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Life Cycle Assessment of Energy Consumption and CO_2 Emission from HEV, PHEV and BEV for China in the Past, Present and Future

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Abstract: In order to fulfill the commitment of China to achieve carbon peak by 2030 and carbon neutrality by 2060, all industries have been taking their respective carbon reduction actions. The transportation industry accounts for 11% of CO_2 emission of the whole society, and its energy conservation and carbon reduction benefit is of great significance to the national carbon reduction process. New energy vehicles are undoubtedly one of the most important means of carbon emission reduction in the transportation sector. However, electric vehicles still have CO_2 emissions, as the fossil fuel use comes from upstream power. To systematically and comprehensively evaluate the CO_2 emissions of HEV, PHEV and BEV in the whole process, this study introduces the life-cycle method to research on the past and current situations, and predict future scenarios for ICEV and EV light-duty vehicles at the national and regional levels, by deeply analyzing the generation mix and generating efficiency from the WTT stage, and fuel economy from the TTW stage. The study shows that compared with ICEV, HEV and PHEV could reduce around 30% of CO_2 emissions. Currently, BEV could reduce 37% of CO_2 emission in the region where the proportion of coal-fired power is high, and 90% of CO_2 emission in the region where the proportion of hydro power is high. This study discusses the impact of the proportion of renewable energy application on the carbon emissions from electric vehicles, analyzes the environmental benefits of promoting electric vehicles in different regions, and lays a foundation for the promotion strategy of electric vehicles for different regions in the future.

Keywords: life cycle analysis; electric vehicles; fossil fuel consumption; CO_2 emissions; generation mix

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1. Introduction

The transportation sector consumes large quantities of fossil fuel, and accounts for 11% of CO_2 emissions in China [1]. Among them, the CO_2 emissions of vehicles account for 80% of the total transportation, due to internal combustion engine vehicles (ICEVs) still occupying mainstream status [1,2]. Furthermore, many researchers believe that the traffic demand and CO_2 emission of the transportation sector in China will continue increasing in the future [3–5]. Given the dual pressure from addressing energy crisis and climate change, it is an inevitable choice for China to develop low-carbon transportation systems, among which the development of new energy vehicles is essential and necessary [6].

Advanced vehicle technologies such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), have been considered as part of the ultimate solution to addressing the challenge of vehicle energy consumption and CO_2 emissions, as they have significantly higher fuel efficiency and low—even zero—tailpipe emissions. Globally, there were more than 16.5 million electric vehicles in 2021—a tripling in just three years. In addition, global EV sales maintained strong growth in 2022, with 2 million units sold in the first quarter, up by 75% from the same period in 2021 [7]. In China, numerous policies and projects have been implemented to support the development of new energy vehicles, with positive results achieved [8]. China's new energy vehicles sales grew from 18,000 units in 2013 to 3.521 million units in 2021, with an average annual growth rate of 93 percent (as shown in Figure 1). By the end of June 2022, the number of new-energy vehicles in China has reached 10.01 million, accounting for 3.23% of the total vehicle population [9].

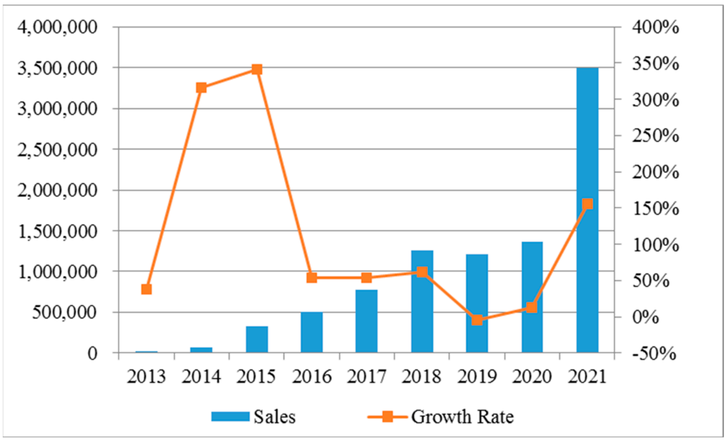


Figure 1. China's new energy vehicle sales trend.

Comparing with different new energy vehicle technologies, HEVs still produce exhaust emissions in the operation stage, as they need to be powered by fossil energy. However, although EVs and PHEVs have few emissions in the operation stage, their impact on the environment mainly depends on the use of clean electricity, as they need to be recharged. Due to the increasing penetration of new energy vehicles in the global automotive market, it is necessary to evaluate the environmental impacts of different propulsion/fuel systems. Multiple methods are available to evaluate the energy consumption and emissions from traditional vehicles and new energy vehicles, such as lab testing, on-road testing and modeling. Considering that the life cycle energy consumption and CO_2 emissions could be affected by various factors, in order to accurately and adequately evaluate the environmental effects of different propulsion/fuel systems, we need to take into account the energy consumption and emissions from upstream fuel/material production processes, as well as from vehicle operations [10]. For example, the environmental performance of EVs is significantly affected by the power generation mix during the upstream stage. In the coal-fired dominated region, EVs may generate more energy consumption and CO_2 emissions in the upstream stage than ICEVs [10,11].

In order to systematically and comprehensively evaluate the energy consumption and CO_2 emissions of HEVs, PHEVs and BEVs from upstream fuel/material production processes, as well as from vehicle operations, this study introduces the life-cycle method to research on the past and current situations and predict future scenarios for ICEV and EV light-duty vehicles at the national and regional level. In particular, we have selected the areas with a typical electricity generation mix that can reflect the impact of clean electricity proportion on upstream emissions.

The remaining part of this paper is organized as follows: Section 2 summarizes the previous work on life cycle assessment of new energy vehicles. In Section 3, the method and calculation principle are proposed based on the GREET model. Section 4 indicates the most important parameters. Based on the data collected in China and two different areas, the energy consumption and CO_2 emission from HEVs, PHEVs and BEVs are evaluated in Section 5, and the conclusions are made in Section 6.

2. Literature Review

An increasing number of studies have provided deep insight into the new energy vehicle technologies to improve energy efficiency and reduce the impact on the environment. Energy management and optimization strategies that can increase the driving range and reduce the emissions and fuel consumption have been put forward [12–16]. Moreover, energy conversion efficiencies and fuel saving effects to different extents can be demonstrated by employing different transmission topologies [17–19]. Al-Samari's research compared the simulation results, and showed an increment of 68% in fuel economy, a reduction of 40% in emission, and an increase of 12% in engine efficiency on real-world driving cycle [20]. Xu et al. found that compared with the series hybrid transmission, the series-parallel hybrid transmission saves approximately 7.2% of fuel for type B vehicles [21].

Researchers have been exploring the impact brought by different factors on fuel economy and emissions. Studied showed that driving scenarios beyond the boundary conditions of real driving emissions can lead to substantial increases of pollutant emissions [22]. Wróblewski et al.'s research results demonstrated the driving techniques that bring measurable effects in terms of reduced energy consumption and the shortest travelling duration [23]. Kazemzadeh et al. analyzed the effect of BEV and PHEV on $PM_{2.5}$ emissions in 29 European Countries [24]. Jung investigated the relationship between vehicle mass and vehicle performance parameters, mainly including fuel economy and the driving range of PHEVs [25].

Many studies focused on the fuel consumption and emissions of ICEVs/HEVs/PHEVs/BEVs from the perspective of the life cycle method under different time and space conditions, and the research results significantly vary globally due to differences in the basic data, modeling process and scenarios [26–38]. Holdway et al. studied the indirect emissions from EVs and compared with the CO_2 emissions from EVs in America [26]. Wu, Huo and Ou developed the research on life cycle analysis of energy consumption and GHG emissions for HEVs/PHEVs/BEVs in China and other significant regions [27–29]. Furthermore, the air pollutant emissions from BEV and CNG in provinces of China were analyzed by Huo et al. [30]. Stephan and Elgowainy mainly analyzed the energy use and greenhouse gas emissions of PHEVs [31,32]. In order to evaluate the impact of PHEVs and EVs, some researchers paid attention to the impact of power generation mix, electric load coming from EVs population and different types of charging mode [33–38]. Studies have increasingly focused on the LCA of hydrogen-fueled FCVs, which have been suggested to have an edge in long-distance transport [39–41]. Research results showed that the life-cycle primary energy consumption varied due to differences in hydrogen pathways. Moreover, Simons and Azimov found that fuel cells could reduce emissions by 34–87% compared with ICEV systems, depending on the source of hydrogen used [42].

Several research gaps have been identified in the existing studies. First, the parameters in the model did not use the latest and fully localized data. Second, most studies did not fully consider the impact of power generation mix on vehicle lifecycle emissions in different areas of China. Third, none of the above-mentioned studies forecast and comprehensively analyzed the variation of vehicle lifecycle energy consumption and emissions in the past, the present and future.

In order to overcome the limitations of current methods for life cycle assessment of energy consumption and environment impact, we systematically calculated the well-to-wheels (WTW) energy consumption and CO_2 emissions in 2010, 2020 and 2030 in China in this study. Two area case studies were presented to evaluate the energy consumption and CO_2 emission of vehicles with different grid compositions, which could give different development paths of vehicles suitable for the future.

3. Methodology

In this research, we adopted the GREET model, which was developed by Argonne National Laboratory (ANL) in 1995 and updated to the GREET 2021 version [43,44], and has been widely used for vehicle life cycle analysis to evaluate energy consumption and CO_2 emission from traditional vehicles and new energy vehicles [29].

The life cycle analysis method comprises two parts: the fuel cycle and vehicle cycle. The fuel cycle covers the whole process of fuel production, fuel transportation and fuel use [43]. The vehicle cycle covers the production and use of vehicle material and parts. This research mainly focuses on the energy consumption and CO_2 emission from fuel cycle, as the proportion of emissions from the fuel cycle is more than 70% in the total life cycle. The fuel cycle is a process from well to wheels (WTW), which includes two stages. The first stage is well-to-tank (WTT), which covers fuel feedstock recovery, fuel production, fuel transportation and refueling stations. The second stage is tank-to-wheels (TTW), which concentrates on vehicle operation activities.

3.1. Research Boundary

The research objectives in this study include ICEVs, HEVs, PHEVs and BEVs. This paper focuses on the comparison of individual energy consumption and CO_2 emissions of different models, and it does not make a horizontal comparison of the overall energy consumption and emissions of the fleet. The base year of the study is 2020, and we have also reviewed the historical scenario in 2010, and predicted the future energy consumption and CO_2 emissions in 2030.

The fuel types involved in this study mainly include gasoline and electricity. Through the simulation of the two fuel paths, the major parameters affecting their energy consumption and CO_2 emissions can be analyzed (shown as Figure 2).

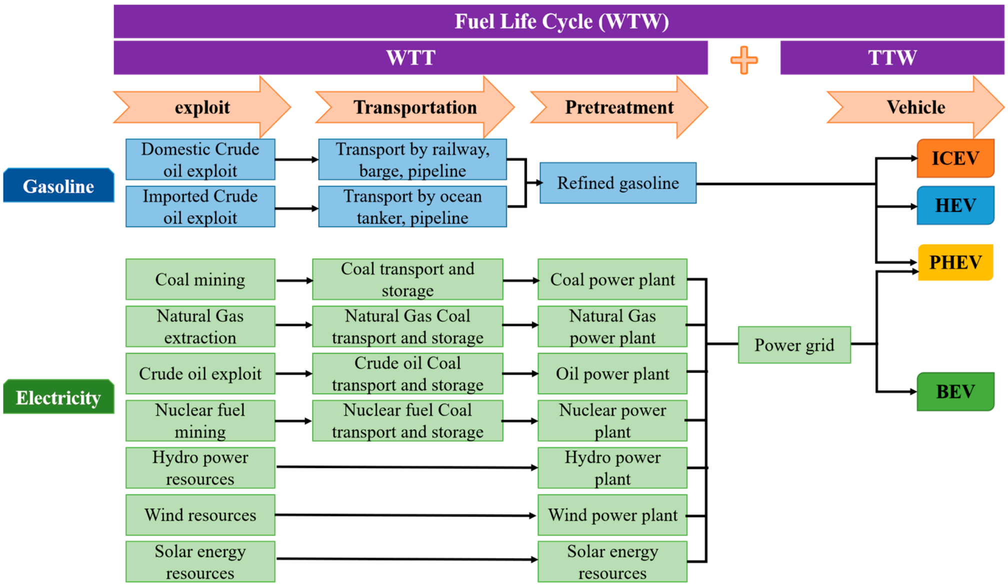


Figure 2. Description of typical fuel paths.

The gasoline fuel path mainly includes the exploitation and transportation of crude oil, the refining and blending of petroleum, the transportation of refined oil and the filling of gasoline. The extraction efficiency of crude oil and the refining efficiency of gasoline have an important impact on energy consumption in the upstream stage, which are the most important parameters in the petroleum fuel path. These parameters will be introduced in detail in Section 4.

The electric path focuses on the process of power plant. The coal, natural gas, oil, and uranium, after mining, storage and transportation, are converted into electricity production. Coal, natural gas and oil power generation will bring CO_2 emissions, while nuclear power, hydro power, wind power and solar energy are renewable energy without the production of CO_2 emissions. Therefore, power generation composition and power generation efficiency have an important impact on energy consumption and CO_2 emissions in the upstream stage of vehicles. In order to systematically evaluate the impact of upstream electricity generation mix on new energy vehicle emissions, we choose national-level and two typical regions as the study area in this paper. The two regions are Inner Mongolia and Sichuan, which represent two different types of electricity generation mix. The detailed parameters will be discussed in Section 4. In this study, we will not only assess the current energy consumption and CO_2 emissions from vehicles, but also review for 2010 and predict for 2030.

3.2. Energy Consumption Calculation

In the WTT stage, energy consumption mainly comes from the fuel production process and transportation process. For the fuel production process, energy consumption is mainly calculated through the energy efficiency of different production stages, and the sum of energy consumption of different fuel production processes is the total energy consumption of the whole stage. For the fuel transportation process, the energy consumption intensity and proportion of each transportation mode were obtained by investigation, and then the energy consumption in the whole fuel transportation process was obtained by weighted summation. It can be seen from the calculation principle of fuel production and transportation process that energy consumption is mainly determined by energy efficiency and energy consumption intensity, as shown in Equation (1):

$$E_{WTT,\,j} = E_{TTW,\,j}/\eta \tag{1}$$

Here, $E_{WTT,\,j}$ is the energy consumption intensity of WTT stage (kJ/km), $E_{TTW,\,j}$ is the energy consumption intensity of TTW stage (kJ/km), calculated by Equation (2), and η is the energy efficiency at this stage.

The energy consumption in TTW stage is the fuel consumption during vehicle operation, which is closely related to vehicle fuel economy, as shown in Equation (2):

$$E_{TTW,\,j} = LHV_j \times \rho_j \div FE_j \div 100 \tag{2}$$

Here, $E_{TTW,\,j}$ is the energy consumption of fuel j in TTW stage (kJ/km), LHV_j is the low calorific value of fuel j (kJ/kg), ρ_j is the density of fuel j (kg/L), and FE_j is the fuel economy of fuel j (L/100 km).

The total energy consumption of the whole fuel cycle is the sum of the total energy consumption of the WTT stage and TTW stage, as shown in Equation (3):

$$E_{WTW,\,j} = E_{WTT,\,j} + E_{TTW,\,j} \tag{3}$$

Here, $E_{WTT,\,j}$ and $E_{TTW,\,j}$ denotes the energy consumption of fuel j in the WTT and TTW stages (kJ/km), respectively.

3.3. CO_2 Emissions Calculation

In the WTT stage, the calculation of CO_2 emission is based on the carbon balance method, which is mainly determined by the amount of fuel used and the carbon content of fuel. The carbon in the directly emitted CO_2 emission is obtained by subtracting the carbon in the combustion products VOC, CO and CH_4 from the carbon in the fuel before combustion. However, due to the short survival time of VOC and CO in the atmosphere, they will eventually be converted into CO_2, so the indirect CO_2 emissions should also be considered from the conversion of VOC and CO, which add together to obtain the total CO_2 emissions. The CO_2 emissions in the WTT stage can be calculated by Equation (4):

$$CO_{2,WTT,j,k} = \begin{bmatrix} E_{WTT,j} \div LHV_j \times C\_ratio_j - \\ (VOC_{j,k} \times 0.85 + CO_{j,k} \times 0.43 \\ +CH_{4,j,k} \times 0.75) \\ +\left(VOC_{j,k} \times 0.85 + CO_{j,k} \times 0.43\right) \end{bmatrix} \times \frac{44}{12} \times 1000 \tag{4}$$

Here, $CO_{2,WTT,j,k}$ is the CO_2 emission from fuel j combustion using technology k (g/km), $E_{WTT,\ j}$ is the energy consumption intensity of WTT stage (kJ/km), LHV_j is the low calorific value of fuel j (kJ/kg), C_ratio_j is the carbon content of fuel j, $VOC_{j,k}$ is the emission factor of VOC from fuel j combustion using technology k (kg/km), 0.85 is the average carbon content of VOC, $CO_{j,k}$ is the emission factor CO from fuel j combustion using technology k (kg/km), 0.43 is the average carbon content of CO, $CH_{4,j,k}$ is the emission factor CH_4 from fuel j combustion using technology k (kg/km) and 0.75 is the average carbon content of CH_4.

The carbon balance method is also adopted for calculating CO_2 emissions in the TTW stage. Similar to upstream emissions, direct and indirect CO_2 emissions also need to be considered, as shown in Equation (5):

$$CO_{2,TTW,j} = \begin{bmatrix} E_{TTW,j} \div LHV_j \times C\_ratio_j - \\ (VOC_j \times 0.85 + CO_j \times 0.43 \\ +CH_{4,j} \times 0.75) \\ +(VOC_j \times 0.85 + CO_j \times 0.43) \end{bmatrix} \times \frac{44}{12} \times 1000 \tag{5}$$

Here, $CO_{2,TTW,\ j}$ is the CO_2 emission from fuel j during vehicle operation (g/km), $E_{TTW,\ j}$ is the energy consumption intensity of TTW stage (kJ/km), LHV_j is the low calorific value of fuel j (kJ/kg), C_ratio_j is the carbon content of fuel j, VOC_j is the emission factor of VOC from fuel j during vehicle operation (kg/km), 0.85 is the average carbon content of VOC, CO_j is the emission factor CO from fuel j during vehicle operation (kg/km), 0.43 is the average carbon content of CO, $CH_{4,j}$ is the emission factor CH_4 from fuel j during vehicle operation (kg/km) and 0.75 is the average carbon content of CH_4.

The CO_2 emission in the whole fuel cycle is the sum of the emissions in the WTT stage and TTW stage, which can be calculated by Equation (6):

$$CO_{2,WTW,j} = CO_{2,WTT,j} + CO_{2,TTW,j} \tag{6}$$

Here, $CO_{2,WTT,j,k}$ and $CO_{2,TTW,\ j}$ denote the CO_2 emission of fuel j in the WTT and TTW stages (g/km), respectively.

4. Data and Assumptions

According to the above method and calculation principle, the most important parameters include extraction efficiency, transportation share and distances, electricity generation mix during the WTT phase and fuel economy during the TTW phase.

4.1. Parameters in WTT Phase

The key parameters during the WTT phase include extraction efficiency, transportation share and distances, electricity generation mix, and so on.

4.1.1. Extraction Efficiency and Transportation Distance

As traditional vehicles and new energy vehicles are both the research objectives, the oil and electricity pathways are specifically analyzed. The oil pathway includes oil extraction, storage and transportation, refining and fuel production. The electricity power mainly comes from thermal power, and coal power makes up a major part of this in China. During these two pathways, the extraction efficiency, transportation share and distances are subsequently discussed.

For oil pathway, the national oil and import oil are both considered in this study. Based on reviewing a large amount of literature, including the China Energy Statistics Yearbook, the calculation result of the national oil extraction efficiency is 91% [45–47]. After the analysis of the oil import sources, we adopt the GREET Model's default 98% as the efficiency of import oil extraction. By using the weighted average of national oil and import oil, the foreign oil dependence is set to 54% [48]. Thus, the comprehensive efficiency of oil extraction was 94.8% in 2020. In future, foreign oil dependence would increase to 75%, according to the IEA projection and Wu et al. results, and therefore the comprehensive efficiency of oil extraction would increase to 96.3% in 2030 [49]. We calculate the shares of process fuels for crude oil from China Energy Statistics Yearbook, and evaluated the transportation share and distances of crude oil from General Administration of Customs of China, China Transportation Yearbook and other researches [50–55]. The results show that the ocean tanker accounted for 44%, with a distance of around 14,000 km, followed by rail with 29% and pipeline with 22%.

For the electricity pathway, our investigation shows that the major generation in China includes coal-fire power, gas-fire power, hydro power, nuclear and wind power, in which coal-fired power accounts for the largest proportion. The specific regional variations in power generation mix would be detailed in the following sections. Furthermore, our calculation of the coal extraction is 97%, according to Ou's result [46]. By using the same calculation method with the oil pathway, the transportation share and distances of coal are evaluated [50–55]. The road accounted for 44% of transportation share, with a distance of around 200 km, followed by rail with 35% and barge with 12%. It should be noted that our primary concern includes the energy consumption and combustion CO_2 emissions from the production, and the non-combustion CO_2 emissions during the power plants construction are neglected, as they are too small compared with the combustion emission [56].

4.1.2. Generation Mix and Generating Efficiency

In order to accurately calculate the WTW energy use and CO_2 emissions, the electricity generation mix and generating efficiency are systematically analyzed. The current national and regional (Inner Mongolia and Sichuan) power generation mix are calculated, according to the China Energy Statistical Yearbook [45]. Meanwhile, the future national and regional generation mix are predicted, with reference to the results from other development plan and organizations [57–59].

For the national electricity generation mix, the coal power plays a dominant role. In 2010, the coal power contributed 79% of the total power generation, followed by 16% hydro power and 2% other resources (nuclear, gas and wind). In 2020, the thermal power contributed 68% of the total power generation. Furthermore, the prediction results of generation mix show that thermal power and clean power will contribute 48% and 52%, respectively, by 2030 [57–59]. For the regional electricity generation mix, there are great differences due to the difference of resource endowment. The thermal power contributed 83% of the total power generation in Inner Mongolia, while it contributed 13% of the total power generation in Sichuan [58,59]. The similar scenarios for regional generation mix are then assumed based on the national projection. The national and regional generation mix in 2010, 2020 and 2030 are presented in Figure 3.

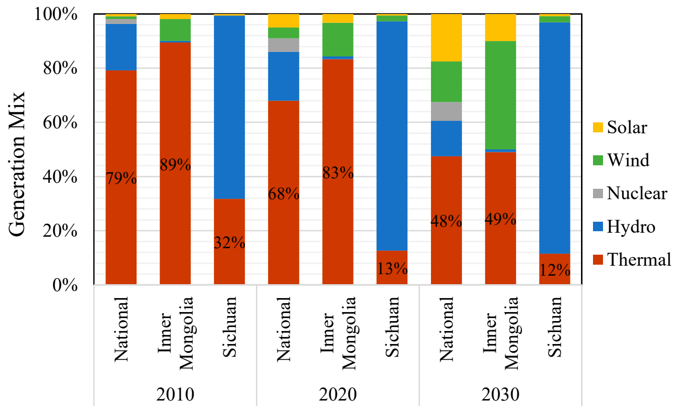


Figure 3. Electricity generation mix in China and two regions in 2010, 2020 and 2030.

Our calculation of the coal-fire efficiency is 34%, according to the hypothesis of IEA [60]. We also considered the advanced technologies such as supercritical, ultra-supercritical power and integrated gasification combined cycle (IGCC), which would take up 65% of total coal-fired power. The parameters are set to 39%, 42% and 45% of electricity generation efficiency for supercritical, ultra-supercritical power and IGCC, respectively, derived from Feng, Han et al., IEA [60–63]. We then predict that the average coal-fire efficiency will be 40% in 2030.

4.2. Parameters in TTW Phase

The key parameters during the TTW phase include fuel economy of ICEV and HEVs/PHEVs/BEVs.

For ICEVs, we adopt 6.5 L/100 km as the fuel consumption in 2020, according to the fuel consumption result under engine dynamometer test from the Ministry of Industry and Information Technology of China [64]. Furthermore, the real operating condition adjustment is obtained from the fuel consumption report of Xiao Xiong You Hao [65]. The fuel consumption would decrease to 4.8 L/100 km by 2030, according to the *Energy saving and new energy vehicle technology Roadmap 2.0* with the real operating condition adjustment [66].

For HEVs and BEVs, we adopt 5.0 L/100 km and 15.5 kwh/100 km as the fuel consumption in 2020, according to the fuel consumption result from Ministry of Industry and Information Technology of China [64]. For PHEVs, we use the fuel consumption increase proportion of 270%, based on the result from the Ministry of Industry and Information Technology of China and the default of the GREET model. It is assumed that the fuel consumption of HEVs/PHEVs/BEVs would decrease the same proportion with the ICEVs [44].

All the parameters in the WTT and TTW stages are listed in Table 1.

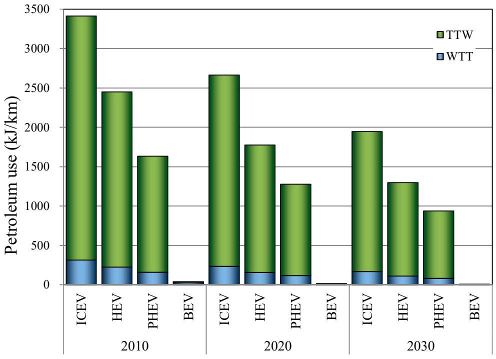
Table 1. Parameters for shares of process fuels, transportation, generation mix and fuel economy.

		Type of Process Fuel			**Crude Oil**		**Coal**	
WTT	**Shares of process fuels** [50–55]	Crude oil			22%		/	
		Residual oil			1%		/	
		Diesel fuel			9%		3%	
		Gasoline			1%		1%	
		Natural gas			44%		0%	
		Coal			4%		79%	
		Electricity			14%		15%	
		Refinery gas			2%			
		Loss			3%		1%	
		Mode	**Share**	**Distance/km**		**Share**	**Distance/km**	
	Transportation [50–55]	Ocean Tanker	44%	13,900		/	/	
		Pipeline	22%	2500		/	/	
		Rail	29%	940		35%	640	
		Barge	16%	700		12%	1250	
		Road	/	/		53%	180	
		Year	**Type**	**Thermal**	**Hydro**	**Nuclear**	**Wind**	**Solar**
	Generation mix [45,57–59]	2010	National	79%	17%	2%	1%	1%
			Inner Mongolia	89%	1%	0%	8%	2%
			Sichuan	32%	68%	0%	0%	1%
		2020	National	68%	18%	5%	4%	5%
			Inner Mongolia	83%	1%	0%	12%	3%
			Sichuan	13%	85%	0%	2%	1%
		2030	National	48%	13%	7%	15%	18%
			Inner Mongolia	49%	1%	0%	40%	10%
			Sichuan	12%	85%	0%	2%	1%
TTW	**Fuel Economy**	2010	ICEV(L/100 km)				7.5	
			HEV relative to ICEV				130%	
			PHEV relative to ICEV				230%	
			BEV relative to ICEV				330%	
		2020	ICEV(L/100 km)				6.5 [64–66]	
			HEV relative to ICEV				150% [64]	
			PHEV relative to ICEV				270% [44]	
			BEV relative to ICEV				450%	
		2030	ICEV(L/100 km)				4.8	
			HEV relative to ICEV				150%	
			PHEV relative to ICEV				270%	
			BEV relative to ICEV				450%	

5. Results and Discussion

5.1. WTW Petroleum Consumption

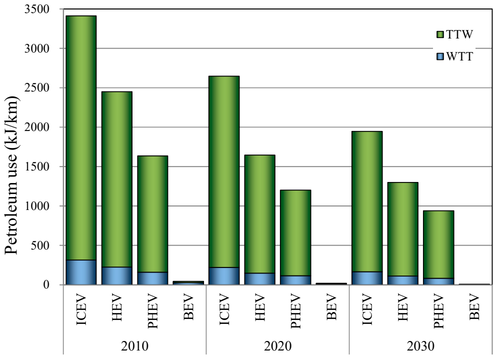
WTW petroleum consumption results for national and regional ICEVs/HEVs/PHEVs/BEVs are presented in Figures 4–6. ICEVs, HEVs and PHEVs consume around 90% petroleum in the TTW stage. HEVs could decrease petroleum consumption by 28% relative to ICEVs. PHEVs could decrease petroleum consumption by 50% relative to ICEVs. BEVs could reduce petroleum use by 99% relative to ICEVs. For BEVs, the rare petroleum consumption results from the small proportion of oil-power plant and high refining efficiency.



WTW petroleum consumption reduction compared with ICEVs in China (%).

Year	2010	2020	2030
HEV	28	33	33
PHEV	52	52	52
BEV	99	99	99

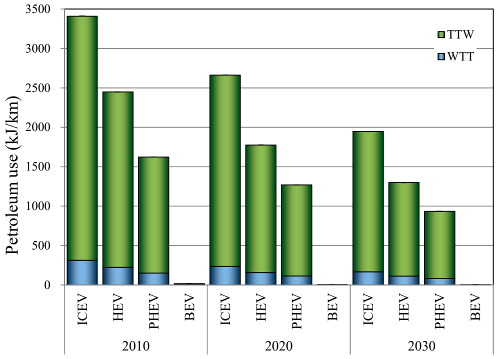
Figure 4. WTW petroleum consumption of ICEVs/HEVs/PHEVs/BEVs in China.



WTW petroleum consumption reduction compared with ICEVs in Inner Mongolia (%).

Year	2010	2020	2030
HEV	28	38	33
PHEV	52	55	52
BEV	99	99	99

Figure 5. WTW petroleum consumption of ICEVs/HEVs/PHEVs/BEVs in Inner Mongolia.



WTW petroleum consumption reduction compared with ICEVs in Sichuan (%).

Year	2010	2020	2030
HEV	28	33	33
PHEV	52	52	52
BEV	99	99	99

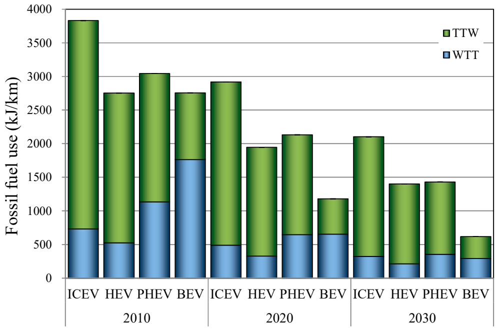
Figure 6. WTW petroleum consumption of ICEVs/HEVs/PHEVs/BEVs in Sichuan.

From the prospective of time, the petroleum consumption for ICEVs/HEVs/PHEVs/BEVs continues declining from 2010 to 2030, due to improved oil extraction efficiency and strengthened fuel consumption standard. In 2010, the petroleum consumption for ICEVs and HEVs are 3410 kJ/km and 2450 kJ/km, which would decrease to 1950 kJ/km and 1300 kJ/km by 2030, respectively, with decrement rates of 43% and 47%. The petroleum consumption for PHEV and BEV in 2030 could further decrease by 42% and 80%, respectively, compared with the petroleum use in 2010.

From the prospective of region, there is no significant difference among the two regions in WTW petroleum consumption results for ICEVs/HEVs/PHEVs/BEVs. The results in the two regions show the same trends with the national results. BEVs are considered the best option to solve the oil crisis, as they can significantly reduce the petroleum consumption in either region.

5.2. WTW Fossil Fuel Consumption

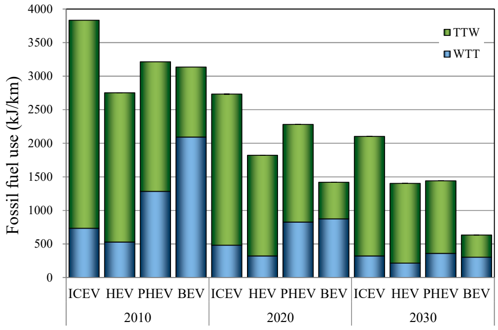
WTW fossil fuel consumption results for ICEVs/HEVs/PHEVs/BEVs in national and the two regions are presented in Figures 7–9. In 2010, the fossil fuel consumption in the TTW stage takes up around 80% of the total for ICEVs/HEVs, while the proportion falls to 30% for BEVs. With the decline of fossil fuel consumption in the WTT stage for BEVs, due to the clean power applications, the fossil fuel consumption in TTW will increase to 53% by 2030. HEVs/PHEVs could decrease the fossil fuel consumption by 25–35%, relative to ICEVs. From the prospective of time, the fossil consumption for ICEVs/HEVs/PHEVs/BEVs continues declining in 2030, due to improved generation efficiency and fuel economy, and the use of clean energy.



WTW fossil fuel consumption reduction compared with ICEVs in China (%).

Year	2010	2020	2030
HEV	28	33	33
PHEV	21	27	32
BEV	28	60	71

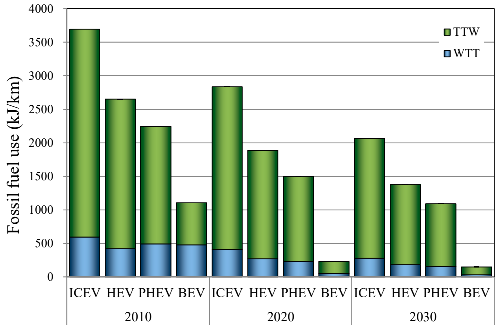
Figure 7. WTW fossil fuel consumption of ICEVs/HEVs/PHEVs/BEVs in China.



WTW fossil fuel consumption reduction compared with ICEVs in Inner Mongolia (%).

Year	2010	2020	2030
HEV	28	33	33
PHEV	16	16	31
BEV	18	48	70

Figure 8. WTW fossil fuel consumption of ICEVs/HEVs/PHEVs/BEVs in Inner Mongolia.



WTW fossil fuel consumption reduction compared with ICEVs in Sichuan (%).

Year	2010	2020	2030
HEV	28	33	33
PHEV	39	47	47
BEV	70	92	93

Figure 9. WTW fossil fuel consumption of ICEVs/HEVs/PHEVs/BEVs in Sichuan.

HEVs in the two regions show a reduction of 28% on fossil fuel consumption, with both 28% reduction during the WTT and TTW stages, relative to ICEV. With improved generation efficiency, ICEVs and HEVs could decrease fossil fuel consumption by 45–50% in the two regions from 2010 to 2030.

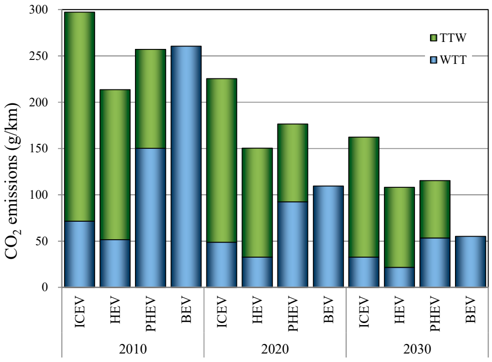
PHEVs show a decrease of 16% and 47% on fossil fuel consumption, compared with ICEVs in Inner Mongolia (thermal power generation accounted for 83%) and Sichuan (thermal power generation accounted for 13%) in 2020, respectively. In Inner Mongolia, the fossil fuel consumption during the WTT stage of PHEVs increased by 70%, compared with the WTT stage of ICEVs. For Sichuan, however, the fossil fuel consumption during the WTT stage of PHEVs decreased by 40%, compared with the WTT stage of ICEVs. Such diversity during the WTT stage mainly comes from the generation mix.

For BEVs, the results are different by regions and period. In 2010, BEVs could decrease fossil fuel consumption by 18%, with an increase of 185% during the WTT stage and a decrease of 66% during the TTW stage in Inner Mongolia (thermal power generation accounted for 89%). For Sichuan (thermal power generation accounted for 32%), BEVs could achieve a reduction of 70% with a decrease of 20% during the WTT stage, and a decrease of 80% during the TTW stage in 2010. The significant differences during the WTT stage would influence the overall environmental benefits for BEVs. With improved generation efficiency and fuel economy, BEVs could reduce the fossil fuel consumption by 70% and 90%, respectively, in 2030.

5.3. WTW CO_2 Emission

WTW CO_2 emission results for ICEVs/HEVs/PHEVs/BEVs nationally and in the two regions are presented in Figures 10–12. The CO_2 emission in the TTW stage takes up nearly 80% of the total for ICEVs/HEVs, while the CO_2 emission all comes from the WTT stage for BEVs. HEVs and PHEVs could decrease CO_2 emissions. For BEVs, the results are similar with the fossil fuel consumption. In the future, the CO_2 emissions for ICEVs/HEVs/PHEVs/BEVs will keep descending, due to improved generation efficiency, clean energy and fuel economy. In 2010, the CO_2 emissions for ICEVs, HEVs, PHEVs and BEVs were 290 g/km, 210 g/km, 250 g/km and 260 g/km, and they would decrease to 160 g/km, 110 g/km, 120 g/km and 50 g/km by 2030, respectively.

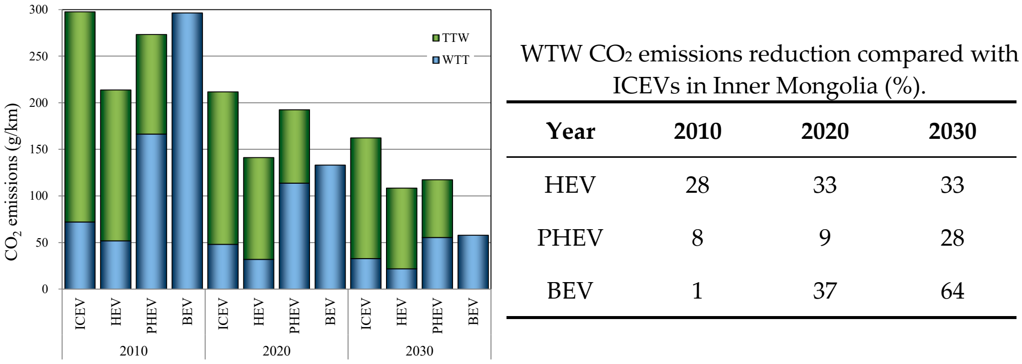
For HEVs nationally and in the two regions, there is a reduction of 30% on CO_2 emission, similar to the result of fossil fuel consumption. ICEVs and HEVs could decrease CO_2 emissions both by around 40% in the two regions from 2010 to 2030, with improved generation efficiency. PHEVs could reduce CO_2 emissions by 10–20% in Inner Mongolia (thermal power generation accounted for 49–89%), and reduce CO_2 emissions by 35–45% in Sichuan (thermal power generation accounted for 12–32%), relative to ICEVs. From 2010 to 2030, CO_2 emissions from PHEV could further decline by 42%.



WTW CO_2 emissions reduction compared with ICEVs in China (%).

Year	2010	2020	2030
HEV	28	33	33
PHEV	14	22	29
BEV	12	51	66

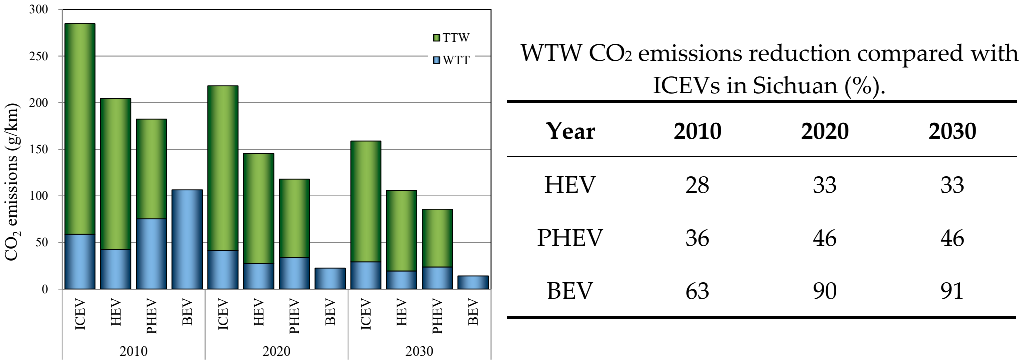
Figure 10. WTW CO_2 emissions of ICEVs/HEVs/PHEVs/BEVs in China.



WTW CO2 emissions reduction compared with ICEVs in Inner Mongolia (%).

Year	2010	2020	2030
HEV	28	33	33
PHEV	8	9	28
BEV	1	37	64

Figure 11. WTW CO$_2$ emissions of ICEVs/HEVs/PHEVs/BEVs in Inner Mongolia.



WTW CO2 emissions reduction compared with ICEVs in Sichuan (%).

Year	2010	2020	2030
HEV	28	33	33
PHEV	36	46	46
BEV	63	90	91

Figure 12. WTW CO$_2$ emissions of ICEVs/HEVs/PHEVs/BEVs in Sichuan.

For BEVs, the CO$_2$ emission benefit is less than fossil fuel consumption benefit, as the coal has the highest carbon content per unit among the three types of fossil fuel (coal, petroleum and natural gas). In 2010, BEVs had no benefit of CO$_2$ emission, with an increase of 310% during the WTT stage and a decrease of 100% during the TTW stage in Inner Mongolia (thermal power generation accounted for 89%). For Sichuan (thermal power generation accounted for 32%), BEVs could achieve a reduction of 60% with an increase of 81% during the WTT stage and a decrease of 100% during the TTW stage in 2010. With improved generation efficiency and fuel economy, BEVs could reduce the CO$_2$ emission by 60% and 90%, respectively, in 2030.

6. Conclusions

In this paper, we consulted a large number of researchers and investigated the key parameters: pathway, generation mix and fuel economy on the life cycle analysis to ensure these data can reflect the real situation for China and typical regions. We then evaluated the WTW energy consumption and CO$_2$ emissions for ICEVs/HEVs/PHEVs/BEVs based on the GREET model to provide the fundamental conclusion and suggestions as follows.

From the prospective of type, HEVs should be steadily developed for an effective reduction on petroleum and fossil energy. Considering that HEVs have a carbon dioxide emission reduction benefit of about 30%, the study concludes that the promotion of HEVs alone falls short of helping China achieve carbon peak in the transportation sector. BEVs also have the significant effect on petroleum reduction, which could achieve more fossil fuel reduction and CO$_2$ reduction in the region with clean power. The research suggests that battery electric vehicles should be promoted in different regions in the future. In areas with a high proportion of coal and electricity, electric vehicles and hydrogen fuel vehicles can be promoted simultaneously. In areas that are rich in renewable energy, battery electric vehicles should be rapidly developed with appropriate charging or battery replacement modes.

From the prospective of time, HEVs, PHEVs and BEVs could achieve more environment benefits in 2030, while the situation would be different in 2010. Consequently, the spread of EVs should coordinate with the improvement of CCS, the enhancement of clean energy and vehicle-to-grid technology in the long term.

We also found that we have been conservative in our forecasts of new energy development, such as the generation mix projection. We assumed that the coal power would decrease to 50% by 2030 a decade ago, but might decrease to 40% according to the new plan [67]. Therefore, the future development of new energy vehicles could be much faster than we currently predicted.

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Abbreviations

ANL	Argonne National Laboratory
CO_2	carbon dioxide
BEV	battery electric vehicles
CNG	compressed natural gas
EV	electric vehicle
FCV	fuel cell vehicles
GHG	greenhouse gas
HEV	hybrid electric vehicles
ICEV	internal combustion engine vehicle
IGCC	integrated gasification combined cycle
LCA	life cycle analysis
NG	natural gas
PHEV	plug-in hybrid electric vehicles
TTW	tank-to-wheels
WTT	well-to-tank
WTW	well to wheels
PTW	pump-to-wheels
WTP	well-to-pump

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