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Life cycle environmental assessment of electric and internal combustion engine vehicles in China

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ABSTRACT

Promoting electric vehicles (EVs) is an important measure to ensure energy security, improve air quality, and mitigate global climate change. However, the emission reduction impacts of EVs in China have been widely debated and the conclusions of existing studies are still controversial. In this study, we adopted the life cycle assessment (LCA) method to evaluate the carbon dioxide (CO_2) and air pollutant emissions from the stage of vehicle production, vehicle use and vehicle end-of-life. We further compared the emissions of three types of passenger vehicles in China, including internal combustion engine vehicle (ICEV), plug-in hybrid electric vehicle (PHEV), and battery electric vehicle (BEV). Compared with ICEV, BEV and PHEV were found to reduce the emissions of CO_2, VOCs, and NO_X, but increase the emissions of $PM_{2.5}$ and SO_2. These differences were primarily caused by EV's high fuel efficiency and high fuel consumption of ICEV. Additional findings indicate that the emissions of $PM_{2.5}$ and SO_2 of BEV were 2.6 and 2.1 times that of ICEV, respectively; and the emissions of $PM_{2.5}$ and SO_2 of PHEV were 1.8 and 1.5 times that of ICEV, respectively. Moreover, we found the emissions of $PM_{2.5}$ and SO_2 of EV will be higher than that of ICEV in high renewable energy scenario with higher biomass share if keeping the emission factor of electricity constant.

1. Introduction

With rapid economic and population growth, China's automobile stock has increased from 62.8 million units in 2008 to 240 million units in 2018, making China the second highest automobile ownership country globally (MPS, 2019; NBS, 2018). The rapid development of the automobile industry has also led to issues of energy security and environmental pollution (Wang et al., 2017). Energy consumption by China's transport sector maintained an average annual growth of 11.14% throughout the past decade. Air pollutant emissions in the road transport sector increased each year as well (Yu et al., 2017). In 2016, the energy consumption in the transport sector comprised 13.7% of the total energy consumption in China, while the road transport energy consumption accounted for nearly 80% of the total transport energy consumption (Wei et al., 2018; Zhang et al., 2018). China has become the world's largest carbon dioxide (CO_2) emitter country, contributing to 28% of global energy-related CO_2 emissions in 2017 (IEA, 2018). Motor vehicle emissions have become an important source of air pollutant in China. For example, the $PM_{2.5}$ emissions from the vehicles in cities like Beijing and Shanghai have contributed 20–50% of total $PM_{2.5}$ emissions in 2018 (Fan et al., 2017; MEE, 2018). In addition, vehicle ownership is relatively low in China, which is only 170 vehicles/1000 people in China in contrast to 500–600 vehicles/1000 people in Europe and 800 vehicles/1000 people in the U.S. (Huo et al., 2013). According to IRENA (2018) and Tang et al. (2019), the transport energy consumption in China will continue to grow rapidly as vehicle ownership increases. This implies that energy

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Acronyms

ANL	Argonne National Laboratory
BEV	Battery electric vehicle
CO_2	Carbon dioxide
EV	Electric vehicle
EOL	End-of-life
GHG	Greenhouse gas
GWP	Global warming potential
GV	Gasoline vehicle
ICEV	Internal combustion engine vehicle
LCA	Life cycle assessment
Mg, g, kg	Milligram, gram, kilogram
NO_X	Nitrogen Oxides
$PM_{2.5}$	Particular matter with a diameter of less than 2.5 μm
PHEV	Plug-in hybrid electric vehicle
SO_2	Sulfur dioxide sulfur dioxide
SUV	Sport utility vehicles
t	ton
VOCs	Volatile organic compounds
WTW	Well-to-wheel

security and environmental pollution issues will become more severe in China's transport sector in years to come.

Promoting electric vehicles (EVs) is regarded as an important measure to ensure energy security, mitigate climate change, and reduce air pollutant from the transport sector (Fan et al., 2020; Onat et al., 2018; Peng et al., 2018; Requia et al., 2018). In recent years, the Chinese government has released a series of policies to incentivize EVs' adoption (Zhang and Bai, 2017). This has led to increase in sales of EVs in China. In 2018, the annual sales and stocks of EVs in China were approximately 1.26 million units and 2.61 million units, accounting for 50.4% and 39.5% of global figures, respectively. China has become the world leader in EVs sales and stocks (CAAM, 2019; MPS, 2019).

Although EVs are promoted as a viable solution in the reduction of air pollutant emissions, there is no consensus on the emission reduction effect of EVs. As a country that owns abundant coal resources, researchers doubt whether promoting EVs can reduce emissions in China. Additionally, most scholars, in China, only focus on GHG emissions but ignore the effect on air pollutant emissions when assessing the life cycle environmental impact of EVs. Some studies indicated that automobiles contributed the main air pollutant emissions in China's transport sector (Ji et al., 2012; MEE, 2018). Hence, it is essential to study the emission reduction effect of EV in comparison with internal combustion engine vehicles (ICEVs) from the entire life cycle perspective. Three questions were explored in this study: (1) Can EV reduce CO_2 emissions and air pollutants? (2) To what extent can CO_2 and air pollutants be reduced by using EV? (3) How can EV reduce CO_2 and air pollutants? Our study focused on China's passenger vehicle industry in 2018. In this paper, ICEV only refer to gasoline-based ICEV, EV includes battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

The remainder of this paper is organized as follows: section 2 is literature review, section 3 presents the methods and data used in the study, section 4 and 5 contain the results and discussions of the analysis, and section 6 presents conclusions and policy implications.

2. Literature review

A large number of studies have discussed the CO_2 and air pollutants associated with passenger vehicles. Part existing studies only took into account the vehicle use phase (including petroleum extraction and production, electricity generation, transmission and distribution) by using well-to-wheel (WTW) method. In these studies, most scholars indicated that EV have lower CO_2 emissions and higher NO_X and SO_2 emissions than that of ICEV. Some studies have pointed out that EV reduced 15–32% of CO_2 emissions compared to gasoline-based ICEV in China (Ke et al., 2017; Shi et al., 2016; Zhou et al., 2013). Shen et al. reported that in 2012 the ICEV generated 229 g CO_2 eq of GHG emissions per km, and BEV generated 129–205 g CO_2 eq/km, and the emissions of ICEV and BEV had declined to 199 and 91–171 g CO_2 eq/km in 2015, respectively (Shen et al., 2014, 2019). Moro and Lonza (2018) indicated that the use of EVs instead of gasoline vehicles (GVs) can save (about 60% of) GHG in all or in most of the EU Member State. However, a few studies also presented different findings. Huo et al. (2010) thought that BEV could not reduce CO_2 emissions, while Yuan et al. (2015) reported that only short-driving-range (<250 km) BEV with low driving speeds (<80 km/h) can reduce CO_2 emissions compaired with ICEV. Regarding air pollutant emissions, Huo et al. reported that BEV could increase SO_2 emissions by 3–10 times and double NOx emissions while decrease $PM_{2.5}$ emissions compared to GV (Huo et al., 2010, 2015).

However, WTW method ignores other stages of a vehicle's life cycle (Moro and Helmers, 2017), which may underestimate the life cycle emissions of the vehicle. LCA method is increasing adopted by many scholars on account of more reasonable and comprehensive system boundary. From the global perspective, the studies from different countries always have different results. Hawkins et al. (2013) found that EV powered by the European electricity mix offer a 10%–24% decrease in global warming potential (GWP) relative to GV assuming lifetimes of 150,000 km. One study from Europe also presented similar conclusion: EV have much lower GWP than that of ICEV, based on a lifetime of 200,000 km (Rosenfeld et al., 2019). Furthermore, the CO_2 emissions of BEV and PHEV, operated by electricity from wind, were 42 and 33 g/km, respectively, while gasoline-based ICEV was 225 g/km for all analyzed sport utility vehicles (SUV) types. Souza et al. (2018) found that the CO_2 emissions of BEV and GV were 151 and 291 g/km in Brazil, respectively. Karaaslan et al. (2017) thought that the life cycle GHG emissions of gasoline-based ICEV and BEV were 117.8 and 77.2 t CO_2 eq, respectively, by using 200,000 vehicle miles of travel for SUV in U.S. Some scholars thought that EV performs better than ICEV in term of CO_2 emissions in Italian, Poland and Czech Republic (Burchart-Korol et al., 2018; Girardi et al., 2015). However, the study from Lithuania presented opposite conclusion: BEV of 2015 electricity mix generate 26% more GHG than those of ICEV fuelled with petrol (Petrauskienė et al., 2019). In term of environment impact, Girardi et al. (2015) indicated that EV performs better than ICEV for VOCs and SO_2 emissions in Italian, while Held and Schücking (2019) thought BEV have better environmental effects due to a lower impact per driven mile during utilization in Germany.

Similar to the other countries, more and more studies focus on GHG and CO_2 emissions in China. Wu et al. (2018) compared the emissions from ICEV and BEV from the life cycle prospective and found that the life cycle GHG emissions of ICEV and BEV were 34.9 and 31.4 t CO_2 eq, respectively, in 2014, of which 62–70% was attributed to vehicle operation. Qiao et al. (2019) indicated that the life cycle GHG emissions of an EV were about 41.0 t CO_2 eq in 2015, 18% lower than those of an ICEV. By using Tsinghua-LCAM model, Zhou et al. (2013) assessed the GHG emissions of BEV, PHEV and

ICEV and found them to be 206.1, 227.4 and 248.7 g CO_2 eq/km, respectively, in China with the average electricity mix. Wu et al. (2019) thought that the carbon footprint is approximately 250.6 g CO_2 eq/km for ICEV and 217.6 g CO_2 eq/km for BEV under a nationwide electricity mix when choosing A-class segment as research object. Ou et al. (2010) thought that the reduction of life cycle GHG emissions of EV charged by electricity generated from coal could be 3–36% when compared to gasoline-based ICEV. Shi et al. (2016) compared CO_2 and air pollutant emissions of BEV and ICEV in Beijing and reported an increase in CO_2, NO_X and SO_2 emissions of BEV by −50%, 100% and 104%, respectively.

Based on above studies, we found that, most existing studies in the context of China focus on GHG emissions when assessing the environmental impact of EVs while only few studies considered EV effect on air pollutant emissions. According to the two reports by Ji et al. (2012) and MEE (2018), the automobile subsector is the main contributor of air pollutant emissions which have potential to harm the human health. In this regard, it is very essential to research the EV's effect on air pollutant emissions. Additionally, we also found that the findings of many previous studies largely differ on the impact of EV on the reduction of CO_2 and air pollutants' emissions. The main reason is that different literatures used different vehicle models and electricity mix. In this study, we attempted to address the above shortcomings by: firstly, investigating the carbon emissions and air pollutant emissions including VOCs, NOx, $PM_{2.5}$ and SO_2 from the entire life cycle perspective; and secondly, using the industry average parameter of passenger vehicle models and setting various electricity mix to address the divergence of the findings of the previous studies. We expect that this approach will provide better findings on the reduction effect of EVs on CO_2 emissions and air pollutant emissions.

3. Methods and data

Life cycle assessment is a method of quantifying the potential environmental impacts associated with the full life cycle of a product (ISO, 2006a, b; Li et al., 2016). This process has been regarded as an effective approach to identify environmental hotspots and guide research work in relevant areas (Yu et al., 2018). Fig. 1 presents the stages considered in the calculation logic of the energy and material consumption (inputs) and CO_2, air pollutant emissions and wastes (outputs) of the process. According to Sullivan et al. (2013), the vehicle life cycle has three phases: vehicle production, vehicle use and vehicle end-of-life (EOL). *The first phase*, vehicle production includes material production, parts manufacturing, vehicle assembly and distribution. The material production includes mining, beneficiation, smelting, and refining for metals, etc. Part manufacturing includes the gathering of essential components. Vehicle assembly considers pre-techniques such as stamping, welding and painting. Vehicle distribution is the transport process for three types of vehicles. *The second phase*, vehicle use includes fuel consumption and vehicle maintenance. *The last phase*, vehicle EOL includes recycling, disposal and reuse. In our study, we consider one more sub-phase in vehicle use: parts replacement, which includes the replacement of tires, fluid and lead-acid batteries. For each life cycle phase, both direct and indirect emissions were considered. The former corresponds to the direct emissions from the energy combustion during each life cycle phase, whereas the latter refers to the indirect emission from production of energy and material inputs for each stage.

For the assessment, we choose the following vehicles as research objects because they are the top-selling models in their subindustry and they also have similar parameters, including: Toyota Corolla luxury 2019 (ICEV), Nissan Leaf 2019 (BEV) and Toyota Corolla double engine E + pioneer 2019 (PHEV) (see detailed parameters in Table 1). In 2018, the stocks of Toyota Corolla in the world were 45 million units that took up the largest share among the ICEVs; and Nissan Leaf were 400,000 units, accounting the largest share among the BEVs. In China, Toyota Corolla double engine was the best-selling vehicle model in 2018, whereby more than 82,000 sales were recorded. In order to conform to China's reality, we did couple of revisions for the parameters of three vehicle models: (1) we changed the battery capacity and energy intensity of BEV and PHEV according to the industry average level. (2) gasoline or electricity consumption in the vehicle use phase is set as the average energy consumption of new passenger vehicles. The spatial and temporal boundary of this analysis are China and 2018. We analyzed the total life cycle emissions at the national average level without considering the regional differences. Considering the uncertainty of vehicle efficiency and battery capacity, we set the average industrial level as the baseline scenario, meanwhile also set the low and high scenarios, respectively, see Table 2.

This study assumed that the lifetime and life cycle driving kilometer of passenger cars were 10 years and 150,000 km, respectively, and no battery replacement will be required in the life cycle (Girardi et al., 2015; Hao et al., 2017a). The function unit of this study is 150,000 km. In the life cycle of PHEV, the mileage ratio consuming electricity and gasoline is set as 50%, respectively (Wu and Zhang, 2017) and the charging efficiency of BEV and PHEV is 95% (Faria et al., 2013).

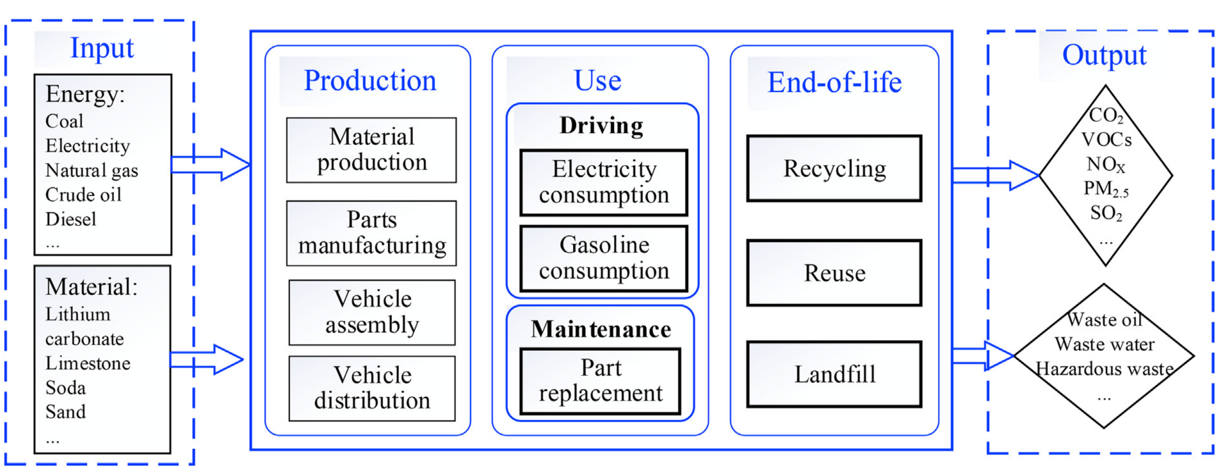

Fig. 1. System boundary of this study.

Table 1
Parameter comparison of three vehicle models (CATRC, 2018; Dongfang Securities, 2019; MIIT, 2019; SAE-China, 2017).

	ICEV	BEV	PHEV
	Toyota Corolla luxury 2019	Nissan Leaf 2019	Toyota Corolla double engine E + pioneer 2019
Size (Length × Width × Height) (mm)	4635 × 1780 × 1455	4480 × 1790 × 1540	4635 × 1775 × 1470
Engine displacement (mL)	1197		1798
Engine power (kW)	85		73
Max. speed (km/h)	180	145	180
Curb weight (kg)	1350	1545 (1608)	1505 (1504)
Wheelbase (mm)	2700	2700	2700
Max. output (bhp)	116	150	99
Tank capacity (L)	50		45
Motor power (kW)		110	53
Vehicle efficiency (L/100 km; kWh/100 km)	5.6 (5.8)	10 (13.8)	4.2 (4.6); 19.1 (21.6)
Storage capacity (kWh)		40 (40)	10 (12.8)
Cruising range of battery (km)		358	55

Note: The number in the "( )" represents the revised parameter according to China's real situation. Specifically, we used the average level of storage capacity and vehicle efficiency in China to replace the original vehicle model (CATRC, 2018; MIIT, 2019); meanwhile, we revised the curb weight of BEV and PHEV according to the storage capacity and energy density of battery in China (SAE-China, 2017). Based on the study of Hao et al. (2017b), we assumed that the adjustment of these parameters will not impact the vehicle's performance.

Table 2
Vehicle efficiency and battery capacity under different scenarios (CATRC, 2018; SAE-China, 2017; SAE-China, 2018).

	Vehicle types	Low	Baseline	High
Vehicle efficiency	ICEV (L/100 km)	6.0	5.8	5.0
	BEV (kWh/100 km)	15.4	13.8	10
	PHEV (L/100 km; kWh/100 km)	5.0;24.0	4.6;21.6	4.2;19.1
Battery capacity	BEV (kWh)	30	40	48
	PHEV (kWh)	10	12.8	15

3.1. Vehicle production

3.1.1. Materials production

The materials production phase includes mining, beneficiation, smelting, and refining for metals, whereas polymer production encompasses oil and gas recovery, refining, and feedstock synthesis. We considered the material composition of the vehicle, given the fact that the emission factors of different materials are different. Table 3 lists the material composition of ICEV, BEV and PHEV based on their material bill. The vehicles major parts include: lead-acid battery, fluid, tire and lithium-ion battery. The curb weight of BEV and PHEV are 19% and 14% heavier than that of ICEV because the electric powertrain components including battery pack are heavier than the internal combustion engine and fuel tank. For the major parts material, steels are the most common material, accounting for 62.3%, 66.4% and 65.2% of the major parts mass of ICEV, BEV and PHEV, followed by average plastic, aluminum and iron. Emission factor (Table 4) and energy consumption (Table 5) of different materials and emission factors of different energy (Table 6) in China were based on the GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model from U.S. Argonne National Laboratory (ANL) (ANL, 2018).

Table 3
Weight of materials and components for the reference vehicles (Li et al., 2013; Qiao et al., 2017; Sullivan et al., 2013). (unit: kg).

	ICEV	BEV	PHEV
Major parts			
Steel	793	827	847
Cast iron	139	25	78
Cast aluminum	28	12	66
Wrought aluminum	59	68	23
Copper	24	59	56
Glass	37	44	38
Average plastic	141	151	138
Rubber	29	22	26
Others	23	37	27
Subtotal	*1273*	*1245*	*1299*
Lead-acid battery	15	15	15
Fluid	26	26	26
Tire	36	36	36
Lithium-ion battery[a]		286[b]	128[b]
Total	*1350*	*1608*	*1504*

Notes.
[a] The lithium-ion batteries mentioned in this paper are all NCM batteries.
[b] The battery energy density of BEV and PHEV is 140.3 Wh/kg and 100 Wh/kg in 2018, respectively.

3.1.2. Parts manufacturing

Parts manufacturing typically involves a number of mechanical and chemical processes such as casting, rolling, stamping, and wire drawing (Sullivan et al., 2013; Wang et al., 2020). At this phase, we only consider the main fuels consumption: natural gas, coal and electricity (Kim et al., 2016; Wang et al., 2020), while the other energy (e.g. residual oil, diesel, and liquefied natural gas, thermal energy) is not considered here. The direct emissions of parts manufacturing are relative small, hence we do not consider it as well (Hu and Li, 2019). We calculated the energy consumption per vehicle in accordance with the studies of Wang et al. (2020) and Kim et al. (2016) (Table 7).

3.1.3. Vehicle assembly

Vehicle assembly encompasses painting, material handling, heating and welding and so on (Sullivan et al., 2013). All these processes consume energy and produce emissions. According to Qiao et al. (2017), vehicle assembly (not include lithium-ion and lead-acid battery) consumes 852 MJ of electricity and 5568 MJ of natural gas per vehicle. In terms of vehicle assembly emissions, we only consider painting phase due to the insufficient data.

Table 4
Emission factor of material production[a] (ANL, 2018).

	CO_2 (kg/kg)	VOC(g/kg)	NO_X (g/kg)	$PM_{2.5}$ (g/kg)	SO_2(g/kg)
Steel	2.00	3.12	1.90	0.74	8.39
Cast iron	0.55	2.52	1.31	0.57	3.67
Cast aluminum	2.62	0.47	2.45	0.74	7.47
Wrought aluminum[b]	5.92	1.13	4.92	1.99	24.10
Copper	2.35	0.32	5.43	0.23	0.14
Glass	1.62	0.24	2.28	0.09919	1.36
Average plastic	3.05	1.12	5.10	0.32	17.46
Rubber	3.62	6.27	5.03	0.44	13.75
Other[c]	2.70	1.77	3.42	0.66	9.39

Notes.
[a] We chose the 90%, 100% and 110% of material emission factor from this table as the low, baseline and high scenarios, respectively, according to the study of Li et al. (2016). Li et al. (2016) thought a variation of 10% for each factor is reasonable when assessing the influence of that factor on the general environmental impact. Thus, we set those two scenarios by comparing with the baseline conditions.
[b] This study assumed that the recycling rates of wrought aluminum is 20%.
[c] We used the average value of emission factor of material production here.

Table 5
Energy consumption of material production used in vehicles (without batteries, tires and fluid) (ANL, 2018; Qiao et al., 2017).

Energy consumption (MJ/t)	Coal	Electricity	Natural gas	Coke	Crude oil	Gasoline	Diesel	BFG	COG
Steel	21300	2001	8277	12117	253	3	39	1087	494
Cast iron	0	692	5742	2639	194	2	30	0	0
Cast aluminum	50426	15368	7977	0	0	0	0	0	0
Wrought aluminum	47802	14660	5699	0	0	0	0	0	0
Copper	4387	5460	0	0	6812	0	9566	0	0
Glass	3172	978	16125	0	326	0	0	0	0
Average plastic	433	1492	19784	0	3566	62	197	0	0
Rubber	0	751	21639	0	17661	0	0	0	0
Others	15940	5175	10655	1845	3602	8	1229	136	62

Notes.
1. Blast Furnace Gas (BFG) and Coke Oven Gas (COG) are the by-products of coke production.
2. Similar to emission factor of material production, we also chose the 90%, 100% and 110% of energy consumption from this table as the low, baseline and high scenarios, respectively.

Table 6
Life cycle emission factors of CO_2 and air pollutant for different types of energy (ANL, 2018; GaBi, 2018; Qiao et al., 2017).

Life cycle emission factor (kg/MJ)	CO_2	VOCs	NO_X	$PM_{2.5}$	SO_2
Coal	0.097500	0.000247	0.000046	0.000001	0.000018
Electricity	0.190798	0.000017	0.000104	0.000014	0.000113
Natural gas	0.064800	0.000256	0.000031	0.000001	0.000018
Coke	0.107500	0.000155	0.000034	0.000001	0.000009
Crude oil	0.091700	0.000045	0.000023	0.000001	0.000013
Gasoline	0.087700	0.000123	0.000028	0.000001	0.000035
Diesel	0.090700	0.000120	0.000024	0.000001	0.000026
BFG	0.260100	0.000374	0.000082	0.000001	0.000022
COG	0.044500	0.000064	0.000014	0.000000	0.000004

Table 7
Energy consumption of parts manufacturing for ICEV, BEV and PHEV (unit: MJ).

	ICEV	BEV	PHEV
Natural gas	5816	5688	5935
Coal	3788	3705	3865
Electricity	4180	4089	4266

3.1.4. Vehicle distribution

In the vehicle distribution phase, the emissions mainly derived from fuel consumption during transportation. The distribution distance, vehicle mass, energy consumption coefficient and emission factors determine the emissions due to fuel consumption (Wang et al., 2013). Currently, China has a great number of auto manufacturers and are dispersing across the country. It is almost impossible to calculate the distribution distance per vehicle. Considering that Guangdong is the biggest production bases of ICEVs and PHEVs, we choose it as the delivery points of ICEVs and PHEVs. For the similar reason, we choose Beijing as the delivery points of BEVs. The distances between the two provinces are showed in Table 8. Additionally, the study of Xiang et al. (2017) showed that vehicle demand was positively correlated with GDP. This means the provinces with high GDP consume more automobiles than those with low GDP. This means the higher the GDP the higher the energy consumption of vehicles distribution. Thus, we choose the GDP of each province as the weight of distribution distances.

$$E_d = D \times M_\nu \times \alpha_{dt} \times EF_d \tag{1}$$

In Eq. (1), $E_d, D, M_\nu, \alpha_{dt}, EF_d$ represent the fuel consumption emissions (kg), distribution distance (km), vehicle mass (kg), energy consumption coefficient (kJ kg^{-1} km^{-1}) and energy emission factor (kg/kJ), respectively. According to the study of Wang et al. (2013), α_{dt} is set as 0.6.

Table 8
Distances from Beijing and Guangdong to other provincial capitals and distances weighted based on GDP percentages (NBS, 2019).

	Beijing (km)	Guangdong (km)	GDP (%)	Distances weighted (%)
Beijing	0.00	1888.76	3.3%	3.3%
Shanghai	1064.68	1213.34	3.6%	3.6%
Tianjin	103.61	1819.35	2.1%	2.1%
Chongqing	1465.23	976.50	2.2%	2.2%
Heilongjiang	1055.41	2791.03	1.8%	1.8%
Jilin	854.47	2556.10	1.6%	1.6%
Liaoning	621.17	2282.85	2.8%	2.8%
Inner Mongolia	408.28	1970.95	1.9%	1.9%
Hebei	270.14	1660.83	3.9%	3.9%
Shanxi	406.24	1639.55	1.8%	1.8%
Shandong	366.20	1543.66	8.4%	8.4%
Henan	617.50	1297.99	5.3%	5.3%
Shaanxi	917.44	1308.22	2.7%	2.7%
Gansu	1187.23	1699.24	0.9%	0.9%
Ningxia	896.52	1815.65	0.4%	0.4%
Qinghai	1333.38	1862.87	0.3%	0.3%
Xinjiang	2417.21	3281.70	1.3%	1.3%
Anhui	898.27	1048.06	3.3%	3.3%
Jiangsu	900.19	1131.81	10.1%	10.1%
Zhejiang	1125.65	1045.01	6.1%	6.1%
Hunan	1341.11	562.08	4.0%	4.0%
Jiangxi	1248.45	670.26	2.4%	2.4%
Hubei	1049.90	839.21	4.3%	4.3%
Sichuan	1520.88	1233.90	4.4%	4.4%
Guizhou	1734.50	763.92	1.6%	1.6%
Fujian	1558.67	693.89	3.9%	3.9%
Guangdong	1888.76	0.00	10.6%	10.6%
Hainan	2233.36	418.97	0.5%	0.5%
Guangxi	2049.95	504.71	2.2%	2.2%
Yunnan	2086.07	1074.47	2.0%	2.0%
Tibet	2563.21	2311.79	0.2%	0.2%
Distance	1065.34	1177.94		

3.2. Vehicle use

The vehicle use phase encompasses petroleum extraction and production, electricity generation, transmission & distribution, and repair & maintenance. Fuel pathways are specified for the different vehicles, including the ways to obtain gasoline and electricity. Regarding gasoline, we use the gasoline that includes 10% ethanol (E10) because the supply of E10 is expected to cover all the regions across the country before 2020 (NEA, 2017). For electricity, the electricity mix and emission factors of different power sources in China are given in Table 9.

During the vehicle use phase, ICEV and BEV are run using gasoline and electricity, respectively, while PHEV is run using both gasoline and electricity. For ICEV, the emissions from vehicle use were determined by gasoline consumption, gasoline emission factor and life cycle driving kilometer. For BEV, the emissions of vehicle use were determined by electricity consumption, electricity emission factor and life cycle driving kilometer. For PHEV, the emissions of vehicle use involved two parts: gasoline consumption emissions and electricity consumption emissions.

$$E_{ICEV} = C_g \times WTW_g \times YM \tag{2}$$

$$E_{BEV} = C_e \times WTW_e \times YM \tag{3}$$

$$E_{PHEV} = (C_{pg} \times WTW_g + C_{pe} \times WTW_e) \times \frac{YM}{2} \tag{4}$$

In Eqs. (2)–(4), $E_{ICEV}, E_{BEV} and\ E_{PHEV}$ represent the emissions (g) of the use phases of ICEV, BEV and PHEV, respectively. $C_g\ and\ C_e$represent gasoline consumption (L/100 km) of ICEV and electricity consumption (kWh/100 km) of BEV, respectively; C_{pg} and C_{pe} represent the gasoline consumption and electricity consumption of PHEV, respectively.WTW_g and WTW_e represent the emission factors (g/L;g/kWh) of gasoline and electricity, respectively.YM represent the life cycle driving kilometer (km). In this study, $C_g\ and\ C_e$are set as 5.8 and 13.8, respectively, while C_{pg} and C_{pe} are set as 4.6 and 21.6, respectively (CATRC, 2018; SAE-China, 2017). The emission factors of gasoline and electricity are provided in Table 9 and Fig. 2.

Table 9
Electricity mix and emission factors of different power source in China (ANL, 2018; CEC, 2019; GaBi, 2018; Yang et al., 2019).

	Proportion in China grid*	CO_2 (g/kWh)	VOCs (mg/kWh)	NO_X (mg/kWh)	$PM_{2.5}$ (mg/kWh)	SO_2 (mg/kWh)
Coal	65.2%	960	79.5	490	56.6	560
Natural gas	3.3%	440	72.8	410	13.3	96.4
Nuclear	4.3%	7.4	3.1	16.9	0.7	10.7
Hydro	17.9%	7.4	0.2	2.6	0.2	1.8
Biomass	1.3%	27.8	150	1040	610	650
Wind	5.3%	12.5	1.9	17.4	1.2	18.8
Solar	2.6%	42.7	33.5	81.1	15.0	119.0
China average		644.2	57.3	350.8	45.8	381.6

Note: * The transmission loss rate of China power grid is 6.21% in 2018.

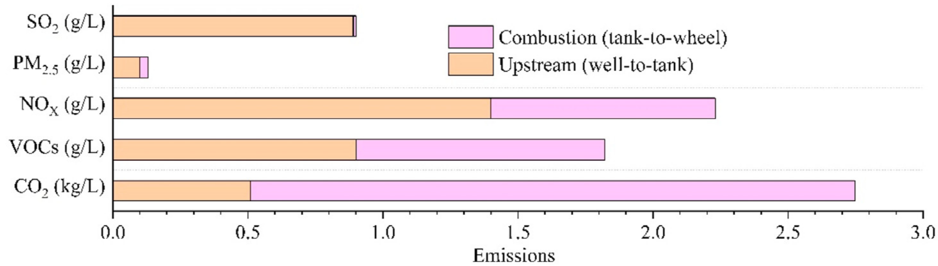

Fig. 2. Emission factors of gasoline for both upstream and combustion processes (ANL, 2018).

For maintenance and repair, the change frequency of every fluid is obtained from automobile use handbook. The use kilometers of the powertrain coolant, transmission fluid, brake fluid and windshield fluid are 30,000 km, 60,000 km, 20,000 km and 12,500 km, respectively. The replacement period of lead-acid battery usually is 3–4 years (this paper assumed 3 years) and the use kilometers of the tire is about 80,000 km (Hu and Li, 2019). Therefore, during the entire life cycle, the powertrain coolant, transmission fluid, brake fluid and windshield fluid, lead-acid battery and tire will be replaced 4, 2, 7, 11, 3 and 1 times, respectively (Table 10).

3.3. Vehicle EOL

The EOL phase includes dismantling and shredding process. For vehicle disposal, the energy consumption emissions were determined by the disposal energy consumption factor (energy consumption per mass of vehicle), vehicle mass and energy emission factors. Electricity is the dominated energy in the EOL phase (Wang et al., 2020), thus we only consider the emissions of energy consumption.

$$E_{dp} = \alpha_{dp} \times M_v \times EF_d \tag{5}$$

In Eq. (5), E_{dp}, α_{dp} represent the energy consumption emissions (kg), vehicle mass (kg) and the product of the disposal energy consumption factor (kJ/kg), respectively. α_{dp} is set as 370 (Wang et al., 2013).

4. Results

A comparison of the life cycle emissions of CO_2, VOCs, NO_X, $PM_{2.5}$ and SO_2 of the three types of vehicles are presented in Fig. 3. The emissions presented in these figures are the total vehicles emission from three phases: vehicle production (material production, parts manufacturing, assembly & distribution, lead-acid battery & fluid & tire, li-ion battery), vehicle use (fuel use, maintenance and repair) and vehicle EOL. The fuel use emissions include the emissions from the fuel extraction, refining, processing, transport and use. The findings indicate that BEV and PHEV produce a lower amount of emissions of CO_2, VOCs and NO_X than that of ICEV and higher emissions of $PM_{2.5}$ and SO_2 than that of ICEV. From section 4.1 to section 4.5, all percentages or times represent the average value of different scenarios.

4.1. CO_2 emissions

The life cycle CO_2 emissions of ICEV, BEV and PHEV are presented in Fig. 3a. The results indicate that life cycle CO_2 emissions of ICEV, BEV and PHEV are 33.0–35.5 t, 26.8–29.3 t and 33.1–34.7 t, respectively. The emissions of fuel production accounts for the largest fraction of CO_2 emissions during the life cycle. For ICEV, the CO_2 emissions generated from gasoline production for ICEV operation are the highest, accounting for 70% of ICEV's life cycle CO_2 emissions on average. The CO_2 emissions from electricity generation for BEV operation account for 52% of BEV's life cycle CO_2 emissions. The CO_2 emissions of fuel production (including gasoline and electricity) from PHEV contribute 63% of PHEV's life cycle CO_2 emissions.

We estimate the CO_2 emissions in g/km (average emissions per kilometer during the vehicle life cycle). The results show that CO_2 emissions from ICEV, BEV and PHEV are 220–236 g/km, 179–195 g/km and 220–231 g/km, respectively. The CO_2 emissions of vehicle production from BEV and PHEV are 81–103 g/km and 74–90 g/km, respectively, which are roughly 133% and 119% of the CO_2 emissions of vehicle production from ICEV. For the production phase of BEV and PHEV, material production contributes 59% and 66% of CO_2 emissions, whereas the battery manufacturing contributes 23% and 12% of CO_2 emissions, respectively. In general, the results indicate that BEV and PHEV reduce CO_2 emissions by 18% and 1% compared to ICEV.

4.2. VOCs emissions

The life cycle VOCs emissions of ICEV, BEV and PHEV are presented in Fig. 3b. The results indicate that life cycle VOCs emission of ICEV, BEV and PHEV are 37.5–38.9 kg, 26.9–30.9 kg and 30.6–33.3 kg, respectively. In all vehicle types, the largest VOCs emission occurs in the vehicle production phase. For the vehicle production phase, ICEV accounts for 55.2% of the life cycle VOCs emissions, while BEV and PHEV contribute 90% and 72% of the life cycle VOCs emissions, respectively.

We estimate the VOCs emissions in mg/km. The findings

Table 10
The replacement times and emission factors of different parts.

	Replacement times	CO_2 (kg)	VOCs (kg)	NO_X (kg)	$PM_{2.5}$ (kg)	SO_2 (kg)
Powertrain coolant	4	20.478	0.088	0.020	0.002	0.045
Transmission fluid	2	7.145	0.005	0.007	0.001	0.020
Brake fluid	7	7.145	0.005	0.007	0.001	0.020
Windshield fluid	11	3.345	0.012	0.002	0.000	0.002
Lead-acid battery	3	182.840	0.292	0.075	0.058	0.204
Tire	1	206.812	0.386	0.202	0.021	0.471

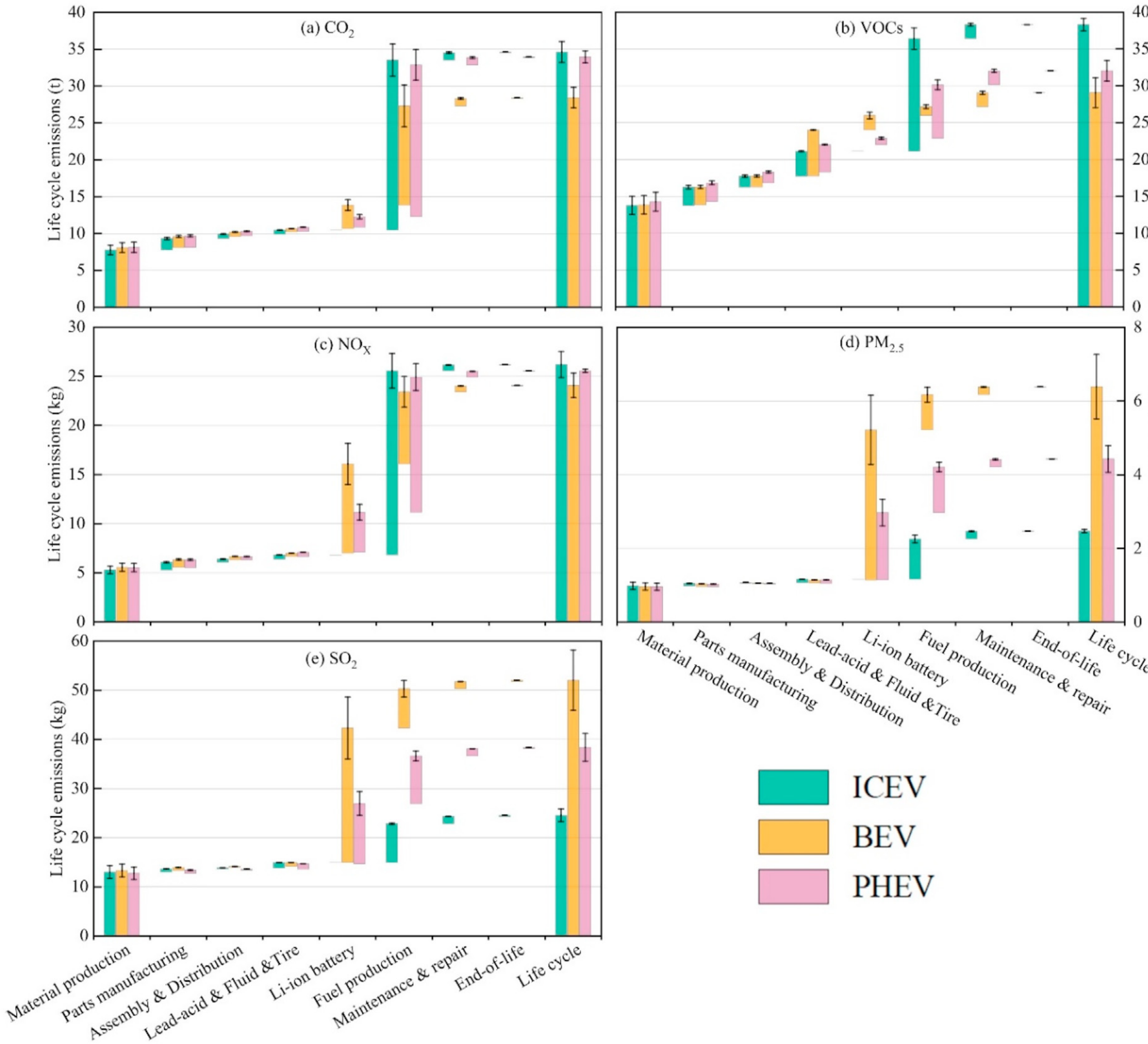

Fig. 3. The impact comparison of three types of vehicles for different emission categories.

indicate that VOCs emissions from ICEV, BEV and PHEV are 250–259 mg/km, 179–206 mg/km and 204–222 mg/km, respectively. For the VOCs emissions of vehicle production, BEV and PHEV are 158–187 mg/km and 140–165 mg/km, which are roughly 123% and 109% of that emitted by ICEV. Material production of ICEV contributes 65% of VOCs emissions of vehicle production, while material production of BEV and PHEV contributes 53% and 63% of VOCs emissions of vehicle production, respectively. The battery manufacturing contributes 8% and 4% of the VOCs emissions of vehicle production from BEV and PHEV, respectively. In the vehicle use phase, the VOCs emissions from fuel production of ICEV are 104–120 mg/km, which is roughly 5.7 and 1.9 times of that emitted by fuel consumption in BEV and PHEV. In general, BEV and PHEV are found to reduce VOCs emissions by 24% and 16% compared to ICEV.

4.3. NO_X emissions

The life cycle NO_X emission of ICEV, BEV and PHEV are presented in Fig. 3c. The results indicate that life cycle NO_X emission of ICEV, BEV and PHEV are 24.7–27.0 kg, 22.6–24.8 kg and 25.5–25.8 kg, respectively. The NO_X emissions from the use phase of ICEV are the highest, accounting for 74% of ICEV's life cycle NO_X emissions. The NO_X emissions of the use phase from BEV and PHEV are equal to 33% and 56% of the BEV's and PHEV's life cycle NO_X emissions, respectively.

We estimate the NO_X emissions in mg/km. The findings indicate that the NO_X emissions from ICEV, BEV and PHEV are 165–180 mg/km, 151–166 mg/km and 170–172 mg/km, respectively. In the vehicle production phase, the NO_X emissions of BEV and PHEV are 89–124 mg/km and 65–83 mg/km, which are roughly 234% and 163% of NO_X emissions of ICEV, respectively. The material production of ICEV, BEV and PHEV accounts for 78%, 35% and 50% of NO_X emission of vehicle production, respectively. The battery manufacturing contributes 56% and 36% of NO_X emissions of vehicle production from BEV and PHEV, respectively. The NO_X emissions of vehicle use from ICEV are 116–138 mg/km, which is roughly 2.5 and 1.3 times of the NO_X emissions of vehicle use from BEV and PHEV. In general, BEV and PHEV are found to reduce NO_X emissions by 6% and 3% compared to ICEV.

4.4. $PM_{2.5}$ emissions

The life cycle $PM_{2.5}$ emission of ICEV, BEV and PHEV are presented in Fig. 3d. The results indicate that life cycle $PM_{2.5}$ emissions of ICEV, BEV and PHEV are 2.4–2.5 kg, 5.5–7.2 kg and 4.1–4.8 kg, respectively. The $PM_{2.5}$ emissions of vehicle production from BEV and PHEV are the highest. For the production of BEV and PHEV, the $PM_{2.5}$ emission accounts for 81% and 67% of BEV's and PHEV's life cycle $PM_{2.5}$ emissions, respectively. The $PM_{2.5}$ emissions from ICEV contribute 47% of its life cycle $PM_{2.5}$ emissions.

We estimate the $PM_{2.5}$ emissions in mg/km. The findings indicate that the $PM_{2.5}$ emissions from ICEV, BEV and PHEV are 16–17 mg/km, 36–48 mg/km and 27–32 mg/km, respectively. The $PM_{2.5}$ emissions of vehicle production from BEV and PHEV are 28–42 mg/km and 17–23 mg/km, which are roughly 4.4 and 2.5 times of the vehicle production from ICEV, respectively. In the vehicle production phase, material production of ICEV contributes 84% of the $PM_{2.5}$ emissions, whereby the battery manufacturing of BEV and PHEV contribute 78% and 61% of $PM_{2.5}$ emissions, respectively. In general, BEV and PHEV are found to increase $PM_{2.5}$ emissions by 159% and 79% compared to ICEV.

4.5. SO_2 emissions

The life cycle SO_2 emission of ICEV, BEV and PHEV are presented in Fig. 3e. The results indicate that life cycle SO_2 emission of ICEV, BEV and PHEV are 23.4–26.0 kg, 45.5–57.7 kg and 35.5–41.1 kg, respectively. For ICEV, the highest SO_2 emissions is generated from the vehicle production, accounting for 61% of the life cycle SO_2 emissions. The SO_2 emissions generated from the vehicle production of BEV and PHEV accounts for 81% and 70% of its life cycle SO_2 emission, respectively.

As in previous sections, we estimate SO_2 emission in mg/km. The findings indicate that the estimated SO_2 emissions from ICEV, BEV and PHEV are 156–173 mg/km, 303–385 mg/km and 236–274 mg/km, respectively. The SO_2 emissions of vehicle production from BEV and PHEV are 229–332 and 154–204 mg/km, respectively, which are roughly 2.7 and 1.8 times of the SO_2 emissions of vehicle production from ICEV. At the vehicle production phase, material production of ICEV accounts for 87% of SO_2 emissions of vehicle production, whereas the battery manufacturing of BEV and PHEV contributes 64% and 45% of SO_2 emissions of vehicle production, respectively. In general, BEV and PHEV are found to increase SO_2 emissions by 111% and 56% compared to ICEV.

4.6. Sensitivity analysis

To represent the uncertainty caused by some main parameters, such as vehicle efficiency, material emission factor, battery capacity, and energy consumption (coal, electricity, natural gas, etc.), we further conduct a sensitivity analysis by evaluating the effect of a 10% increase in the above key parameters. The results of the sensitivity analysis are shown in Fig. 4. It can be seen that the material emission factor, battery capacity and energy consumption have a positive impact on the life cycle emissions. The vehicle efficiency has a negative impact on the life cycle emissions, which means that the higher the vehicle efficiency, the fewer the life cycle emissions of vehicles.

For CO_2 emissions, the vehicle efficiency is the most sensitive input parameter for all vehicle types, followed by the parameter of energy consumption. For VOCs emissions, the energy consumption is the most sensitive input parameter for all vehicle types. Vehicle efficiency is the second largest influential parameter affecting the emissions of ICEV and PHEV while the material emission factor is the second largest influential parameter affecting the emissions of BEV. For NO_X emissions, the vehicle efficiency is the most sensitive input parameter for ICEV and PHEV while battery capacity is the most sensitive input parameter for BEV. For $PM_{2.5}$ and SO_2 emissions, the battery capacity is the most sensitive input parameter for

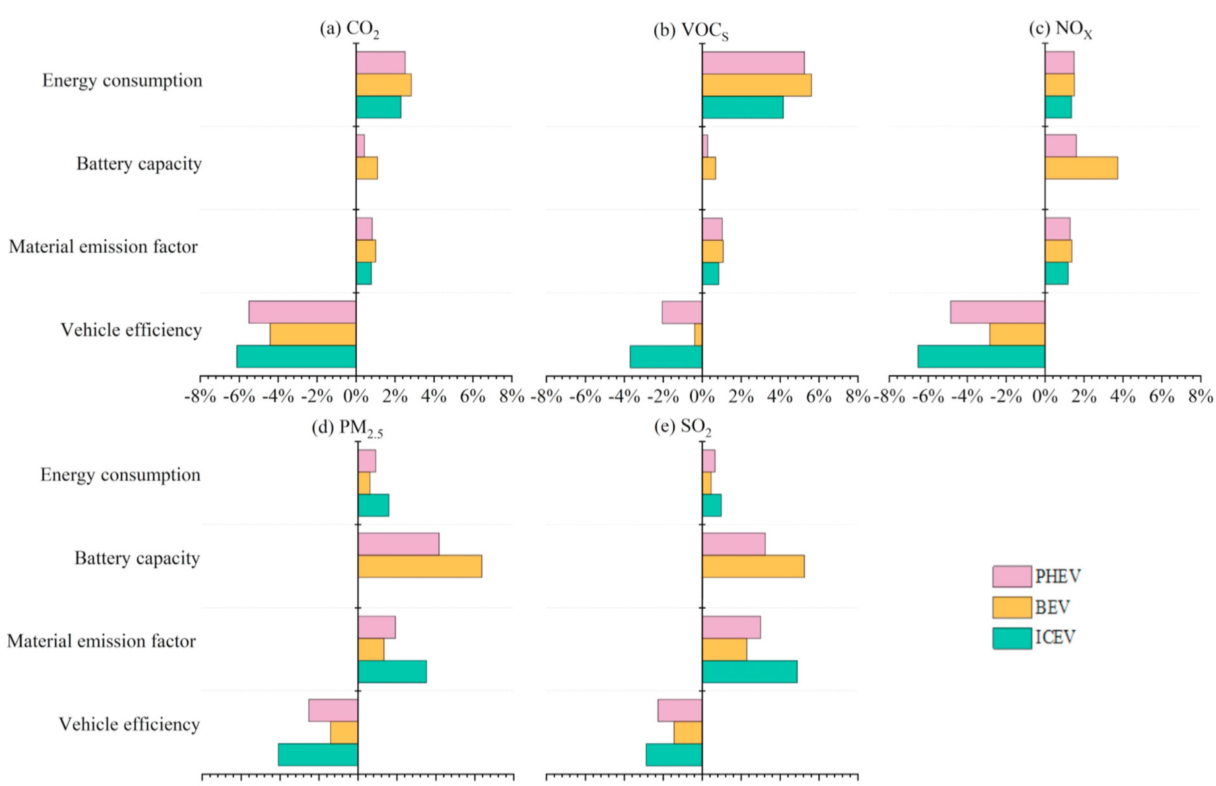

Fig. 4. Sensitivity graphs for main parameters to life cycle emissions.

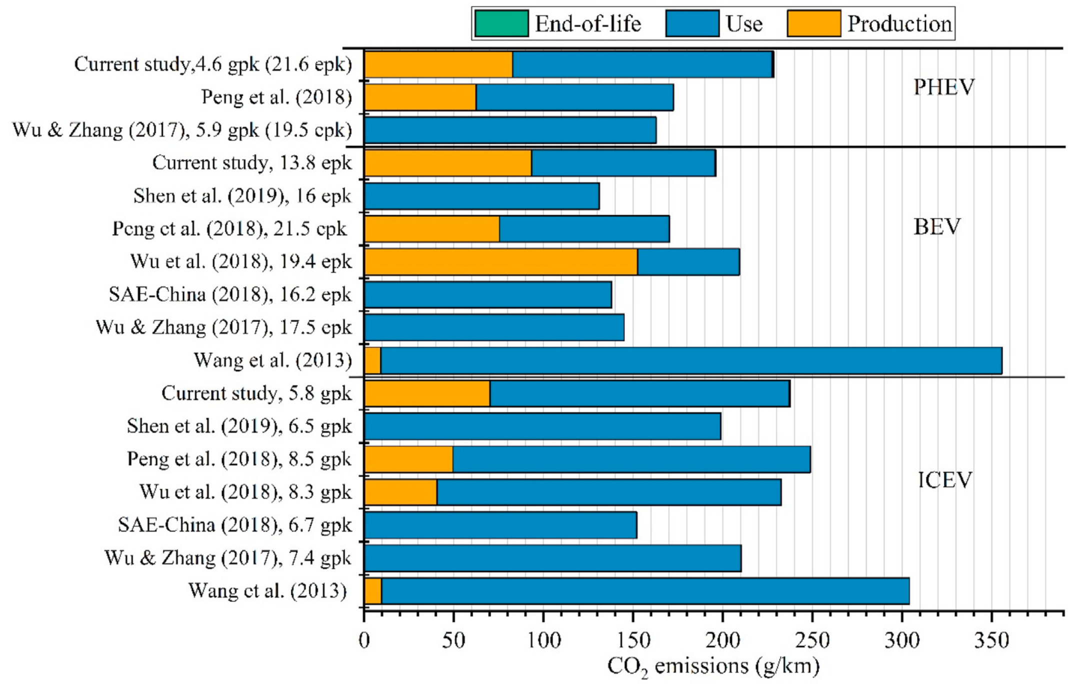

Fig. 5. Comparison of the estimated CO_2 emissions per kilometer. Note: gpk represents gasoline consumption per 100 km (L/100 km), epk represents electricity consumption per 100 km (kWh/100 km).

BEV and PHEV while vehicle efficiency and material emission factor are the most sensitive input parameter for $PM_{2.5}$ and SO_2 emissions from ICEV, respectively. This is why the $PM_{2.5}$ and SO_2 emissions from BEV and PHEV are always higher than those of ICEV.

5. Discussions

We further compare our results with the estimations in the existing research. Considering the electricity mix is one of the key parameters that cause the conflicting results, we conduct a scenario analysis on the life cycle emissions of different vehicles by changing the electricity mix.

5.1. Comparison of the emissions between this study and the previous studies

Since there are always regional differences, we only focus on China in this section. We compare the estimated CO_2 emissions per kilometer of ICEV, BEV and PHEV given by some selected studies (Fig. 5). The emissions of vehicle use from ICEV and BEV estimated by Wang et al. (2013) related to material production, vehicle assembly, vehicle distribution and vehicle disposal, shows that the CO_2 emission in the use phase is the highest. The studies from SAE-China (2018), Shen et al. (2019) and Wu and Zhang (2017) which only included vehicle use phase, reported that their emissions are lower than what we found in our study. However, even the emissions reported in the use phase of these studies differ from what we found in our study (current study). The difference might be due to the difference of vehicles efficiencies used in the studies. However, not all studies' findings differ from our study, the findings reported by Wu et al. (2018) and Peng et al. (2018) were consistent with the findings of our study.

In Fig. 6, we also compare the estimated air pollutant emissions per kilometer of ICEV, BEV and PHEV given by some selected studies. Regarding VOCs emissions, the difference in ICEV's emissions in the vehicle use phase between SAE-China (2018) and our study (current study) might be due to the emission factors and vehicle efficiency used in these studies. Regarding NO_X emissions, the study's estimate of BEV by Wu and Zhang (2017) only considered to the fuel life cycle, is much higher than that of our study. The difference is mainly due to the different NO_X emission factors of coal power used. Besides, we find that Wu and Zhang (2017) used the outdated data from EU in 2010, which did not fully represent China's real situation (Faria et al., 2012). Regarding $PM_{2.5}$ emissions, the result estimated by SAE-China (2018) is lower than that of our study. The difference arose due to the difference of vehicles efficiencies. Regarding SO_2 emissions, the emissions of BEV from Wu and Zhang (2017) was 3.7 times higher than that found in our study. The difference is due to the use of relative high SO_2 emission factors. The use of high SO_2 emission factors as it was done by Wu and Zhang (2017) is inappropriate because China has been implementing strictly desulfurization technology for coal power plant, therefore the SO_2 emission factors are more likely to gradually decline to low level over the years.

5.2. Life cycle emissions comparison in different electricity mix

To study the impact on the life cycle emissions of the vehicles about different electricity mixes, we design three scenarios: baseline scenario (BS), marginal electricity mix scenario (MES) and high renewable scenario (HRS). In our study, the baseline scenario and marginal scenario use China's average electricity mix and the structure of the increased generation in 2018, respectively. The electricity mix set in the high renewable scenario is from EF and ERI (2015) which estimated that renewable energy will account for 85.7% of China's electricity consumption. We identified the emission impact of the vehicles under different electricity mix by setting three scenarios. Table 11 presents China's electricity mix in different scenarios.

Fig. 7 shows the life cycle emissions for ICEV, BEV and PHEV in different electricity mixes. The arrows show the emission change as the electricity mix change. In general, the change of electricity mix

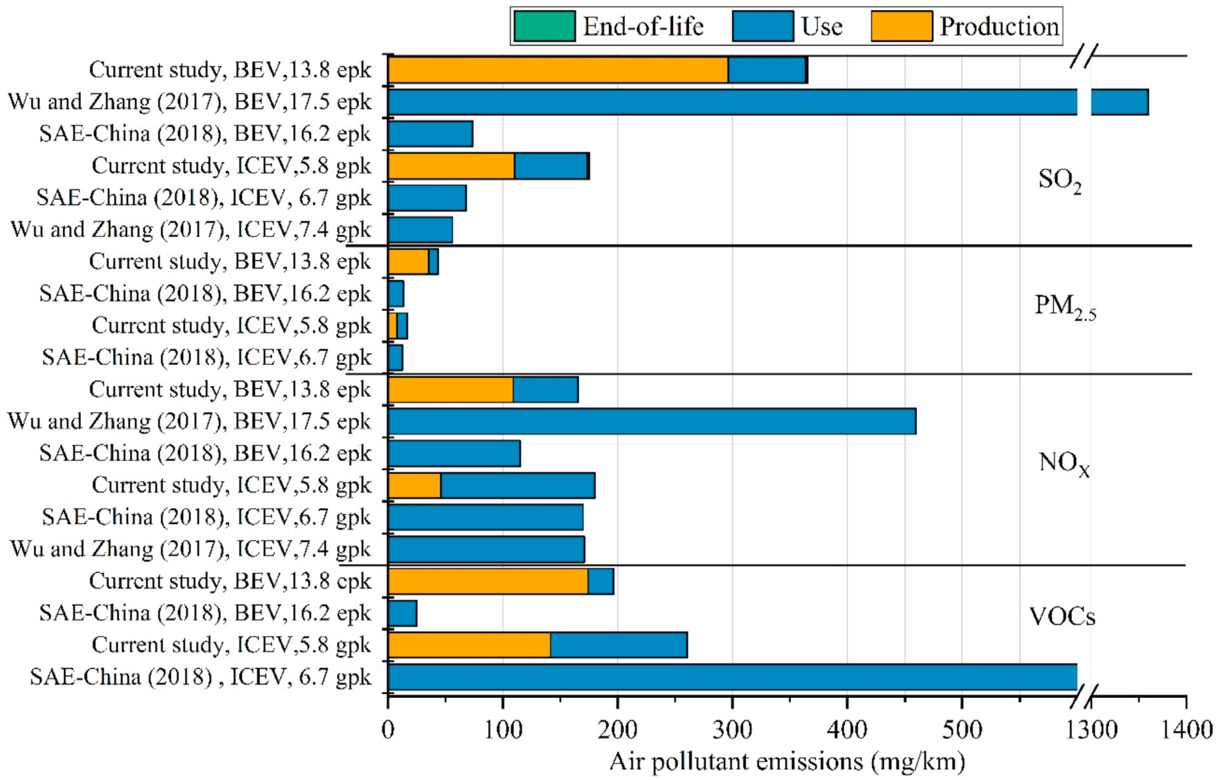

Fig. 6. Comparison of the estimated air pollutant emissions per kilometer.

Table 11
China's electricity mix in different scenarios (CEC, 2019; EF and ERI, 2015).

	Coal	Natural gas	Nuclear	Hydro	Biomass	Wind	Solar
BS	65.2%	3.3%	4.3%	17.9%	1.3%	5.3%	2.6%
MES	41.9%	5.8%	16.4%	8.4%	3.0%	11.7%	12.8%
HRS	6.9%	3.1%	4.3%	14.5%	7.3%	35.4%	28.5%

has a larger influence on BEV and PHEV than on ICEV. Regarding the ICEV, the vehicle production consumes a large amount of electricity while the electricity emission factor is changed with the electricity mix change. The emissions per kilometer of CO_2, VOCs, NO_X and SO_2 have a small decline because their emission factors from electricity consumption have very small change when the electricity mix becomes cleaner than before. However, the emissions per kilometer of $PM_{2.5}$ decreases by 0.02 mg/km (from BS to MES) and increases by 0.15 mg/km (from MES to HRS). This is because the $PM_{2.5}$ emission factor of electricity decreased to 47.9 mg/kWh from 48.8 mg/kWh (from BS to MES) and increased to 57 mg/kWh from 47.9 mg/kWh (from MES to HRS).

Regarding the BEV and PHEV, the CO_2 emissions would decline to 107 g/km and 156 g/km from 296 g/km and 228 g/km

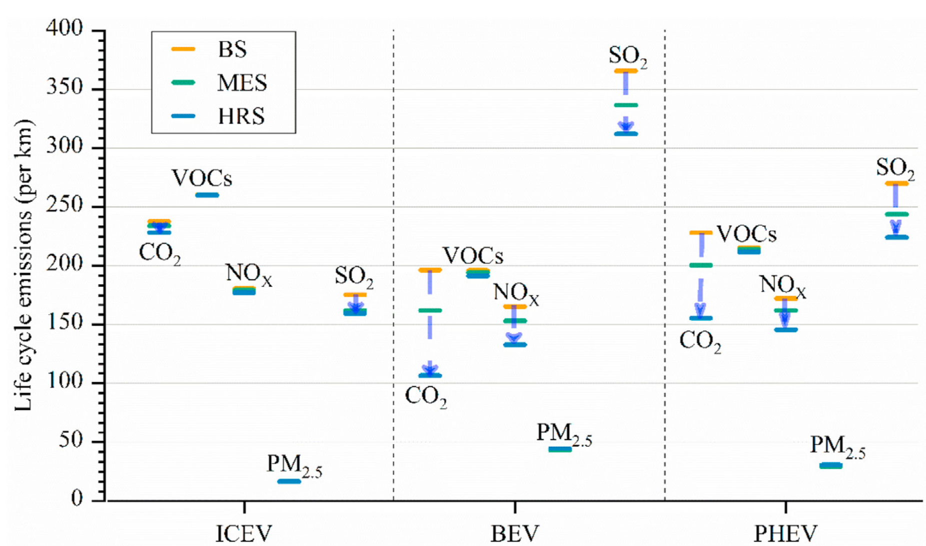

Fig. 7. Life cycle emissions from ICEV, BEV and PHEV in different scenariosNote: The unit of CO_2 and air pollutant emissions are g/km and mg/km respectively.

respectively when the electricity mix shift to HRS from BS. This indicates a large potential for CO_2 emissions reduction due to the use of renewable energy in the electricity mix. When compared to ICEV, the emissions reduction of BEV and PHEV are 53% and 32%, respectively. The VOCs emissions of BEV and PHEV are almost unchanged with the change of electricity mix and have lower emissions than ICEV. However, the $PM_{2.5}$ emissions slightly rise when the electricity mix shift from MES to HRS, while the NO_X and SO_2 emissions declined. For instance, the SO_2 emissions of BEV would decline to 312 mg/km from 366 mg/km when the electricity mix shift from MES to HRS, however, the emissions would be still 96% higher than that of ICEV, which is probably because of the high biomass power share and emission factor. That means we should implement more advanced technology to reduce emissions of biomass power plant in order to reduce the SO_2 emissions of EVs.

Based on this assessment, it can be observed that different electricity mixes have different impacts on emissions from different types of vehicles. It may be very difficult to change the national electricity mix in the short term, however, these findings can be very informative to the different regions that have different electricity mix. Therefore, specific vehicle technologies can be promoted in these regions in accordance with their exisiting regional electricity mix.

6. Conclusions and policy implications

This study adopted the LCA method in response to the controversies on emission reduction capabilities of EVs. The study evaluated the emissions impact of ICEV and EV, focusing not only on carbon emissions but also on air pollutant emissions. The evaluation was done in comparison with previous studies. Furthermore, this study analyzed the entire life cycle of vehicles, including material production, parts manufacturing, assembly & distribution, li-ion battery production, fuel production, vehicle maintenance and repair, and EOL, meanwhile also considered the life cycle emissions impact due to electricity mix change. Base on this analysis, we can draw the following conclusions:

Our study shows that the two types of EVs have different emission reduction effects, mainly due to their unique characteristics. EV are currently less emission intensive than ICEV in terms of CO_2, VOCs and NO_X while emit more $PM_{2.5}$ and SO_2 emissions than ICEV. However, the transition towards cleaner power will narrow this gap.

Compared to an ICEV, one BEV could reduce 6.2 t of CO_2, 9.7 kg of VOCs and 2.2 kg of NO_X, but increase $PM_{2.5}$ by 4.0 kg and SO_2 by 28.5 kg. Compared to ICEV, the emissions reduction by PHEV were 1.4 t of CO_2, 6.7 kg of VOCs and 1.2 kg of NO_X; while one PHEV increased the $PM_{2.5}$ by 1.9 kg and SO_2 by 14.2 kg. Meanwhile, we find that the emissions reduction effect of CO_2, VOCs, NO_X and SO_2 is expected to be improved, and the emission reduction effect of $PM_{2.5}$ is expected to be deceased when electricity becomes cleaner, for example, more renewable energy is introduced.

Based on this study, we try to give some suggestions on reducing CO_2 and air pollutants. First, the material production, power battery manufacturing of EV should be placed in regions where there is high renewable energy utilization. Secondly, biomass power plants, which emit higher air pollutants such as $PM_{2.5}$ and SO_2, should be upgraded to reduce indirect emissions from EV. Lastly, considering the path dependencies in regions with a high percentage of fossil fuels, it is not possible to change the energy mix in short term, therefore, decision-makers should prioritize the use of energy-saving cars, including hybrid electric vehicle, in short and long term plans.

Despite the above contributions, we also realize some limitations. For example, we only analyse the total life cycle emissions of EVs and ICEVs at the national average level without considering the regional differences. However, distinguishing between global and local effects is important, especially for the air pollutants such as $PM_{2.5}$ and SO_2. Therefore, the high-resolution local effects of EVs and ICEVs could be analyzed in the future research so as to identify the heavier emission or polluted regions and design the local policies.

CRediT authorship contribution statement

Lai Yang: Formal analysis, Software, Investigation, Data curation, Writing - original draft. **Biying Yu:** Conceptualization, Resources, Writing - review & editing, Visualization, Supervision. **Bo Yang:** Data curation, Writing - review & editing. **Hao Chen:** Data curation, Writing - review & editing. **Gabriel Malima:** Data curation, Writing - review & editing. **Yi-Ming Wei:** Conceptualization, Resources, Writing - review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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