption has decreased. Since the usage stage is the largest contributor of life cycle GHG emissions for both vehicles, this is the major source of the gap of GHG emissions between them. This gap would be smaller but still very large under low-mileage situation. At the same time, GHG emissions of the manufacturing stage of EV are about 20% higher than those of ICEV in 2020, which indicates that promoting green manufacturing for EV could be an important way besides green energy for reducing its life cycle GHG emissions. Finally, recycling can help reduce the GHG emission of manufacturing by up to 35% for both vehicles.

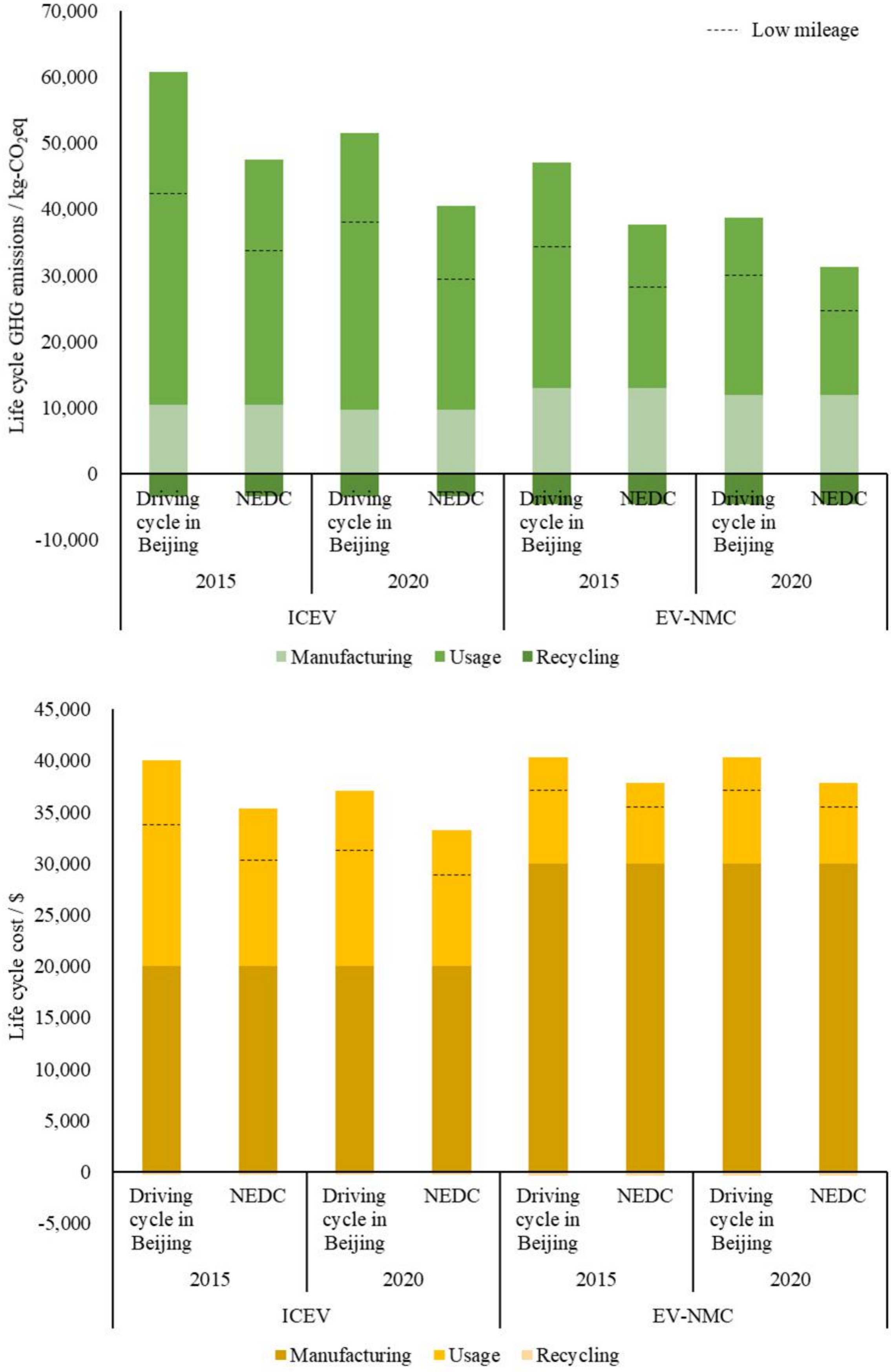

Fig. 2 Cost and GHG emission evaluation results

3.2 Cost of usage

Fig. 3 shows more details of the cost of usage. There is not doubt that EV has large advantage in this part under both driving cycles even under low-mileage situation. Firstly, EV benefits from lower fuel price and lower fuel consumption than ICEV, which is the major contributor for the cost of usage. Secondly, the maintenance of EVs in China is quite cheap because batteries are maintenance-free due to its durability, and EV owners do not have to pay vehicle ownership tax according to the latest policy. Finally, although the charging infrastructure construction causes additional cost for EV, it only accounts for 13% of the cost of usage under Beijing driving cycle and 17% under NEDC. It is worth noting that this study assumed no battery change during the 10 years of vehicle lifetime. If battery change is needed, the cost of usage for EV will be a lot higher.

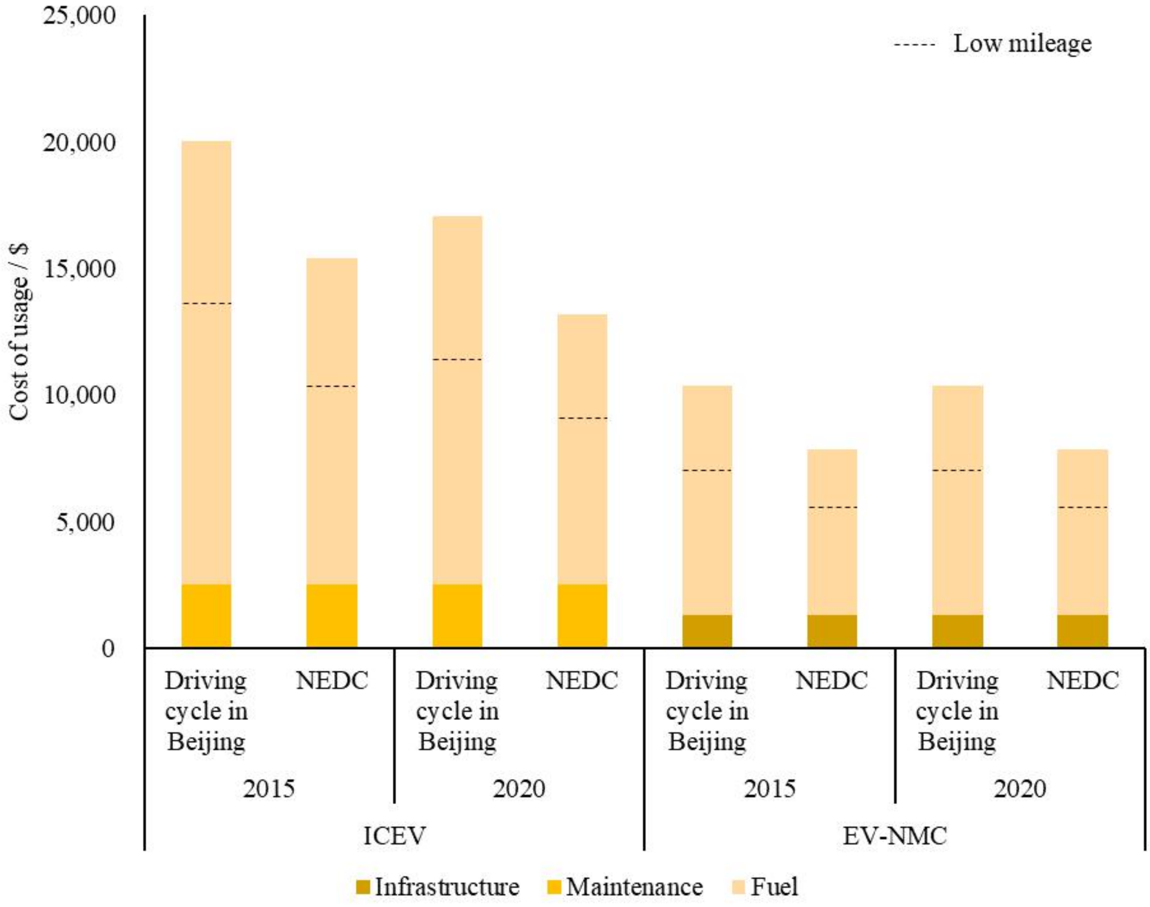

Fig. 3 Cost of usage

3.3 Recycling benefits

Recycling can provide huge benefits for the life cycle GHG emission, while pilot use has potentials to help reduce LCC for EV. Fig. 4 indicates that recycling can reduce the life cycle GHG emissions of EV by 4,553 kg CO_2eq in 2015 and 4,578 kg CO_2eq in 2020. These numbers for ICEV are 3,478 and 3,428 kg CO_2eq, respectively. This gap is mainly caused by the recycling of NMC battery, which could become a great opportunity to reduce its GHG emission of manufacturing, probably by up to 35%. Battery pilot use is still in a very primary stage and its penetration rate is quite low in China at present. This study would discuss the potential of pilot use, which is not likely to be realized soon. Results indicate that pilot use could contribute \$4,278 to LCC reduction under 100% penetration rate, which is over double of the revenue from direct recycling. Benefits from low-speed vehicle and energy storage contribute by 41% and 59% respectively. However, the penetration of pilot use is not clear or promising in China. Its contribution would be only \$856 under 20% penetration rate scenario, a more likely scenario in China in the near future.

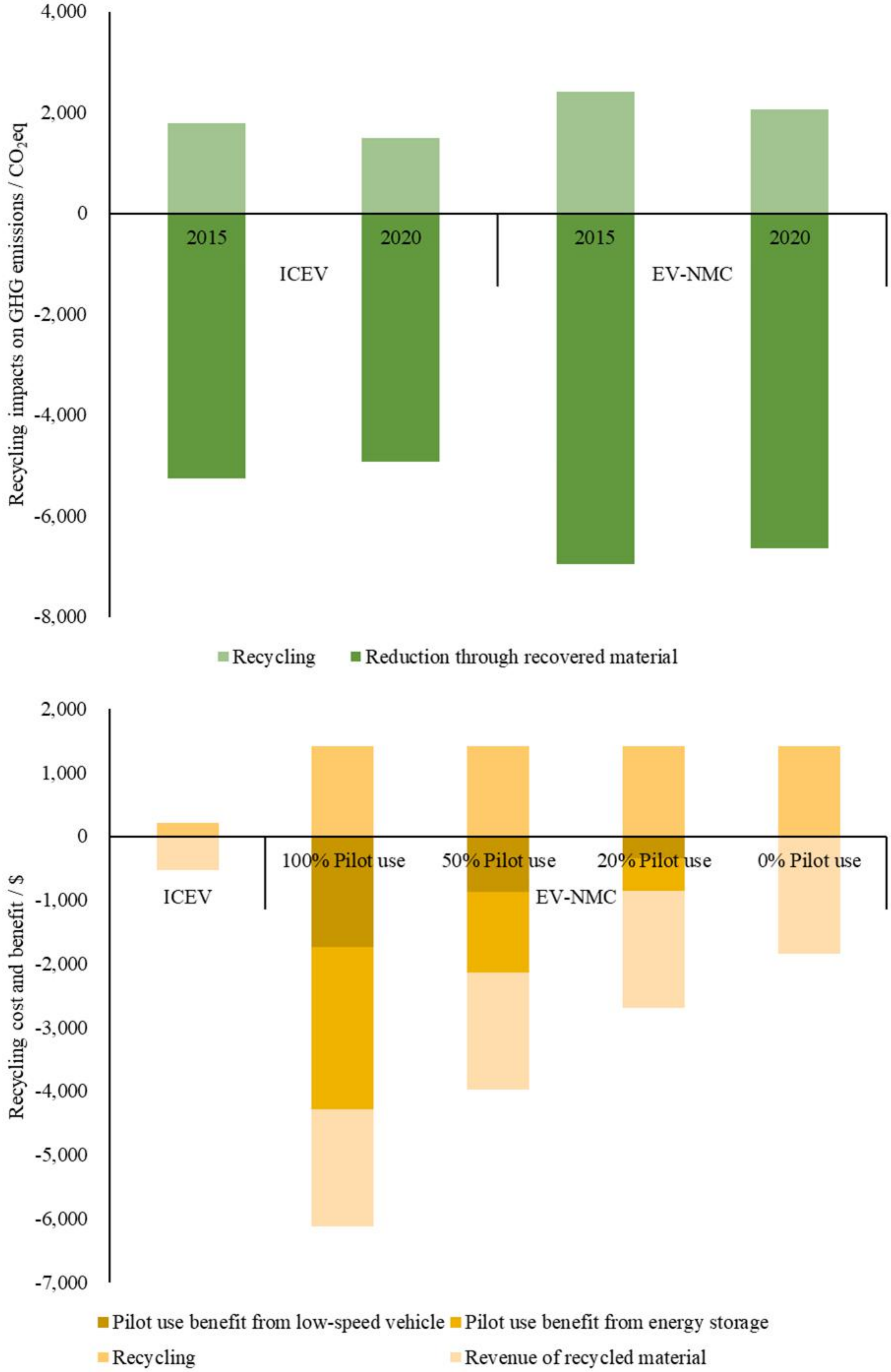

Fig. 4 Recycling benefits

3.4 Pilot use and cost effectiveness

Fig. 5 reveals cost effectiveness, which refers to the reduction of GHG emissions per dollar of additional cost, of replacing an ICEV with an equivalent EV without pilot use. EV's LCC would be higher than ICEV's if pilot use is not adapted, and its life cycle GHG emissions are lower. It is clear that the cost effectiveness of EV in GHG emission reduction would be much lower in 2020 due to ICEV's fuel consumption reduction. These results indicate that the society would pay for the GHG emission reduction through EV. In 2015, the cost for GHG emission reduction would be about 58 kg CO_2eq/$ under driving cycle in Beijing, and 5 kg CO_2eq/$ under NEDC, which means that the cost would be much higher under real driving cycle than tested under NEDC. The cost effectiveness would be much smaller in 2020 under driving cycle in Beijing, about 4 kg CO_2eq/$ under driving cycle in Beijing and 2kg CO_2eq/$ under NEDC. In the low mileage scenario, the cost effectiveness of EV would be lower, only about 4 kg CO_2eq/$ under driving cycle in Beijing in 2015, and 3 kg CO_2eq/$ in 2020.

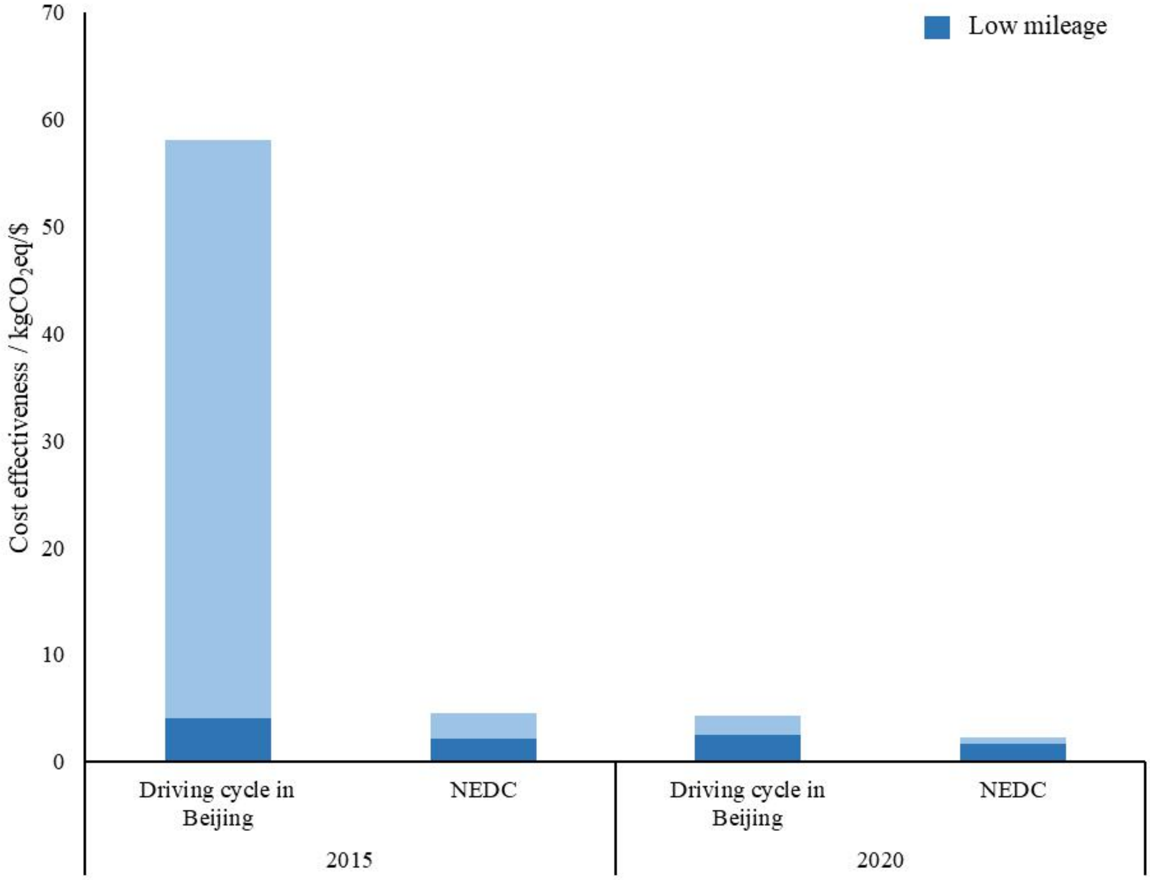

Fig. 5 Cost effectiveness without pilot use

Considering the potentials of pilot use, the situation would be a little different. End-of-life batteries would be much more valuable if they can be used by low-speed EVs and then energy storage. Fig. 6 shows the LCC and life cycle GHG emission saving by EV under different scenarios. Under the driving cycle in Beijing in 2015, EV would have lower LCC as well as lower life cycle GHG emissions even with only 20% pilot use rate. These two benefits would also be available in 2020 if with 100% pilot use rate. Under NEDC, the results indicate that EV would have both LCC and GHG emission benefits only in 2015 with 100% pilot use rate. Furthermore, EV would not have benefit in LCC under NEDC in 2020 even if the pilot use rate is 100%. The GHG emission reduction benefit would be lower in 2020 than in 2015 for both driving cycles due to ICEV's fuel consumption reduction. In the most ideal scenario, EV can help reduce the LCC by $4,024 as well as life cycle GHG emissions by 14,750 kg CO_2eq in 2020.

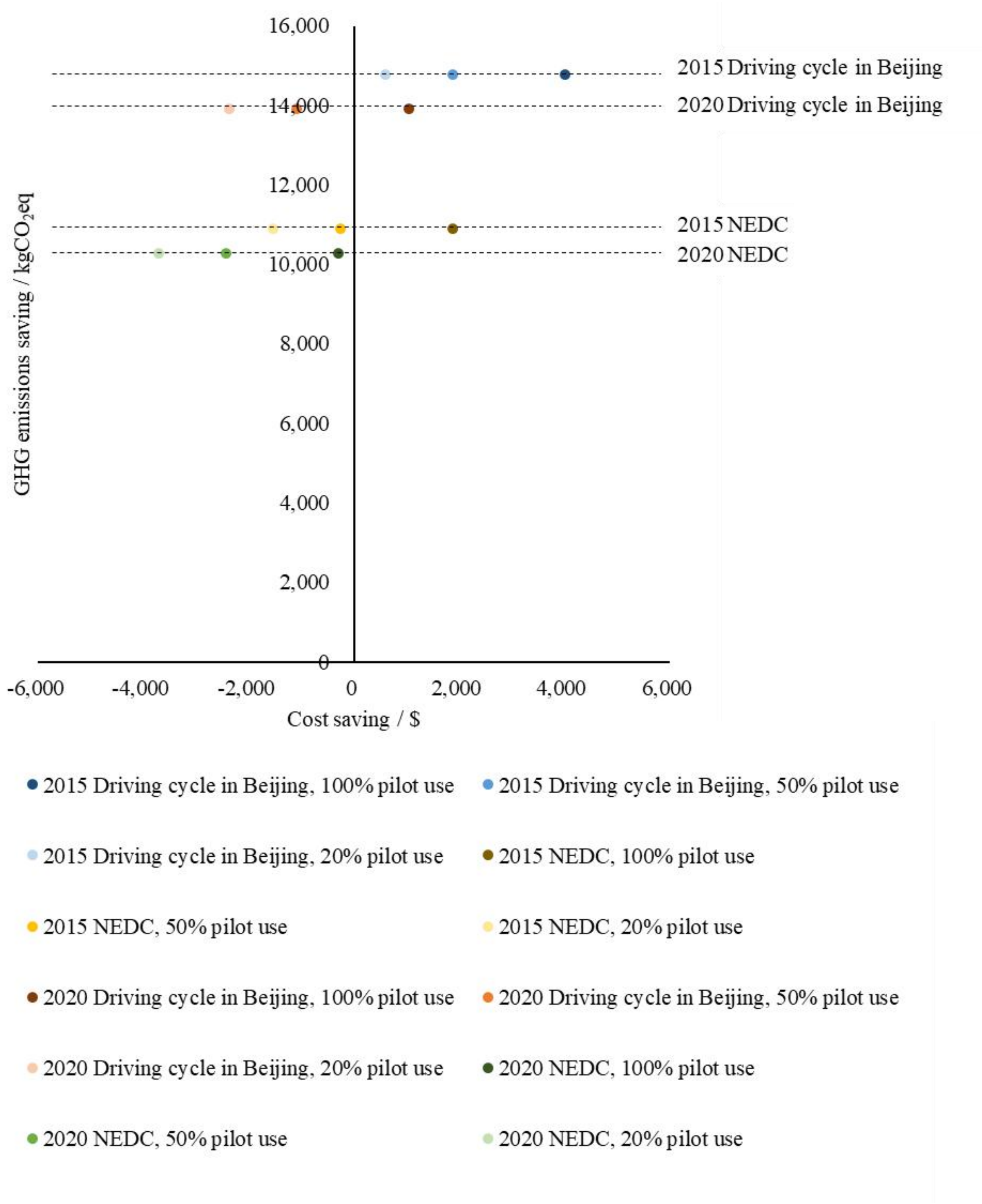

Fig. 6 Benefits of different pilot use scenarios

3.5 Sensitivity analysis

In order to get quantitative results, this study has adopted a series of assumptions, which may cause deviations. The impacts of two major assumptions, mileage and pilot use, have already been calculated, but there are still some influential factors worth discussion.

First, this study adopts certain A-class vehicle models for calculation. Since the GHG emissions are nearly linearly related with curb weight, deviations may exist if the vehicle models change. This impact can be considerable on the whole life cycle. Secondly, although this study provides evaluation results under two driving cycles, they still cannot cover all the driving scenarios. This factor would influence both cost and GHG emissions of the WTW stage, which can also be considerable in the whole life cycle. Thirdly, the GHG emission factors of different energy are estimated by other studies. These factors are continuously changing with the technology development. For example, with the penetration of renewable energy in power grid, the emission factor of electricity is decreasing, causing the reduction of life cycle GHG emissions, especially for EVs.

3.6 Discussion

Overall, according to the evaluation, EV’s LCC is expected to be 9% higher than it of ICEV in 2020 under driving cycle in Beijing, which is similar with WLTP. Its life cycle GHG emission would be 29% lower than ICEV’s at the same time. The difference in LCC is mainly caused by EV’s higher retail price without subsidy, which indicates that the manufacturing cost of EV is quite high at this moment. Although the charging infrastructure cost is involved, it does not account for a large part. EV's advantage in life cycle GHG emissions is mainly from its low GHG emission in the usage stage. Additionally, if the mileage is not as long as expected, the LCC gap would be larger and the GHG emission gap would be smaller between two vehicles. This would also be a concern for EVs.

Recycling can be a great method to reduce the GHG emissions from manufacturing for both vehicles. It would make the gap of life cycle GHG emission even larger between EV and ICEV. However, recycling is not efficient in dealing with the high LCC of EV since the recycling cost is close to its revenue. Policy is the key driver of vehicle recycling industry development. In fact, Chinese government has already made a series of policies, regulations and standards for vehicle and battery recycling since 2001, but they are not implemented properly. In recent years, Chinese government has reformed the recycling chain and made it clear that manufacturers should take responsibility. This method has been proved to be effective in the US and Japan, so the key point for Chinese government is enhancing monitoring in the future. On the other hand, further policies are necessary to promote battery pilot use, which would be an important and efficient way to reduce the LCC of EV if fully penetrated. Chinese government could pay more attention to the profitability of pilot use companies and provide political supports including certification or subsidies in the early stage.

Based on these results, it is clear that the society should pay for the GHG emission reduction from EV. If pilot use is not adapted, the price would be about 4 kg CO_2eq/$ in 2020 under driving cycle in Beijing. This number would be higher if the mileage is not as long as expected. At this moment, pilot use is one way to make this situation better and even make the LCC of EV lower than ICEV. However, the effectiveness of pilot use has not been completed validated by the industry yet, meaning that it would still be a long time before the benefits come true.

Some studies have shown life cycle GHG emissions of EVs in other countries. According to Hawkins' study [18], an EV with 200,000km mileage would cause 39,400kg-CO_2eq in its whole life cycle in Europe in 2012. This number is about 7% lower than it in China in 2015. This gap is mainly caused by the emission factor difference between China and Europe. Vehicle model difference between these two countries is a great contributor as well. Similarly, Sharma's study [62] has shown that an EV with 150,000km mileage in Australia would cause about 31,000kg-CO_2eq in 2013, which are about 21% lower than those in Europe and 27% lower than those in China. Obviously, this difference is mainly caused by the different mileage, but the emission factor and vehicle model are still great contributors. The high GHG emissions of EVs in China indicate that there is still large space for improvement. That is also the reason why this study pays much attention to the improvement paths.

There are still some limits in this study. First, the reference vehicle adopted in this study is an A-class vehicle, which can not represent the performance of large EV models. Secondly, some technology cost data are imported from the U.S. and converted into the currency value in China, which might cause deviation due to the different technical level. Finally, with the development of China's energy structure, the GHG emission data would change in the future, which needs continuous tracking.

4. Conclusions

With the growing of EVs in China, the LCC and GHG emission of EV have been evaluated by many scholars from different degrees. Existing results have already revealed the GHG emission benefits of EVs in China, and some of them have discussed about the cost of ownership. This study aims to combine LCC and GHG emission together and provide a comprehensive life cycle evaluation under two driving cycles in 2015 and 2020. These results can be helpful to all the players in the value chain of EV in China, including the government, vehicle manufacturers, consumers and recycling companies.

This study adopts a complete life cycle scope for evaluation, including CTG, WTW and GTC. The cost of charging infrastructure construction has also been taken into consideration since the EV-charging pile ratio is much smaller than the ICEV-gas station ratio. Chinese government has announced that WLTP would be adopted as the official driving cycle instead of NEDC for testing, and WLTP is similar with the real driving cycle in Beijing. Therefore, this study provides results under the driving cycle in Beijing and NEDC to show the difference. Finally, this study has discussed about the impacts from lifetime mileage to show how would EV performance if the mileage is not as long as expected.

The evaluation results indicate that EV would be about 9% more expensive than ICEV with about 29% lower GHG emissions under driving cycle in Beijing in 2020, and the cost-effectiveness is about 4 kg CO_2eq/$. The LCC gap would be larger and the GHG emission gap would be smaller in the low-mileage scenario. Recycling is an efficient way to reduce the GHG emissions from manufacturing for EV, but it is not a good choice for LCC reduction. Pilot use has large potentials to reduce EV's LCC, but it still needs a long time to realize full pilot use.

In the next step, deep dive in the cost effectiveness of EV is necessary. Further studies can provide a routine to improve the LCC and GHG emission performance of EV. We can try to figure out how to take advantage of the GHG emission benefit of recycling. We can also pay attention to the availability of pilot use in the near future, which is an efficient way to reduce LCC.

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