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Article

Energy and Environmental Implications of Hybrid and Electric Vehicles in China

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Abstract: The promotion of hybrid and electric vehicles (EVs) has been proposed as one promising solution for reducing transport energy consumption and mitigating vehicular emissions in China. In this study, the energy and environmental impacts of hybrid and EVs during 2010–2020 were evaluated through an energy conversion analysis and a life cycle assessment (LCA), and the per-kilometer energy consumptions of gasoline, coal, natural gas (NG), oil, biomass, garbage and electricity for EVs and HEVs were estimated. Results show that the EVs and HEVs can reduce the energy consumption of vehicles by national average ratios of 17%–19% and 30%–33%, respectively. The study also calculated the detailed emission factors of SO_2, NO_X, VOC, CO, NH_3, PM_{10}, $PM_{2.5}$, OC, EC, CO_2, N_2O, CH_4, Pb and Hg. It is indicated that the HEVs can bring significant reductions of NO_X, VOC and CO emissions and lesser decreases of SO_2 and CO_2 for a single vehicle. The EVs could decrease many of the VOC, NH_3, CO and CO_2 emissions, but increase the SO_2, NO_X and particles by 10.8–13.0, 2.7–2.9 and 3.6–11.5 times, respectively. In addition, the electricity sources had significant influence on energy consumption (EC) and emissions. A high proportion of coal-fired energy resulted in large ECs and emission factors. The total energy consumption and pollutants emission changes in 2015 and 2020 were also calculated. Based on the energy use and emission analysis of HEVs and EVs, it is suggested that EVs should be promoted in the regions with higher proportions of hydropower, natural gas-fired power and clean energy power, while HEVs can be widely adopted in the regions with high coal-fired power ratios. This is to achieve a higher energy consumption reduction and pollutant emission mitigation. Moreover, the results can also provide scientific support for the total amount control of regional air pollutants in China.

Keywords: air pollutants; greenhouse gases; emission factors; energy consumption; policy assessment

1. Introduction

Motor vehicles represent a major oil consumption sector and their number has experienced a sharp growth in China during the past decade. The number of vehicles has grown from 42 million in 2000 to nearly 200 million in 2010, and as a consequence, the gasoline consumption has increased from 13.9 million tons in 2000 up to 32.0 million tons, which accounts for 46.5% of the total gasoline use in 2010 [1,2]. Furthermore, according to the previous studies this number may be even underestimated [3,4]. However, more than half (about 53.4%) of the crude oil used in China was imported from other countries [5], and this high import ratio will greatly impact the energy security and economic development of China, making the reduction of the gasoline consumption with the sharp increase of vehicle numbers an important but difficult problem to solve. On the other hand, motor vehicles are also a major contributor to the air pollutants and greenhouse gas emissions [6,7], and it exert a significant adverse influence on the air pollution and human health [8,9]. As a result, the mitigation of vehicular emissions will play a vital role in the improvement of air quality and public health. However, Lang *et al.* [10] found that although the implementations of numbers of emission mitigation measures (such as the implementation of stringent vehicular emission standards, the elimination of high emission vehicles, the development of public transport, and the enhancement of fuel quality) have produced remarkable results in decreasing the level of most of the vehicular emissions, the rate decrease is still proving to be slow and the level of some of the pollutants emissions has even gone up due to a rapid growth in the vehicle population. Other control measures should be studied and implemented to achieve a higher emission mitigation effect. In the context of saving transport energy consumption and reducing air pollutant and greenhouse gas emissions, the promotion of electric vehicles (EVs) was proposed as one effective solution to the high energy use and pollutant emission problems. Consequently, the study of actual energy and environmental implications of EVs is of great importance and necessity, in order to provide a scientific basis for the development of a strategy for promoting EVs.

A number of studies have been carried out worldwide to assess the impacts of hybrid and electric vehicles on energy and environment. Campanari *et al.* [11] studied the energy balances for electric vehicles using batteries and fuel cells based on a well-to-wheel (WTW) analysis and the ECE-EUDC driving cycle simulations. The analysis showed that EVs equipped with fuel cells could give better performance in the medium-to-long driving range than that of those with pure batteries. Stephan and Sullivan [12] analyzed the environmental effect of promoting plug-in hybrid electric vehicles (PHEVs) in the United States and found that compared to the conventional HEVs, PHEVs could reduce 25% and 50% of CO_2 emissions in the short term and in the long term, respectively. Hawkins *et al.* [13]

synthesized the results of previous studies and compared the global warming potential (GWP) of EVs and CGVs. It was concluded that although EVs could lead to a reduction of GWP compared to CGVs, high efficiency CGVs and grid-independent HEVs perform better than EVs using coal-fired electricity. Huo *et al.* [14] evaluated the potential impact of nine alternative vehicle/fuel systems on the environment. The Greenhouse gases, Regulated Emissions and Energy use in Transport (GREET) model was used to estimate the emissions of VOC, NO_X, PM_{10}, $PM_{2.5}$ and CO of different alternative systems by a life-cycle analysis. A few more studies were conducted on the EVs' environment and energy implications in China. Huo *et al.* [15] examined the fuel-cycle CO_2, SO_2 and NO_X emissions of EVs and found that if connected to the current electricity grid in China, EVs could produce higher SO_2 and NO_X emissions than those resulting from gasoline vehicles. Wu *et al.* [16] selected three developed regions (Beijing-Tianjin-Hebei, Yangtze-River-Delta and Pearl-River-Delta) in China and evaluated the influences of EVs, HEVs and PHEVs in terms of their fossil energy consumptions and per-kilometer CO_2 emissions during 2010–2030. It was found that the promotion of PHEVs and EVs could help cut per-kilometer petroleum use to a great extent; however, it makes the CO_2 emission mitigation becomes even more difficult to achieve. The evaluation of HEVs emissions were also studied in [17].

However, most of the previous studies focus on limited types of the powers or pollutants. It is necessary to conduct a comprehensive quantitative evaluation of the energy and environment implications for EVs and HEVs through a life cycle assessment (LCA) in China. The purpose of this study is to estimate the energy and environment impacts from the view points of different power generation methods and various pollutants in the city driving condition. The considering internal combustion engine vehicles (ICEVs) were new conventional light duty gasoline vehicles (CGVs) (compact cars). Emissions and energy consumptions of five types of power generation methods (including coal-, natural gas (NG)-, oil-, biomass- and garbage-powers) were considered. The per-kilometer energy consumption (PKEC) of gasoline, coal, NG, oil, biomass, garbage and electricity of EVs and HEVs were calculated. Emission factors of four main categories and 14 sub-categories were estimated, including gaseous pollutants (SO_2, NO_X, VOC, CO and NH_3), particles (PM_{10}, $PM_{2.5}$, OC and EC), greenhouse gases (CO_2, N_2O and CH_4) and heavy metals (Pb and Hg). Furthermore, the total energy consumption and emission changes caused by the penetration of EVs and HEVs in 2015 and 2020 in China were evaluated. The results can provide scientific support for the policy of wide-spread adoption of EVs and HEVs. The detailed PKEC for different fuels and the emission factors of various pollutants can also provide sound basic data for relevant studies on vehicles and transport.

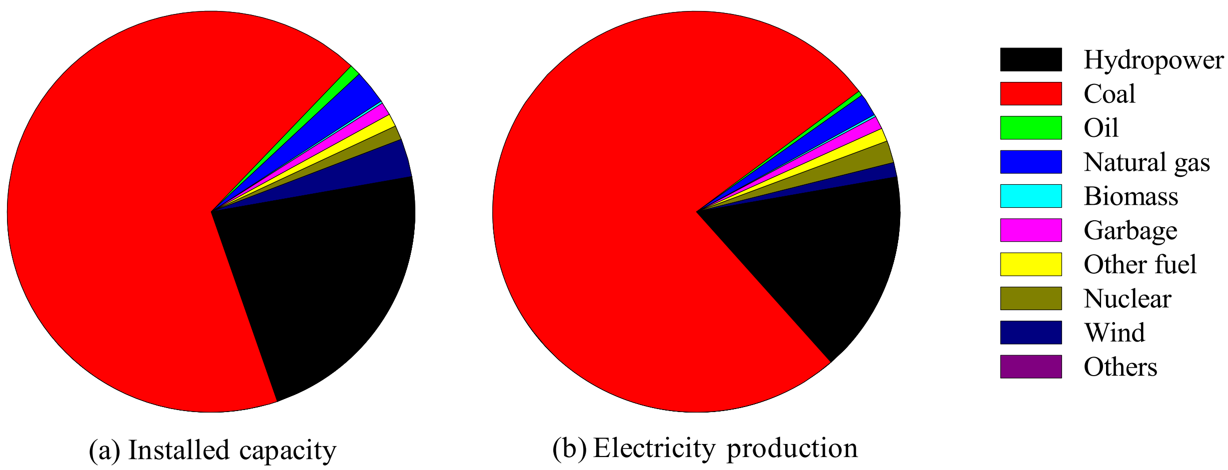
2. Data and Methodology

2.1. Electricity Generation in China

The electricity consumption in China has increased rapidly in recent years. It grew from 1360 TWh in 2000 to 4200 TWh in 2010. This rapid growth of electricity demand has resulted in a corresponding increase in electricity production. The electricity production and installed capacity have reached 4219 TWh and 960 GW in 2010, which were 308% and 301% of those in 2000, respectively [18,19]. Based on the differences of energy sources, there are basically five electricity generation methods: hydropower, fuel-fired power (including coal, oil, NG, biomass, garbage and other fuels), nuclear power, wind power and others (mainly include geothermal, tidal and solar power generations).

Among all these electricity generation methods, fuel-fired power was the dominant one, accounting for 80.8% of the total electricity production and 67.3% of the total installed capacity in 2010 (see Figure 1). In particular, coal was the main fuel used and the proportions of coal-fired power in the total electricity production and in the total installed capacity were 76.2 and 67.3%, respectively. The ratios of oil-, NG-, biomass- and garbage-fired power were 0.4%, 1.8%, 0.2% and 1.1% of the total electricity production, and 0.9%, 2.8%, 0.2% and 1.0% of the total installed capacity, respectively. Hydropower was another important contributor to the electricity production in China. It accounted for 16.3% of the total electricity production and 22.5% of the total installed capacity in 2010. In the three typical regions—Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD), the proportions of coal- and natural gas-fired power were 94.8% and 0.8%, 86.5% and 2.2%, 60.2% and 3.1%, respectively.

Figure 1. Proportion of electricity productions and installed capacity in different power generation methods (Others mainly includes geothermal, tidal and solar power generation).



The energy conversion efficiency (ECE) and transmission efficiency (TE) are important parameters for estimating the energy consumption and emissions of EVs. The coal consumption rates were 0.367, 0.357, 0.349 and 340 gce/kWh (gram of standard coal equivalent per kWh) in 2006, 2007, 2008 and 2010, respectively [20,21]. The calorific values (CVs) of coal equivalent and electricity are 29,271 kJ/kg and 3,600 kJ/kWh, respectively. As a result, the ECE in coal power generation was about 36.2% in 2010. The coal consumption can decrease to 330 g/kWh and the ECE will become 37.3% in 2015 [21]. Based on the change trends of the ECE during the past several years, we assumed the ECE will increase to 39.9% in 2020. The value was between the ECE of India (38.8%) and Japan (42.0%) in 2008 [22]. The ECEs of NG, oil, biomass and garbage in 2010 were 41.4, 37.0, 29.5 and 17.0%, respectively [22–24]. The ECEs of these fuels in 2015 and 2020 were estimated based on the ECEs in 2010 and the ECE change rates of coal in 2010, 2015 and 2020, due to the lack of the study on the ECEs of NG-, oil-, biomass- and garbage-fired electricity in the future of China. Many measures will be adopted to improve the ECE in power generation [19]. For example, the power generation units with small installed capacities and low ECE will be gradually closed down in the following decade. Advanced technologies and new equipments which can increase the ECE will also be used in the new power plants. These will help to improve the energy conversion efficiency of power generation to a great extent. The ECEs of coal and other fuels are listed in Table 1. The TE in China has been increasing during the past several years, from 92.30% in 2000 to 93.47% in 2010 [18,19], and by taking measures such as optimizing the power distribution and sources network and improving the running mode, the TE will grow up to about 93.50% in 2015 [21]. The value in 2020 was also assumed as 93.50%.

Table 1. Energy conversion efficiencies (ECEs) of different fuels during the electricity generation processes (%).

Years	Coal	NG	Oil	Biomass	Garbage
2010	36.2 [21]	41.4 [22]	37.0 [22]	29.5 [23]	17.0 [24]
2015	37.3 [21]	42.7 [b]	38.1 [b]	30.4 [b]	17.5 [b]
2020	39.9 [a]	45.7 [b]	40.8 [b]	32.5 [b]	18.8 [b]

Notes: [a] Assumed by authors based on the ECE of coal during the past several years and the study results in reference [21]; [b] The ECEs of NG, oil, biomass and garbage were estimated based on the ECEs in 2010 and ECE change rates for coal in 2010, 2015 and 2020.

2.2. Energy Consumption Calculation

The energy consumption for a single electric vehicle (EV) can be calculated by Equations (1)–(4):

$$ENG\_U = ENG_e \times CV_e \times (\eta_t \times \eta_g)^{-1} \quad (1)$$

$$ENG\_P = 1 \times (\eta_{ext} \times \eta_{ref})^{-1} - 1 \quad (2)$$

$$ENG\_T = \sum_i EI_i \times R_i \times D_i \quad (3)$$

$$ENG = ENG\_U + ENG\_U \times (ENG\_P + ENG\_T) \quad (4)$$

where *ENG*, *ENG_U*, *ENG_P* and *ENG_U* are the energy consumptions for a single EV and for the stages of fuels (coal, NG, oil, biomass and garbage) usage, production (extraction and refining) and transportation, in units of MJ/km, MJ/km, MJ/MJ and MJ/MJ, respectively; ENG_e represents the electricity consumption for a single EV per km, in unit of kWh/km; CV_e means the calorific value (CV) of electricity, MJ/kWh; η_g, η_t, η_{ext} and η_{ref} are the energy efficiencies of power generation, power transmission, fuel extraction and fuel refinery, respectively; *i* represents different transportation mode, including sea tanker, rail, pipeline, waterway and road transport; *EI*, *R* and *D* are the energy intensity, ratio and distance for each transportation mode. The energy conversion efficiencies of different stages can be found in Tables 1 and 2. The transmission efficiencies have been described in Section 2.1. The electricity consumption for a single EV is listed in Table 3. The energy intensity, ratio and distance are shown in Table 4. The energy consumptions during the fuels production and transportation are listed in Table 5. The energy consumption of EV can also be transformed from MJ/km to kg/km through the calorific values (CVs) of electricity and different fuels as listed in Table 6.

Table 2. Energy conversion efficiencies during the fuels' extraction and refinery stage (%) [25].

Production stages	Coal	NG	Oil
Extraction	97.0	96.0	93.0
Refining	97.0	94.0	89.4

Table 3. Energy consumption for a single vehicle in China.

Vehicle types		CGVs	HEVs	EVs
Energies (unit)		**Gasoline (L/100 km)**		**Electricity (kWh/100 km)**
Year	2010	8.0 [15]	5.6 [15]	24.0 [15]
	2015	7.4 [a]	5.1 [c]	23.0 [a]
	2020	6.8 [a]	4.5 [b]	22.0 [a]

Notes: [a] The values were calculated by linear interpolation based on the energy consumptions gave in reference [15] in 2008 and in 2030, and the estimation of the value has considered the charging efficiency; [b] In the *Energy Saving and New Energy Vehicles Development Planning* (*2012–2020*) document [26], the gasoline consumption should decrease to 4.5 L/100 km for fuel-efficient vehicles; [c] Estimated as the mean value of gasoline consumption in 2010 and 2020.

Table 4. Energy intensity, proportion and distance for various modes of transportation [25].

Transportation modes	Sea tanker	Rail	Pipeline: oil	Pipeline: NG	Water Way	Road 1 [a]	Road 2 [a]
			(kJ t^{-1} km^{-1})				
Energy intensity	23	240	300	372	148	1,362	1,200
			Proportion and distance (km)				
Coal		50%/1,000			17%/650	100%/50	8%/310
NG				100% (1,500)			
Oil	50%/11,000	45%/950	80% (500)		10%/250		
Gasoline/Diesel	25%/7,000	50%/900			15%/1,200	10%/50	

Notes: [a] Road 1 represents short distance, road 2 means long distance.

Table 5. The energy consumption during the fuels' production and transportation stage.

Energies	Coal	NG	Diesel	Gasoline	Biomass/Garbage [a]
	MJ/MJ	**MJ/MJ**	**MJ/MJ**	**MJ/MJ**	**MJ/MJ**
CVs	0.08	0.12	0.21	0.22	0.10

Note: [a] The value was calculated based on the energy consumption in [27].

Table 6. Calorific values (CVs) of different fuels in China.

Energies	Electricity	Coal	NG	Oil	Biomass	Garbage
	kJ/kWh	**kJ/kg**	**kJ/m^3**	**kJ/kg**	**kJ/kg**	**kJ/kg**
CVs	3,600	20,908 [5]	38,931 [5]	42,652 [5]	15,054 [5]	15,545 [28]

The total energy consumptions changes in the years of 2015 and 2020 will be estimated. Equations (5)–(10) give the calculation method:

$$ENG_{t-f,2015,\min} = ENG_{f,2015} \times VKT_{2015} \times P_{2015} \quad (5)$$

$$ENG_{t-f,2015,\max} = ENG_{f,2010} \times VKT_{2015} \times P_{2015} \quad (6)$$

$$ENG_{t-f,2015} = (ENG_{t-f,2015,\max} + ENG_{t-f,2015,\min}) / 2 \quad (7)$$

$$ENG_{t-f,2020,\min} = ENG_{f,2015} \times VKT_{2020} \times P_{2015} + ENG_{f,2020} \times VKT_{2020} \times (P_{2020} - P_{2015}) \quad (8)$$

$$ENG_{t-f,2020,\max} = ENG_{f,2010} \times VKT_{2020} \times P_{2015} + ENG_{f,2015} \times VKT_{2020} \times (P_{2020} - P_{2015}) \quad (9)$$

$$ENG_{t-f,2020} = (ENG_{t-f,2020,\max} + ENG_{t-f,2020,\min})/2 \quad (10)$$

where $ENG_{t\text{-}f,2015.\min}$, $ENG_{t\text{-}f,2015,\max}$, $ENG_{t\text{-}f,2015}$ and $ENG_{t\text{-}f,2015.\min}$, $ENG_{t\text{-}f,2015,\max}$, $ENG_{t\text{-}f,2020}$ are the maximum, minimum and mean values of the fuel consumptions in 2015 and 2020, respectively; $ENG_{f,2015}$ represents the fuel consumption for a single vehicle (g/km); VKT is the annual average travel mileages of a single vehicle that can be replaced by EVs or HEVs (km); P_{2015} is the number of EVs or HEVs. The VKT of CGVs and HEVs was about 19,134 km in 2010 [29]. This is much higher than that in the developed countries, which are mainly with a range of 10,000–18,000 km, due to the lower private car (PC) ownership rate (vehicles/1000 people) [30]. With the increasing PC ownership rate and the development of public transport, the frequency of PC usage will decrease [10,30] and the VKT for PCs can be expected to be 18,000 km in 2015 and 16,787 km in 2020 [29]. As for the EVs, the VKT was about 15,856 km (9910 miles), which was obtained based on real world driving data [31]. This value was less than that for the PC. Their limited range will have significant effects on the purchase intention of consumers and the penetration of EVs. However, the differences will change to become smaller and the influence of VKT will become lesser. In addition, the charging infrastructure construction and longer battery charging time could also affect the promotion of EVs. For the vehicle numbers, according to the *Energy Saving and New Energy Vehicles Development Planning* (*2012–2020*) document [26], the total numbers of EVs and HEVs in China in 2015 and 2020 should reach 500 thousand and five million, respectively. In this study, we will assess the energy and environmental implications of the electric vehicles promotion policy based on these two vehicle numbers.

2.3. Emission Calculation

The air pollutants, particles, greenhouse gases and heavy metals emission factors of CGVs, HEVs and EVs were calculated based on the energy consumption and the corresponding emission factors of fuel combustions, as shown in the following equations:

$$EF_{CGVs,p} = ENG_f \times EF_{f,p,P\&T} + EF_{p,CGVs,U} \quad (11)$$

$$EF_{HEVs,p} = ENG_f \times EF_{f,p,P\&T} + EF_{p,HEVs,U} + EF_{p,B-P} \quad (12)$$

$$EF_{EVs,f,p} = ENG_f \times (EF_{f,p,P\&T} + EF_{f,p,U}) + EF_{p,B-P} \quad (13)$$

where subscript f includes coal, NG, oil, biomass and garbage; subscript p includes four main categories and 14 sub-categories, which are gaseous pollutants (SO_2, NO_X, VOC, CO and NH_3), particles (PM_{10}, $PM_{2.5}$, OC and EC), greenhouse gases (CO_2, N_2O and CH_4) and heavy metals (Pb and Hg); $EF_{EVs,f,p}$ is the emission factor of electric vehicles using the electricity generated by a certain kind of fuel combustion (g/km); ENG_f is the fuel consumption for a single vehicle (kg/km or m^3/km), which was calculated in Section 2.2; $EF_{f,p,P\&T}$ and $EF_{f,p,U}$ are the emission factors during the stage of fuel production & transportation and usage (g/kg or g/m^3), $EF_{p,CGVs,U}$, $EF_{p,HEVs,U}$ and $EF_{p,B-P}$ are the emission factors of driving CGVs, driving HEVs and lithium-ion battery production, (g/km). The $EF_{f,p,P\&T}$ and $EF_{f,p,U}$ are summarized and estimated based on previous studies, as shown in Tables 7 and 8. In addition to the emissions during the fuels production, transportation and usage, the production of battery is another substantial emission source in the life cycle of EVs [32]. Previous study indicated that the energy consumption of lithium-ion batteries for HEVs are 5.7 kJ/km coal, 3.9 kJ/km NG and

2.0 kJ/km petroleum, which were directly obtained from the GREET model calculation (based on a U.S. grid mix) [33]. In order to reduce the effect caused by the limited range in the EVs' promotion to the greatest extent, it is assumed that the EVs were with battery packs sized for 240 km of usable electric energy, and the energy consumptions for EVs were about 31.8 times of those for HEVs [32]. Based on the corresponding CVs (Table 6) and emission factors (EFs) of combustion (Table 7) of different fuels, the $EF_{p,B\text{–}P}$ of lithium-ion battery production can be estimated. As for the CGVs and HEVs, because that the Euro III emission standard was being implemented in 2010 and the Euro IV and Euro V standards are expected to be implemented during the periods of 2010–2015 and 2015–2020, the emission factors of CGVs with Euro III, Euro IV and Euro V emission standards will be used to be compared with these of the EVs and HEVs in 2010, 2015 and 2020. The emission factors (EFs) of CGVs and HEVs were calculated by the EU's COPERT IV model, which is thought more appropriate for China [10,34]. Driving condition was an important parameter for the COPERT model. In this study, we estimated the EFs of CGVs and HEVs under the city driving condition. And the average speed was assumed as 20 km/h [34]. The $EF_{p,CGVs,U}$, $EF_{p,HEVs,U}$ and $EF_{p,B\text{–}P}$ are listed in Table 8.

The method for calculating pollutants emissions is similar with that for the total energy consumption described in Section 2.2. The total pollutants emissions of vehicles can be estimated by the Equations (14)–(19):

$$EMI_{p,2015,\min} = EF_{p,2015} \times VKT_{2015} \times P_{2015} \tag{14}$$

$$EMI_{p,2015,\max} = EF_{p,2010} \times VKT_{2015} \times P_{2015} \tag{15}$$

$$EMI_{p,2015} = (EMI_{p,2015,\max} + EMI_{p,2015,\min})/2 \tag{16}$$

$$EMI_{p,2020,\min} = EF_{p,2015} \times VKT_{2020} \times P_{2015} + EF_{p,2020} \times VKT_{2020} \times (P_{2020} - P_{2015}) \tag{17}$$

$$EMI_{p,2020,\max} = EF_{p,2010} \times VKT_{2020} \times P_{2015} + EF_{p,2015} \times VKT_{2020} \times (P_{2020} - P_{2015}) \tag{18}$$

$$EMI_{p,2020} = (EMI_{p,2020,\max} + EMI_{p,2020,\min})/2 \tag{19}$$

where $EMI_{p,2015,\min}$, $EMI_{p,2015,\max}$, $EMI_{p,2015}$ and $EMI_{p,2020,\min}$, $EMI_{p,2020,\max}$, $EMI_{p,2020}$ are the maximum, minimum and mean values of the total pollutant emissions in 2015 and 2020; $EF_{p,2015}$ represents the pollutant emission factors considering the actual electricity generation ratios of various fuels (g/km); the meaning of VKT and P are the same as the description in Section 2.2.

3. Results and Discussion

3.1. Energy Implications of HEVs and EVs

3.1.1. Per-Kilometer Energy Consumption

Based on the method proposed in Section 2.2, the energy consumptions (ECs) for a single vehicle were calculated. As shown in Figure 2, with the development of vehicle technology, the energy consumptions of CGVs, HEVs and EVs will be decreasing in the future, by 6.1%–9.7% during 2010–2015 and 8.5%–10.7% during 2015–2020. The increase of energy conversion efficiencies in the power generation process and the decrease of electricity transmission loss will also contribute to the reduction of the energy consumptions for EVs (Table 1).

Table 7. Emission factors of different fuels used to generate electricity.

Fuels	Gaseous pollutants					Particles				Greenhouse gas [35]			Heavy metals	
	SO_2	NO_X	VOC	CO	NH_3	PM_{10}	$PM_{2.5}$	OC	EC	CO_2	N_2O	CH_4	Pb	Hg
Coal (g/kg, mg/kg for heavy metals)														
2010	7.27 [a]	6.85 [b]	0.15 [36]	2.48 [37]	0	1.68 [d]	1.20 [6]	0.48 [d]	0.019 [d]	2055	0.031	0.021	0.27 [38]	0.76 [39]
2015	5.74 [a]	6.38 [b]	0.15 [c]	2.48 [c]	0	1.01 [e]	0.72 [e]	0.29 [e]	0.012 [e]	2055	0.031	0.021	0.16 [e]	0.46 [e]
2020	5.17 [a]	5.92 [b]	0.15 [c]	2.48 [c]	0	0.67 [e]	0.48 [e]	0.19 [e]	0.008 [e]	2055	0.031	0.021	0.11 [e]	0.31 [e]
NG (g/m^3)														
2010	0.18[40]	1.76 [40]	0.18 [36]	1.30 [37]	0	0.24 [40]	0.17 [40]	0	0	2184	0.004	0.039	0	0
2015	0.14 [f]	1.64 [f]	0.18 [c]	1.30 [c]	0	0.14 [e]	0.10 [e]	0	0	2184	0.004	0.039	0	0
2020	0.13 [f]	1.52 [f]	0.18 [c]	1.30 [c]	0	0.10 [e]	0.07 [e]	0	0	2184	0.004	0.039	0	0
Oil (g/kg, mg/kg for heavy metals)														
2010	2.24 [40]	9.62 [41]	0.09 [40]	0.78 [40]	0	0.31 [40]	0.31 [40]	0.004 [42]	0.03 [42]	3161	0.013	0.085	0	0.06 [43]
2015	1.77 [f]	8.97 [f]	0.09 [c]	0.78 [c]	0	0.19 [e]	0.19 [e]	0.002 [e]	0.02 [e]	3161	0.013	0.085	0	0.03 [e]
2020	1.59 [f]	8.32 [f]	0.09 [c]	0.78 [c]	0	0.12 [e]	0.12 [e]	0.002 [e]	0.01 [e]	3161	0.013	0.085	0	0.02 [e]
Biomass (g/kg)														
2010	0.53 [44]	1.29 [44]	4.06 [45]	2.48 [46]	0.52 [46]	3.27 g	1.64 g	0.66 [g]	0.03 [g]	1115	0.005	0.030	0	0
2015	0.42 [f]	1.20 [f]	4.06 [c]	2.48 [c]	0.52 [c]	1.96 [e]	0.98 [e]	0.40 [e]	0.02 [e]	1115	0.005	0.030	0	0
2020	0.38 [f]	1.12 [f]	4.06 [c]	2.48 [c]	0.52 [c]	1.31 [e]	0.65 [e]	0.26 [e]	0.01 [e]	1115	0.005	0.030	0	0
Garbage (g/kg)														
2010	0	2.50 [47]	0.74 [47]	5.00 [47]	0.21 [48]	0.35 [46]	0.15 [46]	ND	ND	1152	0.005	0.031	0	0
2015	0	2.33 [f]	0.74 [c]	5.00 [c]	0.21 [c]	0.21 [e]	0.09 [e]	ND	ND	1152	0.005	0.031	0	0
2020	0	2.16 [f]	0.74 [c]	5.00 [c]	0.21 [c]	0.14 [e]	0.06 [e]	ND	ND	1152	0.005	0.031	0	0

Notes: [a] Estimated by the authors based on the SO_2 emission factors in the [6] and the SO_2 emission change trends in [49]; [b] Based on reference [15], the NO_X emission factors (EFs) for coal-fired plant in 2004 and 2030 are 7.4 and 5.0 g/kg. Using linear interpolation, the EF in 2010, 2015 and 2020 were estimated; [c] The emissions control were focused on particles, SO_2 and NO_X at present and in the following several years in China. In the case that there are few quantitative studies about the future emission control for CO, VOC and NH_3 in China, we assume that the EFs will be the same with those in 2010; [d] Calculated based on the $PM_{2.5}$ emission factor in [6] and the relations of PM_{10}, $PM_{2.5}$, OC and EC in [40]; [e] Based on the old and new emission standards, the particle concentrations of flue gas should be decrease from 50 μg/m^3 to 30 and 20 μg/m^3. It is assumed the EFs of particles will decrease 40% and 60% in 2015 and 2020 on the basis of 2010; [f] Estimated based on the emission factors in 2010 and the corresponding pollutans changes for coal; [g] Estimated based on the study in [40].

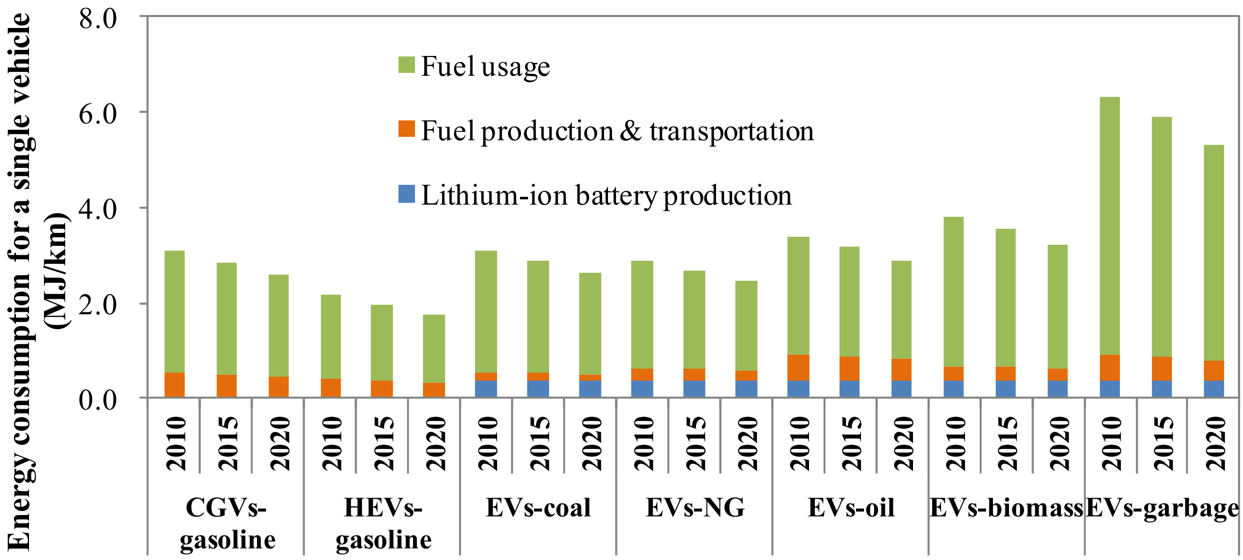
Table 8. Emission factors (EFs) of CGVs and HEVs' driving stage and fuels' production and transportation phase.

Fuels/vehicle types	Gaseous pollutants					Particles				Greenhouse gas			Heavy metals	
	SO_2	NO_X	VOC	CO	NH_3	PM_{10}	$PM_{2.5}$	OC	EC	CO_2	N_2O	CH_4	Pb	Hg
Coal (g/kg) [50]														
2010	0.74	1.22	0.2	0.19	0	0.19	0.09	0.03	0.009	77	0.26	0.028	0	0
2015	0.58	1.14	0.2	0.19	0	0.12	0.05	0.02	0.006	77	0.26	0.028	0	0
2020	0.52	1.06	0.2	0.19	0	0.08	0.04	0.01	0.004	77	0.26	0.028	0	0
NG (g/kg) [50]														
2010	0.66	0.92	0.23	0.35	0	0.013	0.006	0.002	0.0006	470	0.19	0.032	0	0
2015	0.52	0.86	0.23	0.35	0	0.008	0.004	0.001	0.0004	470	0.19	0.032	0	0
2020	0.47	0.80	0.23	0.35	0	0.005	0.002	0.001	0.0002	470	0.19	0.032	0	0
Oil (g/kg) [50]														
2010	0.96	2.05	7.0	0.48	0	0.08	0.04	0.013	0.004	270	0.43	0.976	0	0
2015	0.76	1.91	7.0	0.48	0	0.05	0.02	0.008	0.002	270	0.43	0.976	0	0
2020	0.68	1.77	7.0	0.48	0	0.03	0.01	0.005	0.002	270	0.43	0.976	0	0
Biomass/Garbage (g/kg)														
2010	0.05	0.08	0.01	0.01	0	0.01	0.006	0.002	0.001	4.9	0.02	0.002	0	0
2015	0.05	0.08	0.01	0.01	0	0.01	0.006	0.002	0.001	4.8	0.02	0.002	0	0
2020	0.04	0.07	0.01	0.01	0	0.01	0.005	0.002	0.001	4.5	0.01	0.002	0	0
Lithium-ion battery production of EF_{HEVs} (g/km) ($EF_{EVs} = 31.8 \times EF_{HEVs}$)														
2010	0.003	0.0017	0.0001	0.004	0	0.0009	0.0004	0.0001	0.00004	0.9	0.00	0.00	0	0
2015	0.002	0.0016	0.0001	0.004	0	0.0005	0.0003	0.0001	0.00003	0.9	0.00	0.00	0	0
2020	0.002	0.0015	0.0001	0.004	0	0.0004	0.0002	0.0001	0.00002	0.9	0.00	0.00	0	0
CGVs (g/km, mg/km for heavy metals)														
2010	0.008	0.11	0.19	1.96	0.01	0.021	0.012	0.001	0.0002	262	0.004	0.025	0.001	0
2015	0.008	0.08	0.11	0.60	0.01	0.020	0.011	0.001	0.0002	241	0.003	0.017	0.001	0
2020	0.007	0.07	0.10	0.55	0.01	0.018	0.010	0.0005	0.0002	221	0.003	0.017	0.001	0
HEVs (g/km, mg/km for heavy metals)														
2010	0.006	0.009	0.034	0.51	0.01	0.021	0.011	0.0005	0.0002	183	0.003	0	0.0004	0
2015	0.006	0.007	0.020	0.15	0.01	0.020	0.011	0.0005	0.0002	165	0.002	0	0.0004	0
2020	0.006	0.005	0.019	0.15	0.01	0.020	0.010	0.0005	0.0002	147	0.002	0	0.0004	0

From the view point of the LCA, the energy consumptions from the fuels usage phase accounted for most of the total ECs, with proportions of 71.9%–85.8%, while the percentages of the fuels' production and transportation stage were about 5.1%–18.1%. The contributions of lithium-ion battery production were lower for HEVs (0.5%–0.6%), but higher for EVs (5.8%–15.1%).

The energy consumptions (ECs) for most of the EVs (except for EVs-NG) are higher than CGVs and HEVs, with proportions of 0–108% and 43%–206%, respectively. The ECs of EVs-NG are 5%–7% lower than CGVs, but 33%–40% higher than HEVs. The ECs of HEVs are 30%–33% lower than those for CGVs. For a given EV, the energy consumption is dependent on the electricity generation methods and the energy conversion efficiencies (ECE) of power generation, fuels production and transportation. Among all the five kinds of fuels, the energy consumption for EVs-NG is lowest (*i.e.*, 2.45–2.87 MJ/km, Figure 2). As for the EVs-garbage, because of the lowest ECE, the energy consumption is highest. It is about 105%–108%, 193%–206%, 103%–105%, 118%–121%, 84%–86% and 65%–66% above the energy consumptions of CGVs, HEVs, EVs-coal, EVs-NG, EVs-oil and EVs-biomass, respectively. From the respective of energy-saving, it seems unwise to use EVs-garbage. However, in view of waste reuse, the garbage power technology can transform waste (if not use, the useful energy for waste is zero) to electricity, thus can also reduce the power generated by other means, and indirectly cut down the consumptions of the fossil fuels. In that sense, the EVs-garbage can also contribute to the energy-saving.

Figure 2. Energy consumption for a single vehicle (HEVs-gasoline means the hybrid electric vehicles using gasoline, EVs-fuel means the electric vehicles using the electricity generated by fuel combustion).



Usually, the electricity used is originating from a mixture of sources, and the differences among the electricity grid in various regions may result in distinctions of the EV energy consumptions [51]. As a consequent, the ECs for a single EV in the whole nation and other three representative regions (BTH, YRD and PRD) were estimated based on the proportions of different power generation methods (Figure 3). Results showed that the electricity sources had significant impact on the EVs energy consumptions. The EVs had a much larger EC in the regions with higher proportions of coal-fired power. For example, the EC for a single EV in BTH (2.51–2.95 MJ/km) was about 1.5 times and

1.2 times of that in PRD (1.66–1.95 MJ/km) and the regional average (2.12–2.49 MJ/km), respectively. The EC in YRD (2.29–2.69 MJ/km) was also higher than that in the PRD and the national average. Furthermore, the results were also compared with the ECs in the previous studies (Table 9) [16,52]. It can be found that because of the differences of calculation parameters (such as the gasoline consumption), the ECs of CGVs and HEVs in this study were a little lower than the result in [16]. Except for that, there is no obvious difference between the results in this paper and in other studies using different estimation methods.

Figure 3. Energy consumption for a single EV in different regions of China.

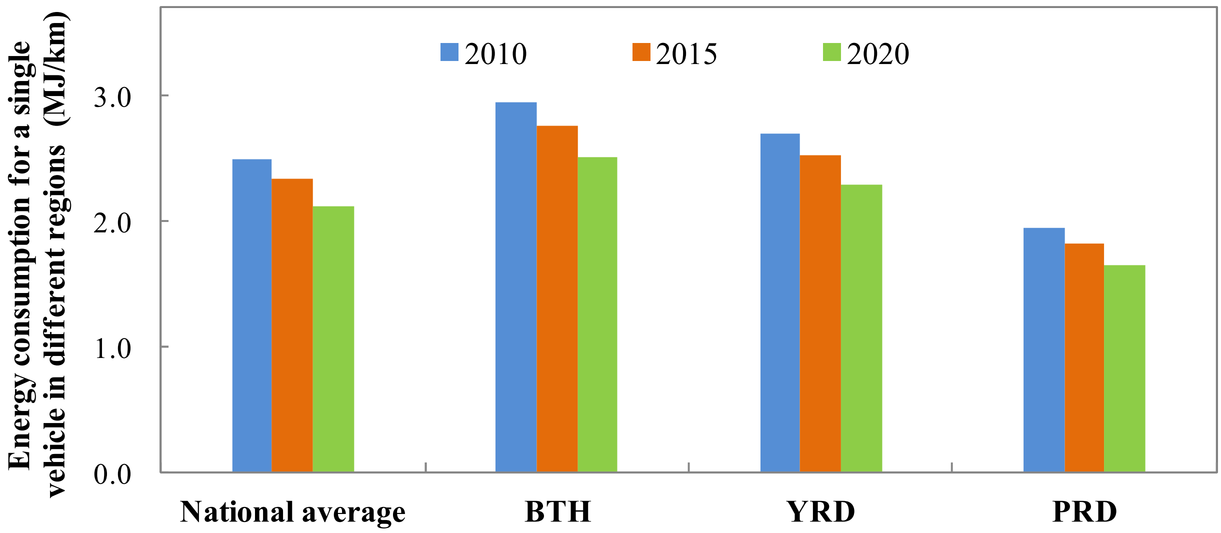


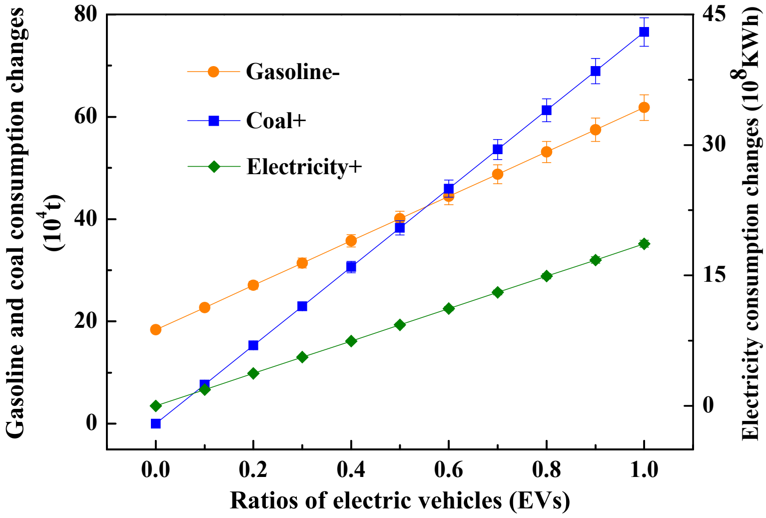
Table 9. The energy consumptions of China in other studies (MJ/km) [16,52].

Sources	**Wu *et al.*** [16]			**Shen *et al.*** [52]		
Vehicles	**CGVs**	**HEVs**	**EVs**	**CGVs**	**HEVs**	**EVs**
2010	3.50–3.59	2.52–2.59	1.75–2.60	3.10	2.23	1.72
2015	3.27–3.37	2.36–2.40	1.54–2.31	-	-	-
2020	2.90–2.96	2.07–2.12	1.29–1.98	2.65	1.89	1.58

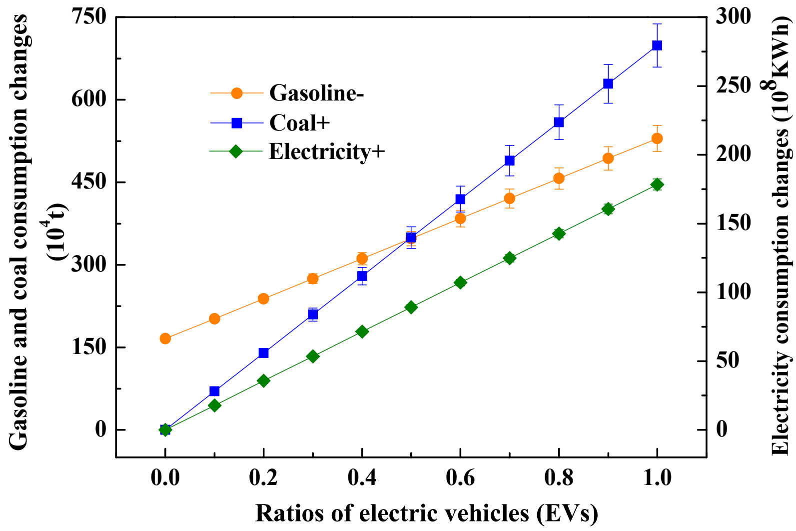
3.1.2. Energy Consumptions Changes in 2015 and 2020

In the *Energy Saving and New Energy Vehicles Development Planning* (*2012–2020*) [26], it is indicated that the total numbers of EVs and HEVs in China in 2015 and 2020 should reach 500 thousand and five million, respectively. Since the gasoline consumption of HEVs is less than that of CGVs, the promotion of HEVs will reduce the gasoline consumption in China. Meanwhile, because the EVs use electricity instead of gasoline to drive, the promotion of EVs will also cut down the gasoline consumption; however, this will increase the demand of fuels which are used for generating electricity. As a result, different population ratios of EVs or HEVs will lead to various energy consumptions changes. Based on the study of the International Energy Agency (IEA), by 2030 coal will remain the dominant fuel in the power generation in China [53]. Therefore, take gasoline, coal and electricity as examples, the energy consumption changes under different EVs population ratios were estimated in 2015 and 2020 in China (Figure 4).

Figure 4. The consumption changes of gasoline, coal and electricity under different ratios of electric vehicles in China ("+" represents increase, "–" represents reduction): (**a**) 2015 and (**b**) 2020.



(**a**)



(**b**)

When the ratio of EVs is zero, the number of HEVs is 500 thousand in 2015 and five million in 2020. In this case, the gasoline consumption reduction would be [18.1, 18.7] × 10^4 t in 2015 and [162.9, 168.5] × 10^4 t in 2020, accounting for [0.56%, 0.58%] and [5.08%, 5.26%] of the gasoline consumed by transport (mainly by the light duty vehicles transport) in 2010 (3204.9 × 10^4 t) [19]. With the increase of EVs ratio, the gasoline consumption keeps decreasing; however, the coal and electricity consumptions will be increasing. Under the scenario that the EVs ratio is 100%, the gasoline consumption reduction would increase to the maximum, about [1.85%, 2.01%] and [15.79%, 17.26%] of the gasoline consumed by transport in 2010 for 2015 and 2020, respectively, and the increased coal consumption would be [73.8, 79.4] × 10^4 t in 2015 and [659.3, 738.0] × 10^4 t in 2020, accounting for 0.05% and [0.44%, 0.49%] of the coal consumed by power generation in 2010 (151,163 × 10^4 t) [19]. The increased electricity consumption would be [18.2, 19.0] × 10^8 kWh in 2015 and [174.4, 182.3] × 10^8 kWh during in 2020, accounting for [0.04%, 0.05%] and [0.44%, 0.49%] of the electricity production in 2010 (4219 TWh) [5]. The changes proportions of gasoline are much higher than that of coal and electricity, indicating that the promotion of HEVs and EVs can have a remarkable impact on the gasoline demand reduction in China.

In addition, it should be noted that the results above were estimated based on the national proportions of different power generation methods. For the regions with high proportions of hydropower and low proportions of coal-fired power, such as the South China (the ratios of hydropower and coal-fired power were 30% and 65% in 2008), the coal consumption will be less (about 14.7% less in the South China) than the results in this study [15]. From the energy-saving perspective, it is suggested that the regions with less proportions of coal-fired power should be given priority to the promotion of EVs.

Moreover, other energy sources, such as the biomass, hydropower, nuclear and solar energy should and will be further exploited and used in the power generation in China. The hydropower will be developed as a priority. The installed capacity will reach to about 284.0 GW in 2015 and 450.0 GW in 2030. As for biomass, there are about 700 million t/a straw and 200 million t/a firewood production in China. About 100 million of straw and firewood can be used for generating power. China will further use the biomass in the following decade. The installed capacity will increase from 1.7 GW in 2010 to 3.0 GW in 2015 and 5.0 GW in 2020. Besides, the installed capacity of nuclear power will grow from 10.8 GW in 2010 up to 42.9 GW in 2015 and 90.0 GW in 2020. The installed capacity for solar power will also be further advanced, from 0.3 GW in 2009 to 2.0 GW and 20.0 GW in 2015 and 2020, respectively [19]. All these developments of the non-fossil fuel-fired power will help reduce indirectly the oil demand and energy consumption of transport.

3.2. Emissions Implications of HEVs and EVs

3.2.1. Emission Factors

Based on the data and equations described in Section 2.3, the emission factors for 14 pollutants of CGVs, HEVs and EVs were estimated (Table 10). It can be found that with the development and further implementation of the air pollutants treatment technology and the improvement of the energy conversion efficiency, all the emission factors would decrease in the following decade. In 2007, the Euro III vehicle emission standard was implemented in most regions of China (except for some large cities, such as Beijing). From 2012, Euro IV emission standard has been carried out nationwide. And Euro V standard is expected to be in place during 2015–2020 (Beijing has implemented the Euro V standard since 2012). At the same time, the gasoline quality has been improved during the past decade. The sulfur content was 0.005% in 2010; and would be reduced to 0.001% within 10 years (the sulfur content of Beijing has been decreased to 0.001% in 2012). The above emission mitigation measures will significantly reduce the emission factors of CGVs and HEVs. As for power plant, SO_2, NO_X and particles are the air pollutants control emphasis during the following decade in China. SO_2 reduction has been carried out since the 1980s. By the end of 2008, the flue gas desulfurization (FGD) system penetration in power sector has reached 60%, and FGD will be further promoted in the following decade [15]. The desulfurization efficiency for large power plants should reach 90%, even 95% before 2020 based on the current Chinese air pollution control plan. The particle controls began in the 1990s.

According to the power plants emission standard implemented before 2012, the upper limit of particle concentration in the flue gas was 50–100 μg/m^3. At the beginning of 2012, a new emission standard was implemented, indicating that the particle concentration of flue gas should be less than 30 μg/m^3. In the critical air pollution regions, such as Beijing, Tianjin, Shanghai and Pearl River Delta (PRD), the emission limit is even more stringent, with a particle concentration of 20 μg/m^3. Under the new standard, the particle emissions in power plants will be further reduced. NO_X has been another key pollutant that needs to be mitigated since 2010. The low-NO_X burner (LNB) and other advanced technologies such as the selected catalytic reduction (SCR) technology will be widely applied in China. This will significantly reduce the NO_X emission in the power plants. The removal efficiency of NO_X for the power generation could reach 40%–80% in the following decade. All these control measures will effectively mitigate the air pollutant emissions.

And from the viewpoint of LCA, the gasoline usage phase (*i.e.*, the driving stage) for the CGVs accounted for most of the $PM_{2.5}$, CO and CO_2 emissions, with proportions of 85%–92%, 95%–99% and 93%–94%, respectively. While the contribution ratios of the gasoline production and transportation stage were about 85%–87%, 53%–61% and 68%–80% for SO_2, NO_X and VOC, respectively. The HEVs had similar emission characteristics with CGVs. As for the EVs, most of the emissions were from the power generations, except for VOC, N_2O and CH_4. The lithium-ion battery production (LIBP) contributed about 6%–7%, 8%–12%, 7%–11%, 6%–14% and nearly 100% of the SO_2, OC, EC, Pb and Hg emissions in HEVs, whereas much less contribution to other pollutants. The influence of LIBP to EVs' emissions was more obvious, with percentages of 8%–10%, 29%–33%, 8%–9%, 27%–31% and 10%–12% for SO_2, CO, $PM_{2.5}$, EC and CO_2, respectively.

Table 10 also showed that the HEVs can provide significant reductions of NO_X (58%–62%), VOC (46%–51%) and CO (71%–73%) emissions for a single vehicle, and a lesser decrease of the SO_2 (26%–36%) and CO_2 (30%–34%) emissions. As for EVs, they can decrease more than 90% of the VOC and NH_3 emissions, 18%–74% of the CO emissions and 5%–7% of the CO_2 emissions on a national average, but EVs can lead to an obvious increase of SO_2 emissions. In China, the electricity in China is generated primarily from coal (Figure 1). The sulfur content of coal is 4.2–14.7 g/kg (*i.e.*, 0.42%–1.47%), much higher than that of gasoline (0.001%–0.005%) [15]. As a result, the SO_2 emission factors of EVs will be much higher than that of CGVs. The EVs can also increase the NO_X emission by 2.7–2.9 times and increase the particles (except for OC) by 3.6–11.5 times. Moreover, the EVs would also make the heavy metals (Pb and Hg) emissions increase.

The emission factors of EVs in the whole nation and other three representative regions (BTH, YRD and PRD) were also calculated (Table 10). It is indicated that similar with the energy consumptions, the electricity sources also had significant influence on the EVs emissions. The emissions factors of EVs in the BTH, where the coal-fired power percentage was higher (94.8%), were about 34%–36% higher than those in the PRD, where there was a lower coal-fired power ratio (60.2%). Based on the discussion above, it is suggested that the differences of power constitutions in various regions should be considered when the EVs and HEVs are promoted. In order to achieve higher energy reduction and pollutants emission mitigation, the EVs should be penetrated in the regions with higher hydropower, NG-fired power and clean energy power proportions; while the HEVs can be widely adopted in the regions with high coal-fired power ratios.

Table 10. Emission factors of CGVs, EVs and HEVs (g/km, mg/km for heavy metals).

Vehicle types	Gaseous pollutants					Particles				Greenhouse gas			Heavy metals	
	SO_2	NO_X	VOC	CO	NH_3	PM_{10}	$PM_{2.5}$	OC	EC	CO_2	N_2O	CH_4	Pb	Hg
CGVs														
2010	0.06	0.23	0.60	1.99	0.01	0.026	0.014	0.001	0.0004	278	0.03	0.08	0.0006	0
2015	0.05	0.20	0.52	0.63	0.01	0.022	0.012	0.001	0.0003	257	0.03	0.07	0.0005	0
2020	0.05	0.17	0.51	0.58	0.01	0.020	0.011	0.001	0.0002	237	0.03	0.07	0.0005	0
HEVs														
2010	0.05	0.09	0.32	0.53	0.01	0.025	0.013	0.001	0.0004	195	0.02	0.04	0.0005	0.0002
2015	0.04	0.08	0.28	0.17	0.01	0.022	0.012	0.001	0.0003	176	0.02	0.04	0.0005	0.0001
2020	0.03	0.07	0.25	0.17	0.01	0.021	0.011	0.001	0.0002	157	0.02	0.03	0.0005	0.0001
EVs-national average														
2010	0.91	0.86	0.04	0.52	0.0009	0.23	0.15	0.06	0.005	260	0.03	0.006	0.03	0.08
2015	0.68	0.76	0.04	0.50	0.0009	0.13	0.08	0.03	0.003	245	0.03	0.005	0.02	0.05
2020	0.56	0.64	0.04	0.47	0.0008	0.08	0.05	0.02	0.002	225	0.02	0.005	0.01	0.03
EVs-BTH														
2010	1.10	1.04	0.04	0.57	0	0.27	0.18	0.07	0.006	306	0.03	0.007	0.04	0.10
2015	0.82	0.91	0.04	0.55	0	0.15	0.10	0.04	0.003	288	0.03	0.006	0.02	0.06
2020	0.67	0.76	0.04	0.52	0	0.09	0.06	0.02	0.002	264	0.03	0.006	0.01	0.03
EVs-YRD														
2010	1.02	0.96	0.04	0.54	0	0.25	0.16	0.06	0.006	284	0.03	0.006	0.03	0.09
2015	0.76	0.84	0.04	0.52	0	0.14	0.09	0.04	0.003	268	0.03	0.006	0.02	0.05
2020	0.62	0.70	0.03	0.49	0	0.09	0.06	0.02	0.002	245	0.03	0.005	0.01	0.03
EVs-PRD														
2010	0.74	0.69	0.03	0.42	0	0.18	0.12	0.04	0.004	210	0.02	0.004	0.02	0.07
2015	0.55	0.60	0.03	0.40	0	0.10	0.07	0.03	0.002	198	0.02	0.004	0.01	0.04
2020	0.45	0.51	0.03	0.38	0	0.06	0.04	0.02	0.002	182	0.02	0.004	0.01	0.02

The emission factors (EFs) estimated in this study were also compared to those in the previous studies (Table 11) [12,14,54]. There are no clear differences between the results in this and other studies for most of the pollutants and vehicles, except for particular ones. For example, in general, the EFs of VOC for CGVs, HEVs and EVs are higher than those of U.S. calculated by the GREET model. This is mainly because that the VOC has not been a control point in China at the present time, resulting in higher emissions than the U.S. and other developed countries.

Table 11. The emission factors of CGVs, HEVs and EVs in other studies (g/km) [12,14,54].

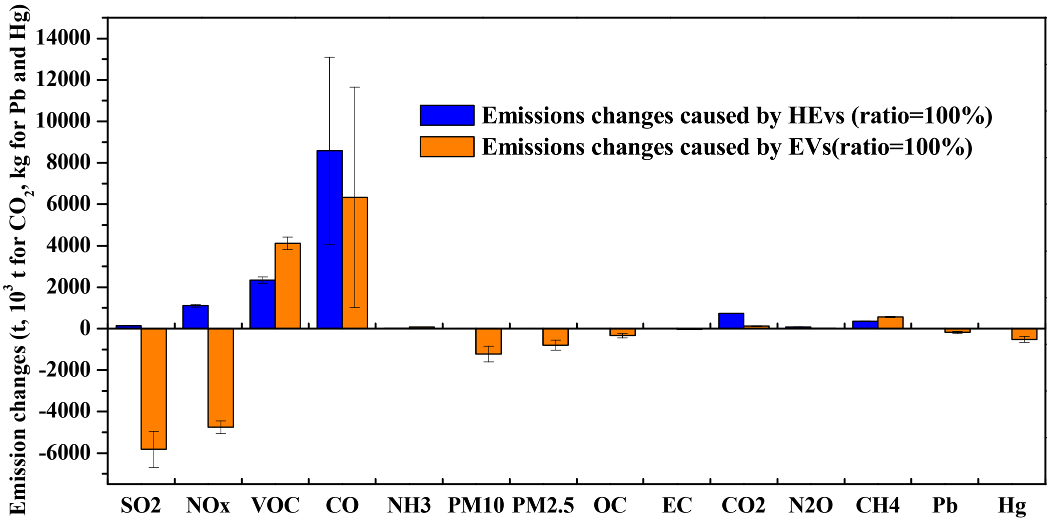
Sources	**Huo *et al.*** [14]			**Silva *et al.*** [54]			**Stephan and Sullivan** [12]		
Vehicles	**CGVs**	**HEVs**	**EVs**	**PHEVs**			**CGVs**	**HEV**	**PHEV**
Countries	**U.S.**			**U.S.**	**Europe**	**Japan**	**U.S.**		
NO_X	0.19	0.13	0.18	0.16	0.25	0.14	-	-	-
VOC	0.18	0.12	0.02	0.17	0.32	0.16	-	-	-
CO	2.22	0.36	0.06	0.60	1.06	0.49	-	-	-
PM_{10}	0.06	0.04	0.25	-	-	-	-	-	-
$PM_{2.5}$	0.02	0.02	0.07	-	-	-	-	-	-
CO_2	-	-	-	109	103	106	432	296	177

3.2.2. Emission Changes in 2015 and 2020

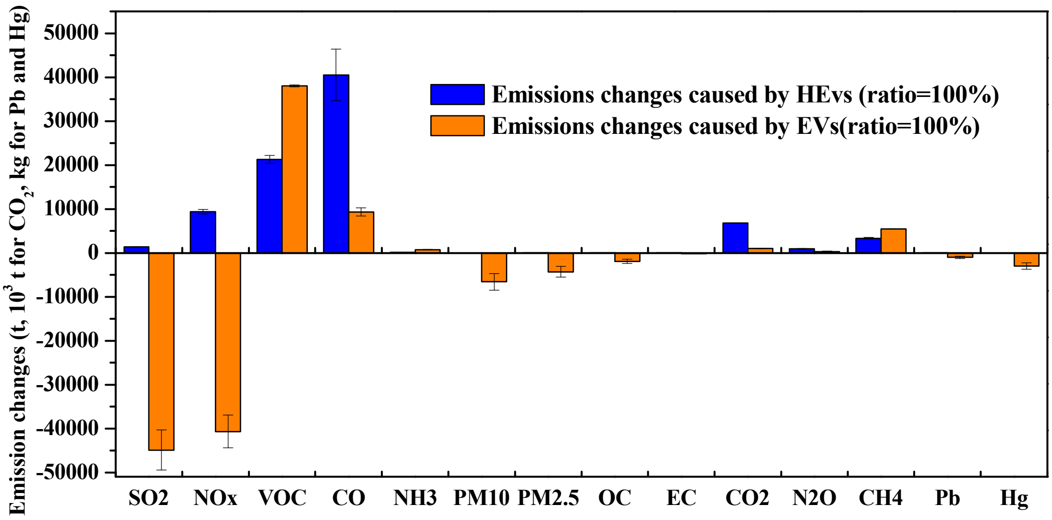
The pollutant emission changes caused by the promotion of EVs and HEVs in 2015 and 2020 were estimated based on the method described in Section 2.3. The EVs will lead to the decrease of the CGVs emissions, but would increase the pollutant emissions of power generation. It is a course to convert the emissions from transport to power generation. However, the HEVs can directly reduce the emissions of vehicles. Figure 5 shows the pollutants emission changes of power generation and vehicles caused by EVs and HEVs in 2015 and 2020.

HEVs have obvious mitigation effects for NO_X, VOC, CO and CO_2, but a much lower impact on other pollutants. In the case that the ratio of HEVs is 100%, about 1109, 2346, 8587 and 735,233 t (in 2015) and 9367, 21,296, 40,510 and 6,753,535 t emissions (in 2020) will be reduced for NO_X, VOC, CO and CO_2, respectively. EVs have obvious and positive mitigation impacts on the CO_2, VOC and CO, but have significant and negative mitigation effects on the SO_2 and NO_X, whereas they have a much lower influence on other pollutants. In the case that the ratio of EVs is 100%, the SO_2 and NO_X emissions will undergo significant changes, with increments of 5820 and 4755 t in 2015 and 44,914 and 40,680 t in 2020, but they can reduce by about 4122, 6340, 1,198,673 t in 2015 and 38,036, 9325, 964,883 t in 2020 VOC, CO and CO_2, respectively. In addition, as compared with CGVs emissions, the increment of particles and heavy metals are also much higher for the penetration of EVs. By comparing the emissions changes caused by EVs with those by HEVs, it can be found that the EVs have better mitigation effects for VOC, while the HEVs have better mitigation effects for NO_X, CO and CO_2. The emission analysis of HEVs and EVs above can provide scientific support for the total amount control of air pollutants in China.

Figure 5. The pollutants emission changes caused by HEVs and EVs in China (positive represents reduction, negative represents increase): (**a**) 2015 and (**b**) 2020.



(**a**)



(**b**)

In addition, it is should be noted that the emission changes in this study were calculated using the average emission factors (AEFs) rather than the marginal emission factors (MEFs). Siler-Evans *et al.* estimated the marginal emission factors of SO_2, NO_X and CO_2 using continuous monitoring emission data (CMED) for eight regions of the North America Electric Reliability Corporation and found that there were obvious differences between MEFs and AEFs [55]. In the regions where the fuel sources (for power generation) were similar to China (with higher coal proportions), such as the Midwest Reliability Organization (MRO), Reliability First Corperation (RFC) and Southern Reliability Council (SRC), the differences between MEFs and AEFs were –5% to 21%, –20% to 20% and –11% to 2% for SO_2, NO_X and CO_2, respectively. As a result, there were some plus or minus errors when using AEFs to assess the environmental impact of EVs. Further studies should be carried out to investigate the marginal emissions for the electricity system in different regions of China.

At the beginning of 2012, a new National Ambient Air Quality Standard (NAAQS) was proposed in China. This new standard introduced the control of $PM_{2.5}$ for the first time in China. $PM_{2.5}$ will be the control emphasis in the following decades. In view of the emission increment for $PM_{2.5}$, SO_2 (could transform to SO_4^- through complex chemical reactions) and NO_X (could transform to NO_3^-), the promotion of EVs maybe not an effective measure for reducing the atmospheric $PM_{2.5}$ concentrations in China. However, just as the descriptions above, the adoption of EVs is a course of converting emissions from transport to power generations and other emissions. The vehicular pollutants alternative by EVs mainly occurs in the urban district and the release heights are low. But the pollutants from power generation were mainly in suburban districts, and the release heights are high. The emissions decrease of low sources and increase of high sources may result in a reduction of local atmospheric pollutants concentrations (APCs), but lead to an increment of regional APCs, as the high release height can facilitate a long range transport of pollutants. In addition, based on the discussion in Section 3.2.1, it would minimize the positive influences on the $PM_{2.5}$ pollution to promote EVs in the regions with less coal-fired power and more hydropower, such as the South China (with hydropower proportion higher than 30%); more NG-fired power, such as Beijing, Pearl River Delta (PRD) and Yangtze River Delta (YRD) (the installed capacity for NG power was about 26 GW in 2010 in China, and most of them were distributed in the Beijing, PRD and YRD region); and more clean energy power, such as Zhejiang and Guangdong (accounting for nearly 80% of the nuclear power in China). And in the regions with high coal-fired power ratios, the HEVs may be a better choice.

4. Conclusions

In this study, the energy and environmental implications of hybrid and electric vehicles (EVs) were estimated through an energy conversion and life cycle assessment (LCA). Five kinds of power generation methods (coal-, NG-, oil-, biomass- and garbage-fired) and fourteen kinds of pollutants (gaseous pollutants: SO_2, NO_X, VOC, CO and NH_3; particles: PM_{10}, $PM_{2.5}$, OC and EC; greenhouse gases: CO_2, N_2O and CH_4; heavy metals: Pb and Hg) were considered. The per-kilometer consumptions (PKCs) of gasoline, coal, oil, biomass, garbage and electricity of EVs and HEVs were estimated considering the energy conversion efficiencies of fuels production and transportation, power generation and transmission.

Results showed that the promotion of EVs and HEVs can reduce the energy consumptions (ECs) of vehicles by national average ratios of 17%–19% and 30%–33%, respectively. The PKC of EVs-NG was the lowest in the five fuels. From the view point of the life cycle, the fuels usage phase accounted for most of the total ECs; the second was the stage of fuels production and transportation. The lithium-ion battery production contributed only very small ECs for the HEVs, but represented a much higher contribution for EVs. The ECs for a single EV in the whole nation and other three representative regions (BTH, YRD and PRD) were estimated based on the proportions of different power generation methods. It is indicated that the electricity sources had an obvious impact on the EVs energy consumptions. The EVs in the regions with higher coal-fired power proportions will have much larger ECs. The energy consumption changes caused by the EVs promotion plan in 2015 and 2020 were assessed under different adoption ratios of EVs and HEVs. The implementation of the plan could reduce the gasoline consumption of vehicles to a great extent, but would increase the use of electricity, coal and other fuels, and with the EVs ratio increasing, the consumption of gasoline would keep decreasing and the use of fuels for power generation would continuously increase. With the development of NG and clean energy power in the following years, the EVs will help further reduce the energy consumption of the transport sector in China.

The emission factors of CGVs, HEVs and EVs in 2010, 2015 and 2020 were calculated. With the implementation of new emission standards and the development of various pollutant mitigation measures, the factors of all the pollutants would decrease in the future. The HEVs can bring significant reductions of NO_X, VOC and CO emissions, and lesser decreases of SO_2 and CO_2. The EVs could decrease many of the VOC, NH_3 and CO emissions, but increase the SO_2, NO_X and particles emissions by 10.8–13.0, 2.7–2.9 and 3.6–11.5 times. In view of the life cycle, the gasoline usage phase (*i.e.*, the driving stage) for CGVs and HEVs contributed most of the emissions of $PM_{2.5}$, CO and CO_2, while the gasoline production and transportation stage accounted for higher ratios of the SO_2, NO_X and VOC emissions. As for the EVs, most of the emissions were from the power generation, except for VOC, N_2O and CH_4. The lithium-ion battery production (LIBP) had obvious contributions to the SO_2, OC, EC, Pb and Hg emissions in HEVs and a remarkable effect on the SO_2, CO, $PM_{2.5}$, EC and CO_2 emissions in EVs. Like the energy consumptions, the electricity sources also had significant influence on the EVs emissions. The regions with higher coal-fired power percentages had larger emission factors. The emissions changes caused by EVs and HEVs in 2015 and 2020 were also estimated. The emission analysis of EVs can provide scientific support for the control of the amount of regional total air pollutants in China. Because of the increase of $PM_{2.5}$, SO_2 and NO_X, the wide diffusion of EVs maybe not an effective measure for reducing the atmospheric $PM_{2.5}$ concentration in the regions with high ratios of coal-fired power. Based on the energy and environmental impacts analysis in China, it is suggested that the power constitutions in different regions should be considered when promoting EVs and HEVs. One would get better effects of energy reduction and pollutant emission mitigation if EVs were promoted in the regions with lower coal-fired power and higher hydropower ratios, NG-fired power, clean energy power proportions; and by making a wide-spread adoption of HEVs in the regions with higher coal-fired power ratios a priority.

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References

1. National Bureau of Statistics of China. *China Statistical Yearbook 2002*; China Statistics Press: Beijing, China, 2002.
2. National Bureau of Statistics of China. *China Statistical Yearbook 2012*; China Statistics Press: Beijing, China, 2012.

3. He, K.B.; Huo, H.; Zhang, Q.; He, D.Q.; An, F.; Wang, M.; Walsh, M.P. Oil consumption and CO_2 emissions in China's road transport: Current status, future trends, and policy implications. *Energy Policy* **2005**, *33*, 1499–1507.
4. Yan, X.Y.; Crookes, R.J. Reduction potentials of energy demand and GHG emissions in China's road transport sector. *Energy Policy* **2009**, *37*, 658–668.
5. National Bureau of Statistics of China. *China Energy Statistical Yearbook 2010*; China Statistics Press: Beijing, China, 2011; Appendix IV.
6. Zhang, Q.; Streets, D.G.; Carmichael, G.R.; He, K.B.; Huo, H.; Kannari, A.; Klimont, Z.; Park, I.S.; Reddy, S.; Fu, J.S.; *et al*. Asian emissions in 2006 for the NASA INTEX-B mission. *Atmos. Chem. Phys.* **2009**, *9*, 5131–5153.
7. Cheng, S.Y.; Zhou, Y.; Li, J.B.; Lang, J.L.; Wang, H.Y. A new statistical modeling and optimization framework for establishing high-resolution PM_{10} emission inventory–I. Stepwise regression model development and application. *Atmos. Environ.* **2012**, *60*, 613–622.
8. Che, W.W.; Zheng, J.Y.; Wang, S.S.; Zhong, L.J.; Lau, A. Assessment of motor vehicle emission control policies using Model-3/CMAQ model for the Pearl River Delta region, China. *Atmos. Environ.* **2011**, *45*, 1740–1751.
9. Zhou, Y.; Cheng, S.Y.; Liu, L.; Chen, D.S. A coupled MM5-CMAQ modeling system for assessing effects of restriction measures on PM_{10} pollution in Olympic city of Beijing, China. *J. Environ. Inf.* **2012**, *19*, 120–127.
10. Lang, J.L.; Cheng, S.Y.; Wei, W.; Zhou, Y.; Wei, X.; Chen, D.S. A study on the trends of vehicular emissions in the Beijing-Tianjin-Hebei (BTH) region, China. *Atmos. Environ.* **2012**, *62*, 605–614.
11. Campanari, S.; Manzolini, G.; Iglesia, F.G. Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations. *J. Power Sources* **2009**, *186*, 464–477.
12. Stephan, C.; Sullivan, J. Environmental and energy implications of plug-in hybrid-electric vehicles. *Environ. Sci. Technol.* **2008**, *42*, 1185–1190.
13. Hawkins, T.R.; Gausen, O.M.; Strømman, A.H. Environmental impacts of hybrid and electric vehicles—A review. *Int. J. Life Cycle Assess.* **2012**, *17*, 997–1014.
14. Huo, H.; Wu, Y.; Wang, M. Total *versus* urban: Well-to-wheels assessment of criteria pollutant emissions from various vehicle/fuel systems. *Atmos. Environ.* **2009**, *43*, 1796–1804.
15. Huo, H.; Zhang, Q.; Wang, M.Q.; Streets, D.G.; He, K.B. Environmental implication of electric vehicles in China. *Environ. Sci. Technol.* **2010**, *44*, 4856–4861.
16. Wu, Y.; Yang, Z.D.; Lin, B.H.; Liu, H.; Wang, R.J.; Zhou, B.Y.; Hao, J.M. Energy consumption and CO_2 emission impacts of vehicle electrification in three developed regions of China. *Energy Policy* **2012**, *48*, 537–550.
17. Fang, L.C.; Qin, S.Y.; Xu, G.; Li, T.L.; Zhu, K.M. Simultaneous optimization for hybrid electric vehicle parameters based on multi-objective genetic algorithms. *Energies* **2011**, *4*, 532–544.
18. China Electric Power Yearbook [in Chinese]. Available online: http://hvdc.chinapower.com.cn/membercenter/yearbookcenter/ (accessed on 15 October 2012).
19. *China Electric Power Yearbook*; China Electric Power Press: Beijing, China, 2011; pp. 719–722.
20. Xu, T.; Zhang, L.; Liang, Y.Q. Analysis on energy consumption efficiency of electric vehicle and the solutions to improve the energy consumption economy [in Chinese]. *Energy Eng.* **2011**, *2*, 1–5.

21. Wang, Z.X.; Zhang, J.J. Outlooks of energy conservation and emission reduction in the power generation during the "Twelfth Five-Year" in China [in Chinese]. *Expert Forum* **2010**, *32*, 5–9.
22. Oda, J.; Akimoto, K.; Tomoda, T.; Nagashima, M.; Wada, K.; Sano, F. International comparisons of energy efficiency in power, steel, and cement industries. *Energy Policy* **2012**, *44*, 118–129.
23. Wang, A.J.; Zhang, Y.; Zhang, X.T. Fuel cost analysis of biomass power generation [in Chinese]. *Trans. CSAE* **2011**, *27*, 17–20.
24. Lai, C.M.; Ke, G.R.; Chung, M.Y. Potentials of food wastes for power generation and energy conservation in Taiwan. *Renew. Energy* **2009**, *34*, 1913–1915.
25. Ou, X.M.; Y, X.Y.; Zhang, X.L.; Liu, Z. Life-cycle analysis on energy consumption and GHG emission intensities of alternative vehicle fuels in China. *Appl. Energy* **2012**, *90*, 218–224.
26. Energy Saving and New Energy Vehicles Development Planning (2012–2020) [in Chinese]. Available online: http://www.gov.cn/zwgk/2012-07/09/content_2179032.htm (accessed on 22 May 2013).
27. Sun, L.Y.; Tian, Y.S.; Meng, H.B.; Zhao, L.X. Development of clean development mechanism (CDM) project of biomass densified biofuels in China [in Chinese]. *Trans. CSAE* **2011**, *27*, 304–307.
28. Ding, G.X. Study of Business Environment and Strategy of Qinhuangdao Garbage Power Plant [in Chinese]. Master's Thesis, North China Electric Power University, Baoding, China, 1 July 2011.
29. Huo, H.; Zhang, Q.; He, K.B.; Yao, Z.L.; Wang, M.C. Vehicle-use intensity in China: Current status and future trend. *Energy Policy* **2012**, *43*, 6–16.
30. Wang, H.K.; Fu, L.X.; Zhou, Y.; Du, X.; Ge, W.H. Trends in vehicular emissions in China's mega cities from 1995 to 2005. *Environ. Pollut.* **2010**, *158*, 394–400.
31. Neubauer, J.; Brooker, A.; Wood, E. Sensitivity of battery electric vehicle economics to drive patterns, vehicle range, and charge strategies. *J. Power Sources* **2012**, *209*, 269–277.
32. Michalek, J.J.; Chester, M.; Jaramillo, P.; Samaras, C.; Shiau, C.S.; Lave, L. Valuation of plug-in vehicle life cycle air emissions and oil displacement benefits. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 16554–16558.
33. Ou, X.M.; Yan, X.Y.; Zhang, X.L. Using coal for transportation in China: Life cycle GHG of coal-based fuel and electric vehicle, and policy implications. *Int. J. Greenh. Gas Control* **2010**, *4*, 878–887.
34. Cai, H.; Xie, S.D. Estimation of vehicular emission inventories in China from 1980 to 2005. *Atmos. Environ.* **2007**, *41*, 8963–8979.
35. IPCC. Stationary Combustion. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Gómez, D.R., Watterson, J.D., Americano, B.B., Ha, C., Marland, G., Matsika, E., Namayanga, L.N., Osman-Elasha, B., Saka, J.D.K., Treanton, K., Eds.; Cambridge University Press: Cambridge, UK, 2006; Volume 2, pp. 2:16–2:17.
36. Bo, Y.; Cai, H.; Xie, S.D. Spatial and temporal variation of historical anthropogenic NMVOCs emission inventories in China. *Atmos. Chem. Phys.* **2008**, *8*, 7297–7316.
37. Wang, L.T.; Zhang, Q.; Hao, J.M.; He, K.B. Anthropogenic CO emission inventory of Mainland China [in Chinese]. *Acta Sci. Circumst.* **2005**, *25*, 1580–1585.
38. Qin, J.F.; Zhang, Q.; Hao, J.M.; He, K.B. 2001–2005 China' s provinces (cities) estimation of atmospheric lead emissions from coal–fired [in Chinese]. *Guangdong Weiliang Yuansu Kexue* **2010**, *17*, 31–38.

39. Wang, Q.C.; Shen, W.G.; Ma, Z.W. The estimation of mercury emission from coal combustion in China [in Chinese]. *China Environ. Sci.* **1999**, *19*, 318–321.
40. Zhao, B.; Wang, P.; Ma, J.Z.; Zhu, S.; Pozzer, A.; Li, W. A high-resolution emission inventory of primary pollutants for the Huabei region, China. *Atmos. Chem. Phys.* **2012**, *12*, 481–501.
41. Tian, H.Z.; Hao, J.M.; Lu, Y.Q.; Zhu, T.L. Inventories and distribution characteristics of NO_X emissions in China [in Chinese]. *China Environ. Sci.* **2001**, *21*, 493–497.
42. Bond, T.C.; Streets, D.G.; Yarber, K.F.; Nelson, S.M.; Woo, J.H.; Klimont, Z. A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.* **2004**, *109*, D14203, doi: 10.1029/2003JD003697.
43. Wang, S.X.; Liu, M.; Jiang, J.K.; Hao, J.M.; Wu, Y.; Streets, D.G. Estimate the mercury emissions from non-coal sources in China [in Chinese]. *Environ. Sci.* **2006**, *27*, 2401–2406.
44. Tian, H.Z.; Hao, J.M.; Lu, Y.Q.; Zhou, Z.P. Evaluation of SO_2 and NO_X emissions resulted from biomass fuels utilization in China [in Chinese]. *Acta Sci. Circumst.* **2002**, *22*, 204–208.
45. Zhu, S.L. Study on emission factors of GHG and pollutants from rural stoves in developing countries. *Renew. Energy* **2004**, *114*, 16–19.
46. Li, X.H.; Wang, S.X.; Duan, L. Particulate and trace gas emissions from open burning of wheat straw and corn stover in China. *Environ. Sci. Technol.* **2007**, *41*, 6052–6058.
47. Hong Kong-Guangdong Joint Working Group on Sustainable Development and Environmental Protection (HG-JWGSDEP). *Air Emission Inventory Handbook for Pearl River Delta Region*; CH2M-IDC Hong Kong Ltd.: Hong Kong, China, 2005.
48. Sutton, M.A.; Dragosits, U.; Tang, Y.S. Ammonia emissions from non-agricultural sources in the UK. *Atmos. Environ.* **2000**, *34*, 856–869.
49. Wang, Z.X.; Pan, L.; Yang, F.; Liu, J. Thinking on achievements and problems of energy conservation and emissions reduction for power industry in China during the 11th Five-Year Plan [in Chinese]. *J. Environ. Eng. Technol.* **2012**, *2*, 81–89.
50. Di, X.H.; Nie, Z.R.; Zuo, T.Y. Life cycle emission inventories for the fuels consumed by thermal power in China. *China Environ. Sci.* **2005**, *25*, 632–635.
51. Weber, C.L.; Jaramillo, P.; Marriott, J.; Samaras, C. Life cycle assessment and grid electricity: What do we know and what can we know? *Environ. Sci. Technol.* **2010**, *44*, 1895–1901.
52. Shen, W.; Han, W.J.; Chock, D.; Chai, Q.H.; Zhang, A. Well-to-wheels life-cycle analysis of alternative fuels and vehicle technologies in China. *Energy Policy* **2012**, *49*, 296–307.
53. International Energy Agency. *World Energy Outlook 2007: China and India Insights*; IEA: Paris, France, 2006.
54. Silva, C.; Ross, M.; Farias, T. Evaluation of energy consumption, emissions and cost of plug-in hybrid vehicles. *Energy Convers. Manag.* **2009**, *50*, 1635–1643.
55. Siler-Evans, K.; Azevedo, I.L.; Morgan, M.G. Marginal emissions factors for the U.S. electricity system. *Environ. Sci. Technol.* **2012**, *46*, 4742–4748.