Environmental Implication of Electric Vehicles in China

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Today, electric vehicles (EVs) are being proposed in China as one of the potential options to address the dramatically increasing energy demand from on-road transport. However, the mass use of EVs could involve multiple environmental issues, because EVs use electricity that is generated primarily from coal in China. We examined the fuel-cycle CO_2, SO_2, and NO_x emissions of EVs in China in both current (2008) and future (2030) periods and compared them with those of conventional gasoline vehicles and gasoline hybrids. EVs do not promise much benefit in reducing CO_2 emissions currently, but greater CO_2 reduction could be expected in future if coal combustion technologies improve and the share of nonfossil electricity increases significantly. EVs could increase SO_2 emissions by 3−10 times and also double NO_x emissions compared to gasoline vehicles if charged using the current electricity grid. In the future, EVs would be able to reach the NO_x emission level of gasoline vehicles with advanced emission control devices equipped in thermal power plants but still increase SO_2. EVs do represent an effective solution to issues in China such as oil shortage, but critical policy support is urgently needed to address the environmental issues caused by the use of EVs to make EVs competitive with other vehicle alternatives.

1. Introduction

In order to cope with the oil security issue, many countries worldwide are making substantial efforts to reduce the dependence of their transportation sector on petroleum resources and yet fulfill the fuel demand of the transport (*1*−*3*). China faces the same challenges as other countries. Since the 1990s, China has been experiencing very rapid growth in vehicle population. The vehicle population in China was about 63 million by 2008, and it is projected to be 550−730 million by 2050 (*4*), 38−83% higher than that of the U.S. in 2050 (*5*). One important question raised is how to accommodate this large number of vehicles in terms of energy sources. Today in China one frequently proposed answer is electric vehicles (EVs), which could alleviate dependence on petroleum by using other energy sources such as coal and hydro. Now electric two-wheelers (E-2Ws) and three-wheelers are very popular in China. Some E-2W manufacturers are already producing three- or four-wheel fully enclosed EVs using the same battery technology as E-2Ws (*6*). Recently, China's largest electricity provider announced the construction of charging stations for EVs in Beijing, Shanghai, and Tianjin. Also, the successful demonstration of EVs in Beijing during the Olympic Games encouraged the promotion of EVs in China (*7*). In 2009, the Chinese government initiated a program named "Ten cities and Thousand Vehicles", which plans to select more than 10 cities and to introduce more than 1000 HEVs and EVs (primarily used as taxis and buses) in each of the selected cities in three years with government subsidy. Thirteen cities were selected to participate in this program (see Figure 1 for the location of these cities), and the number of cities is increasing. Nowadays, China is considered to be a very promising market for EVs.

The power of EVs is electricity from the grid. While EVs can offer attractive benefits in petroleum reduction, they could result in more CO_2 emissions than conventional vehicles because of the fact that the majority of electricity is generated from coal in China. Another concern associated with EVs is that they could increase emissions of criteria pollutants like SO_2 and NO_x because power plants are believed to be the largest contributor to China's SO_2 and NO_x emissions (*8*).

In view of this, we evaluate the environmental impacts of EVs by examining their potential CO_2, SO_2, and NO_x emissions in China from a fuel-cycle point of view and comparing them with those of conventional gasoline internal combustion engine vehicles (ICEVs) and gasoline hybrid electric vehicles (HEVs) on a per-kilometer basis. China is in a period of rapid change in composition and combustion technologies of power plants, so we examine two time points - current (2008) and future (2030). The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model (*9*), which is developed by Argonne National Laboratory, is adjusted with data for China and employed for this work to simulate the fuel-cycle emissions of the vehicles.

2. Generation Mix

CO_2 emissions of EVs are dependent on the CO_2-intensity of the generation mix for charging EVs, and their SO_2 and NO_x emissions depend on not only the generation mix but also the emission control technologies in thermal power plants. China consists of six large interprovincial power grids, which are named for the regions they serve: Northeast China, North China, Central China, East China, Northwest China, and South China. The six grids are not strictly independent, as one grid can buy power from another grid if needed. Figure 1 presents the generation mix of these six power grids in 2008 (*10*). Coal and hydro are the two major energy sources of power generation in China, and the split between them varies by region. Coal-based power dominates in the Northeast and North generation mixes, with a proportion as high as 95−98%. The Northwest, Central, and South mixes

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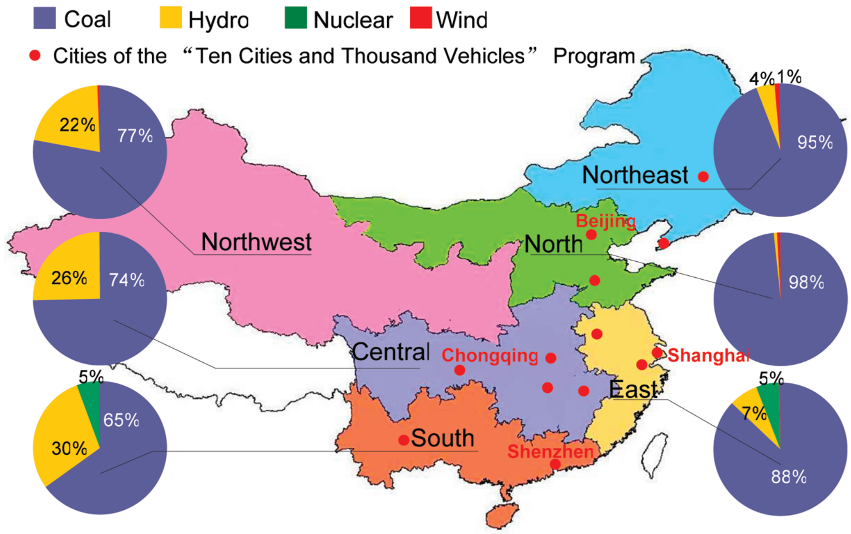

FIGURE 1. Generation mix of the six interprovincial power grids in 2008.

consist of more than 22% hydro power, although coal is still the majority. The South and East grids also have 5% nuclear power.

In the U.S., the electricity consumption has remained stable in recent decades. The annual increase rate of electricity consumption in the U.S. was 0.5% during 2000 and 2009 and is projected by the U.S. Energy Information Administration (EIA) to be 0.8% during 2005 and 2035 (*11*). U.S. studies have argued that the increasing penetration of EVs (or plug-in hybrids) may require additional new power capacity, and the energy and environmental impacts of EVs should be evaluated based on the marginal generation mix (*12*−*14*), which is reasonable because EVs will be the primary reason for the new capacity. But it is different for the case of China. The annual increase rate of electricity consumption in China was 13.5% during 2000 and 2007 (*15*) and is projected to be 5% during 2010 and 2030 (*16*). The growth of generation capacity in China is driven by the increasing electricity demand for industrial, residential, commercial, and transportation sectors (*16*−*18*). The potential growth of EVs is one of the driving forces in China, but it will not be stronger than the growth in other sectors. Based on some projections for Chinese national electricity supply (*16*−*18*) (EVs' potential demand was not taken into account in these projections), we estimate that the spare capacity from newly added plants should always be able to fulfill the new demand from EVs for now and the future (see Table 1) (*10, 14, 16*−*22*), which means that EVs in China will not be able to cause major change in power generation capacity even with the most aggressive scenario of all light-duty passenger vehicles on road as EVs by 2030 (which is far from possible), and thus will not produce marginal effects on power generation capacity. In this work, therefore, we estimate EV emissions on the basis of the average generation mix rather than the marginal generation mix.

With respect to China's potential new plants built in the future, since China has limited resources of oil and natural gas, the major fossil fuel used in China's new plants will still be coal. In addition, China is planning to enhance the fraction of nonfossil generating capacity by expanding hydro and nuclear power and developing new plants based on renewable energy resources such as wind and solar. Obviously, the fraction of coal-based electricity is a critical parameter for evaluating the environmental impacts of EVs. Numerous studies worldwide have made projections of the future options for power supply in China. EIA and the International Energy Agency (IEA) projected that coal would remain the predominant fuel in generation, and 78−81% of electricity used would be drawn from coal by 2030 (*17, 18*). Domestic institutes are more optimistic on this issue, and they project that the share of coal power could be reduced to 72% by 2030 (*16*) or an even more ambitious target −65% by 2020 (*23*).

CO_2 Emissions. The energy efficiency of coal-fired power plants in China is currently about 32−34% (*16, 24*). We estimate the CO_2 emission rate of coal-fired power plants to be 1002 g CO_2/outlet-kWh, according to the low heating values and carbon content of coal, the proportion of each type of coal used in power generation, and the electrical transmission losses (*25*−*27*), as shown in Table S1 (where "S" refers to the Supporting Information). We assume that the coal composition would be unchanged in the future.

There are no reports available on HEVs' or EVs' on-road energy efficiencies in China, so we adopted the ratios of fuel efficiency values of HEVs and EVs to those of conventional vehicles in the GREET model in order to compare the three types of vehicles on the basis of the same weight and driving conditions. The fuel consumption rates of EVs, ICEVs, and HEVs are presented in Table 2 (*28, 29*). The density of gasoline is 0.732 L/kg, and its carbon ratio is 85.5% (*30*). The GREET model shows that power generation is responsible for 99% of total fuel-cycle CO_2 emissions of EVs powered by coal-based electricity, suggesting that power generation is by far the dominant contributor to CO_2 emissions of EVs.

Figure 2 presents the current fuel-cycle CO_2 emissions of EVs powered by the six regional grids and coal-based electricity as well as the CO_2 emissions of gasoline ICEs and HEVs. As shown, the CO_2 emissions of EVs vary significantly by region because of the different regional generation mixes. EVs powered by coal-based electricity could increase CO_2 emissions by 7.3% compared to gasoline ICEVs. Consequently, EVs in the regions where coal contributes a high proportion of power generation (the Northeast, North, and East regions) show very limited benefit in CO_2 reduction or could even increase CO_2 emissions (such as in the North region where Beijing is located), compared to ICEVs. However, in regions that possess about 35% nonfossil electricity (the South regions), EVs could have the same CO_2 emission level as gasoline HEVs, which is 30% lower than gasoline ICEVs. So, the choice of location for using EVs could significantly affect the CO_2 reduction benefit, from positive to negative. In this sense, the regions with smaller fractions of coal-based electricity should be the priority EV markets, such as the South, Central, and Northwest regions. For example, of the cities that are chosen for the "Ten Cities and Thousand Vehicles" Program (see Figure 1), EVs are a good choice for Chongqing (Central) and Shenzhen (South), but

TABLE 1. Number of EVs That Could Be Supported by the Generation Capacity

	2008	2030
total generation capacity (GW)[a]	793	1500−1800
usable capacity for charging EVs (GW)[b]	40	75−90
energy efficiency of EVs (kWh/100 km)[c]	18−25	12−20
kilometers traveled per year	18,000[d]	12,000[e]
maximum number of EVs (million)	77−107	273−548
number of light passenger vehicles (million)[f]	30	186−217

[a] Current capacity value is from ref *10*, future values were projected by refs *16*−*18*. [b] Ideally, recharging of EVs should take place at night-time. Stephan et al. estimated that night-time spare capacity is 9−20% of net generation for charging plug-in hybrids in the U.S (*14*), and this value could be larger for China because the power grid has larger peak-to-valley differences (*19*). Conservatively, 5% of total generation capacity is assumed as the maximum that EVs could utilize in China. [c] Estimated by authors based on the commercial reports on performance of current EVs. The ranges represent the possible maximum and minimum fuel economy values of all sizes of EVs in China to estimate how many electric vehicles could be supported by night-time spare capacity. [d] The assumption is made on the basis of survey results reported in ref *20*. [e] According to Wang et al. (*21*), the level of vehicle use in China in 2030 would be the same as the current level in European countries. Vehicle use could be reduced in the future, because China is in a period of rapid growth in vehicle stock, and when people own more cars, each individual car would be used less intensively. Please refer to ref *21* for a detailed explanation for this assumption. [f] Current value was provided by ref *22*; future values were projected by ref *21*.

HEVs would be a better choice than EVs for Beijing (North) and Shanghai (East) in terms of CO_2 emission reduction.

China is planning to decrease the carbon intensity of electricity generation by increasing the share of nonfossil power capacity, and therefore EVs could be expected to offer greater CO_2 savings in the long run. Figure 3 projects the CO_2 emissions of EVs as a function of the fraction of coal-based electricity. The energy efficiency of coal-fired power plants is assumed to rise to 40% in 2030 (*16*). The fuel consumption rates of the three types of vehicles are also assumed to improve by 2030 (see Table 2). As shown in Figure 3, the theoretical CO_2 breakeven point between EVs and ICEVs is 87% coal power, which means that EVs would have a CO_2-reduction advantage over gasoline ICEVs if the coal fraction is below 87%. The 78−81% coal fractions projected by EIA and IEA (*17, 18*) translate to a CO_2 reduction of 10% compared to ICEVs. Under the more aggressive projections made by Chinese institutes (65−72%) (*16, 23*), the CO_2 emissions of EVs are 18−25% lower than ICEVs, but 7−18% higher than HEVs. With the right locations chosen, the CO_2 reduction-benefit of EVs would be larger. For instance, the Northwest, Central, and South regions, which have plenty of hydro and wind resources, are the key regions to develop nonfossil power in China. If their nonfossil electricity share reaches 50% by 2030, EVs operated in these regions could achieve a very impressive CO_2 reduction of 18% compared to HEVs. Since gasoline HEVs combust petroleum-based fuel, EVs would be more attractive than HEVs with almost zero petroleum use and lower CO_2 emissions. As shown in Figure 3, the benefit could be enlarged by higher energy efficiency of power plants. One percentile point improvement in energy efficiency will bring 2−5% more CO_2 reduction compared to HEVs. Carbon capture and sequestration (CCS) technologies could help to earn more carbon credits for EVs, but they are subject to many technical uncertainties.

SO_2 Emissions. Power plants contribute more than 97% of fuel-cycle SO_2 emissions of EVs charged with coal-based electricity according to the results from GREET. The sulfur content of coal and the penetration of flue-gas desulfurization (FGD) systems are two important factors influencing SO_2 emissions from coal-fired power plants. The sulfur content varies significantly across regions in China, from as low as 4.2 g/kg of coal in the northeast region to as high as 14.7 g/kg in the central region (*31*) (see Table S2). FGD is typically able to remove 85% of sulfur emissions. All units built after 2004 and a large fraction of existing ones are required to be installed with FGD under Chinese law. In 2005, the capacity of units with FGD was only 10% of the total capacity of coal-fired plants (*32*). With the aggressive target set by the Chinese government to reduce national SO_2 emissions by 10% from 2005 to 2010, the FGD penetration in the power sector is rising rapidly, and it was reported to be 60% by the end of 2008 (*32*). Table S2 provides FGD penetration estimates for the six regions in China in 2008 (*32*). We assume that all coal-fired power plants would be installed with FGD by 2030. Coal washing is another technology that can reduce SO_2 emissions by 40%, but it is not widely applied in China yet. The current fraction of washed coal used in power generation is about 2.5% in China (*15*). The share of coal-based electricity in the six regional grids was assumed to range from 50% to 80% in 2030, based on the discussion above.

During recent years, the sulfur content regulation for vehicular fuels had lagged behind the vehicle emission standards in China. The sulfur content of gasoline was 500 ppm in China (*33*) except in a few large cities (for example, the sulfur content of gasoline in Beijing was 50 ppm after 2008). However, China started to remedy this problem. China just issued a new regulation to require the sulfur content of gasoline to be below 150 ppm (the Euro III fuel standard) by the end of 2009. The Euro V emission standard is expected to be implemented within 10 years in China, so we assume that the sulfur content would decrease to 10 ppm (the Euro V fuel standard) nationwide by 2030 (see Table 2). According to the GREET result, the share of vehicle SO_2 emissions out of total fuel-cycle emissions of ICEVs and HEVs decreases from 33% to 2% as the sulfur content of gasoline declines from 500 ppm to 10 ppm.

Figure 4 illustrates the fuel-cycle SO_2 emissions of EVs under the six regional mixes, compared to those of gasoline ICEVs and HEVs. As shown, powered by the current electricity mix, EVs could cause a significant increase in SO_2 emissions by 3−6 times relative to ICEVs and 5−10 times relative to HEVs. Gasoline vehicle exhausts contribute very little to total national SO_2 emission (0.2% in 2006) (*8*), but if they are replaced by EVs, the contribution would rise to 2−4% (the SO_2 emissions of EVs are 9−18 times the emissions of ICEVs at vehicle operation stage). EVs will pose a new challenge to China's target of controlling the total amount of SO_2 emissions. In the future, even with more advanced combustion technologies and 100% FGD penetration, the SO_2 emissions of EVs would still be 1.3−5 times the emissions of ICEVs and 3−7 times the emissions of HEVs. Even with an additional 100% coal washing, which is infeasible in practice, it is not possible to bring the SO_2 emissions of EVs down to the level of ICEVs and HEVs for most regions in China.

NO_x Emissions. NO_x emission rates in coal-fired power plants vary by boiler size, level of NO_x control technology, and coal quality. The average NO_x emission factors of coal-fired power plants in China declined gradually from 8.9 g/kg of coal in 1995 to 7.4 g/kg of coal in 2004 as a result of the increased share of large boilers and the spread of low-NOx burner (LNB) technology (*26*). The NO_x removal efficiency of LNB was reported to be 30% (*34*). The LNB-installed units

TABLE 2. Assumptions Associated with Fuels, Fuel Efficiency, and Emission Factors of Vehicles

		gasoline ICEVs	gasoline HEVs	EVs
fuel consumption rates	2008	8 L/100 km (*28*)	5.6 L/100 km[b]	24 kWh/100 km[b]
	2030	5.5 L/100 km[a]	3.9 L/100 km[b]	20 kWh/100 km[c]
sulfur content of gasoline, ppm	2008	500	500	-
	2030	10	10	-
NO_x emission factors[d], g/km	Euro III	0.15	-	
	Euro IV	0.08	-	
	Euro V/VI	0.06	-	

[a] Future fuel economy of ICEVs is estimated on the basis of policy tendency in China. [b] Fuel economy values of HEVs and EVs are calculated by using the fuel economy ratios of HEVs and EVs to ICEVs in the GREET model. The possible increased congestion in the future would affect the fuel economy of the three vehicle technologies in different ways, but the difference in the impacts of potential congestion on their fuel economy is very small (*29*) and thus is neglected in this work. [c] The improvement in fuel economy of EVs in future refers to the estimation in the GREET model. [d] Here we used the standard limit values instead of on-road emission factors. According to the on-board vehicle emission measurements conducted by Tsinghua University during 2008–2009 (unpublished data), the on-road NO_x emission factor of Euro III cars was 0.11 ± 0.05 g/km, which is close to the standard limit values.

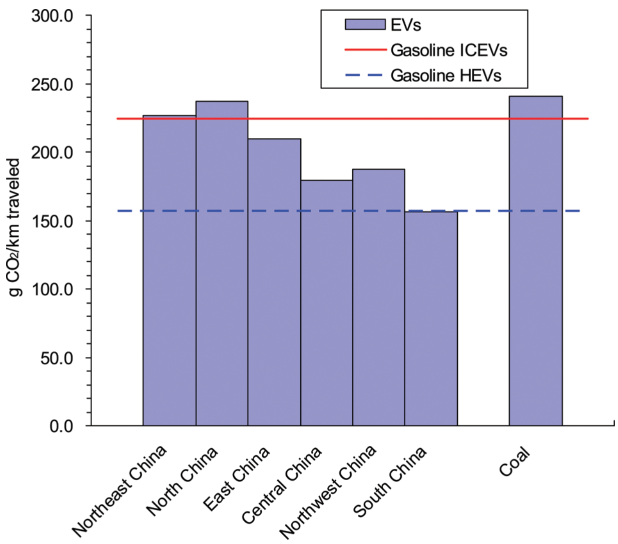

FIGURE 2. Fuel-cycle CO_2 emissions of EVs with the current electricity generation mix in China.

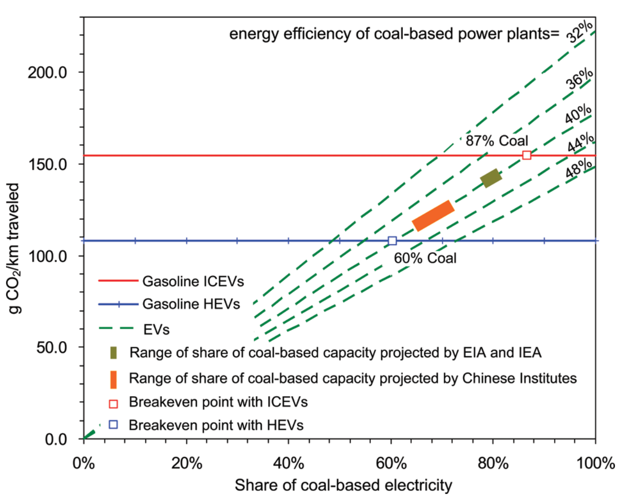

FIGURE 3. Future fuel-cycle CO_2 emissions of EVs as a function of the fraction of coal-based electricity.

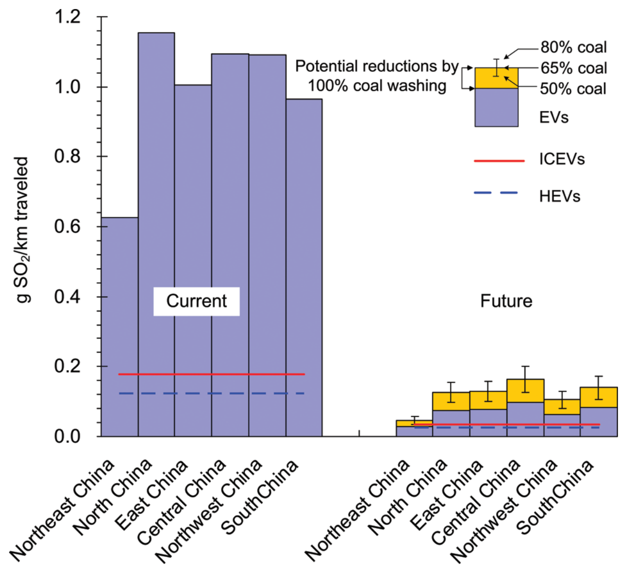

FIGURE 4. Fuel-cycle SO_2 emissions of EVs compared to those of gasoline ICEVs and HEVs in China.

accounted for 62% of the total capacity in 2005, and it was estimated to increase to 77% by 2010 (*35*). As new plants are required to install LNB, the LNB penetration is likely to reach 90% or even more by 2030, and by then, the NO_x emission factor of coal-fired power plants could be as low as 5 g/kg. Advanced technologies such as selective catalytic reduction (SCR) could decrease NO_x emissions even more significantly. At present, the penetration rate of SCR in China was estimated to be lower than 10% (*34*). The removal efficiency of SCR varies from 40% to 90% in China (*34, 36*). In this work, we assume that the removal efficiency of SCR could reach 70%–90%, and for the purpose of sensitivity analysis, 100% removal efficiency of SCR for NO_x is also taken into consideration as a bounding case.

China is implementing the Euro III vehicle emission standard nationwide (except for some large cities where Euro IV is already in effect, such as Beijing), and the Euro IV and V standards are expected to be in place within 10 years. By 2030, gasoline vehicles in China would have already met Euro VI or even stricter standards. Table 2 shows the emission factors of gasoline vehicles under the Euro III, IV, and V/VI standards. Table S3 summarizes the adjusted parameters in the GREET model and other key variables.

Figure 5 presents the current fuel-cycle NO_x emissions of EVs, and the future emissions related to the penetration of SCR under the three generation mix scenarios, in which the shares of coal plants are 80%, 65%, and 50%, respectively. As shown, if charged by the current electricity mix, EVs would double the NO_x emissions of Euro III gasoline vehicles. By 2030, EVs will still increase NO_x emissions by 16–86% compared to Euro V gasoline vehicles if the SCR penetration is zero. If the application ratio of SCR reaches 20%, EVs charged by the generation grid with 50% coal-based electricity

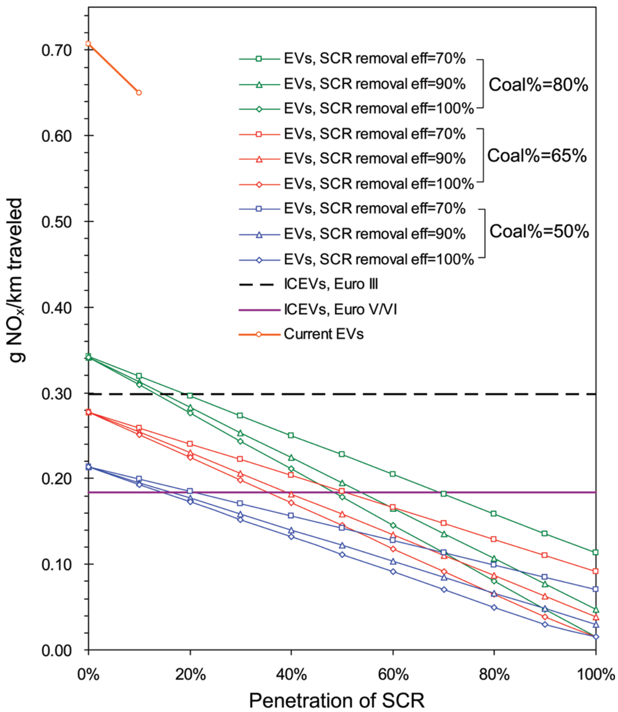

FIGURE 5. Fuel-cycle NO_x emissions of EVs compared to those of gasoline ICEVs and HEVs in China.

could have lower NO_x emissions than gasoline vehicles. EVs charged by higher coal-intensity generation grids would require higher SCR penetration, e.g., electricity with 80% coal will need at least 44% SCR penetration. The widespread application of SCR will be the key for EVs to compete with gasoline vehicles in terms of NO_x emissions.

Implications for EVs. EVs do represent a very promising solution to energy issues due to their solid merits in substituting for petroleum fuels. But for now the high pollution levels of coal-fired power plants will trade off EVs' potential energy benefits in China. Note that the emissions associated with the construction of EV recharging infrastructure were not taken into consideration in this calculation, which could make EVs even more unfavorable as compared to ICEVs and HEVs. In addition, other environmental impacts associated with coal-fired power plants, such as mercury emissions (by a rough estimation, EVs could cause 0.01 mg of mercury emissions for every kilometer driven) (*37*), may become environmental concerns for EVs too.

China is experiencing explosive growth in its vehicle population, and it is projected to exceed the U.S. within 20 years (*4*). Now, policy makers have to consider what types of energy sources will be used to power these vehicles. The energy-related decisions will inevitably involve compromise among multiple objectives. As analyzed in this work, it is the current high emissions of power plants that are going to make EVs a less favorable option than other alternatives in China, such as HEVs, which are more environmentally friendly, more commercially mature, and less cost-intensive. Currently, in the Chinese vehicle market, taking products of the BYD Company as an example, HEVs (20,000−25,000 U.S. dollars) are much more expensive than conventional ICEVs (8000−10,000 U.S. dollars) of equivalent size, but the price of EVs is even higher (>30,000 U.S. dollars). The costs and benefits of different technological options need to be further explored.

In order to make EVs an attractive option for China, special strategies for emission control of coal-fired power plants will be required as the development of EVs progresses. The government should nominate appropriate places with low carbon electricity for the introduction of EVs. Also, advanced coal combustion technologies, as well as technical measures to remove pollutants (such as SCR and coal cleaning), though cost-intensive, but not technically difficult any more, should be applied widely with the financial support of the government, especially considering the fact that there would be huge cobenefits to human health and other environment issues if the performance of power plants was to be improved. It should be noted that because power plants have a longer lifetime than vehicles, the technology shift in the power sector could be slower than that of the transportation sector. Therefore, coordinated policies between these two sectors are needed to reinforce EVs' progress toward a cleaner future.

The good news is that China has shown a firm commitment to prompt renewable energy use, improving energy efficiency and reducing pollutant emissions from power plants. Great efforts have been, and will continue to be, made by the Chinese government to reduce the emissions of power plants, such as setting an aggressive target to reduce national SO_2 emissions by 10% from 2005 to 2010 by installing FGD and closing a large number of small generating units. More actions are under discussion in the "Twelfth Five-Year Plan (2011−2015)" to reduce NO_x emissions. As the mass use of EVs will place further pressures on power plants, there is an urgent need to accelerate this process.

Another important issue worth mentioning is that EVs would probably improve urban air quality by replacing gasoline vehicles, because vehicle exhausts have become the primary contributor to emissions and ambient concentrations of air pollutants in many Chinese cities (*38*). Power plants, especially the new ones, are usually located farther away from urban centers than vehicle tailpipes. From the point of view of health impacts, urban emissions should be one of the indicators of the environmental impacts of EVs (*39*). The next step of our work will be to better understand the impacts of EVs on urban air quality by integrating life-cycle emission inventories of the various vehicle technologies into an air quality modeling framework for Chinese cities.

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Supporting Information Available

Data on specification of coal used in China, FGD penetration in Chinese coal-based power plants, and adjusted parameters in the GREET model and other key variables. This material is available free of charge via the Internet at http://pubs.acs.org.

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