An integrated assessment of emissions, air quality, and public health impacts of China's transition to electric vehicles

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Abstract

Electric vehicles (EVs) are a promising pathway to providing cleaner personal mobility. China provides substantial supports to increase EV market share. This study provides an extensive analysis of the currently unclear environmental and health benefits of these incentives at the provincial level. EVs in China have modest cradle-to-gate CO_2 benefits (on average 29%) compared to conventional internal combustion engine vehicles (ICEVs), but have similar carbon emissions relative to hybrid electric vehicles. Well-to-wheel air pollutant emissions assessment shows that emissions associated with ICEVs are mainly from gasoline production, not the tailpipe, suggesting tighter emissions controls on refineries are needed to combat air pollution problems effectively. By integrating a vehicle fleet model into policy scenario analysis, we quantify the policy impacts associated with the passenger vehicles in the major Chinese provinces: broader EV penetration, especially combined with cleaner power generation, could deliver greater air quality and health benefits, but not necessary for climate change mitigation. The total value to society of the climate and mortality benefits in 2030 is found to be comparable to a prior estimate of the EV policy's economic costs.

Synopsis

The health and climate benefits of China's electric vehicle policy are comparable to the associated societal economic costs.

Keywords

Electric vehicles, Life-cycle assessment, Cost-benefit analysis, Scenario analysis, Fleet modeling, Environmental impacts

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1 Introduction

Growing global awareness of the environmental impacts of combustion is accelerating electric vehicle (EV) adoption; over 50% of the global EV sales – a total of 1.98 million – in 2018 were in China[1]. However, in China where coal-fired power generation has been the backbone of the electricity supply, vehicle electrification offers clear national energy security benefits but unclear climate and air quality benefits. EVs avoid tailpipe emissions of CO_2 and air pollutants from fossil fuel combustion but may lead to greater emissions from the upstream stage of electricity generation. To better understand the environmental benefits of vehicle electrification, life cycle analysis is used to compare emissions per distance driven among different types of vehicle technologies[2–5]. Several studies have incorporated bottom-up fleet models to assess the aggregate life cycle energy demand and CO_2 emissions from China's road transport, at the national level[6–9] and regional/provincial level[10–13].

With increasing public concern regarding air quality, other studies investigated life cycle air pollutant emissions per distance driven between EVs and ICEVs in China[14–19]. For the aggregate impacts of fleet electrification in China, Liang et al.[20] quantified the air quality and health benefits at the regional level, focusing on the mixed impacts of the decrease in vehicle tailpipe emissions and the increase in power plant emissions during the shift from liquid fuels to electrification. However, Liang's study ignored the changes in the upstream emissions (also called well-to-tank emissions) from gasoline production, which may introduce significant bias in their calculations; this is because China's gasoline refineries burn coal as the major process fuel. In the absence of strict emission control standards on those coal burners, the gasoline refining process produces substantial emissions[18]. To the best of our knowledge, the trends of vehicle market size, emissions, and health impacts at the provincial level under various fuel-efficiency and EV policies as well as clean electricity policies have not yet been extensively studied.

Considering that China is the global largest vehicle market, it is of timely importance to conduct a systematic and comprehensive evaluation of the various benefits and costs associated with EV policies. We use "EV policies" this term to include the dual-credit policy[21] (or 'EV mandate'), city-level car ownership restriction policies that often include exemptions for EVs (or 'quota policy')[22,23], and vehicle tailpipe emission standards. This work builds on previous studies that assessed effects of EV policies on the overall Chinese private passenger vehicle market[24] and the national and global EV battery market[25], and estimated the direct economic cost of the policies[26]. The modeling framework established in this study captures how EV policies alter private passenger vehicle ownership demand (which accounts for about 82% of all vehicles in China[27]) and its corresponding environmental externalities across spatial scales (from provincial to national) and time horizons (from 2017 to 2030); for details see Supplementary Information (SI) 1. This paper, first, evaluates how the life cycle emissions of comparable passenger vehicles with different powertrains (including ICEV, hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), and pure battery electric vehicle (BEV)) vary across provinces. Second, we explore the impacts of the EV policies on the private passenger vehicle market, oil demand, climate change, and air quality (and some of its public health consequences) in major Chinese provinces, considering geographical and socioeconomic differences in various provinces. Third, we conduct a sensitivity analysis by considering the uncertainties in projecting future low-carbon mobility transition pathways (as described below in the section of *Scenarios Considered in this Study*). Note that only 29 provinces (Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Hunan, Guangdong, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang) are modeled in the present work because we have access to consistent data on all of them; these provinces represent the great majority of China's population and economy, and are responsible for most of its emissions.

Scenarios Considered in this Study

Our base scenario, called "*EV SCENARIO*", assumes essentially full implementation of current EV policies, including the EV mandate and quota policies, and mandated improvements in fuel economy of passenger cars. This scenario has been used in prior works focused on the vehicle market and economic costs[24,26]. In this realistic scenario based on announced policy, the number of private cars in China is projected to reach 302 million by 2030, with 37% of new car purchases in 2030 being EVs[24]. In the present work, we derive the future provincial EV sales based on "open market index of new energy vehicle"[28], with the assumption that the provinces that are currently leading the national EVs sales will continue to dominate through 2030.

To assess the impacts of the new EV policy, we compare the *EV SCENARIO* with an alternative scenario called "*NO EV POLICY COUNTERFACTUAL SCENARIO*" – representing a future in which nearly 100% of private vehicles are conventional ICEVs through 2030. In this counterfactual scenario, existing vehicle emission standards and fuel consumption rates stay the same, and both the EV mandate and city-level EV quota policy are dropped. The vehicle market and economic costs in this counterfactual scenario were analyzed in prior papers[24,26]. In this less-regulated scenario, the total number of private vehicles in China is projected[24] to rise to 385 million by 2030.

In both of these scenarios, emissions intensity of the electric grid is assumed to be exactly the same, using province-level emission factors derived from 2017 power plant data[29–31]. However, in reality emissions intensity of electricity generation is projected to decrease between now and 2030[5], and the synergies between this improvement and the deployment of EVs are explored in other scenarios. Details on emission intensity of power grid are given in SI 6.

While this study mainly focuses on the environmental impacts of *EV SCENARIO* compared to *NO EV POLICY COUNTERFACTUAL SCENARIO*, we also examine the sensitivity of *EV SCENARIO* to the underlying assumptions by designing various scenarios (well-defined in Table S9): *Fewer Car Scenario* (i.e., same settings as *NO EV POLICY COUNTERFACTUAL SCENARIO* except for the car stock) is designed to distinguish the impacts of diminished vehicle market size from that of others like cleaner ICEV/HEV and EV adoption. Other scenarios designed to assess the exclusive benefits of various low-carbon mobility transition pathways include *Cleaner ICEV/HEV Scenario* (i.e., same conditions as *EV SCENARIO* but with no EV; all the cars on the road by 2030 are ICEVs and HEVs with higher fuel efficiency and less emissions), *EV-Homo Scenario* (i.e., EV sale market share by 2030 across provinces is homogeneous), *EV-Double Scenario* (i.e., EV penetration rate is doubled compared to *EV SCENARIO*), *EV-REN Scenario* (i.e., same conditions as *EV SCENARIO* but combined with cleaner power grids—driven by the increasing ultra-low emissions (ULE) standard compliance rate and expanding renewable energy generation).

2 Methods

2.1 Life cycle emissions comparison

The comparison of per-km life cycle emissions is based on a reference set of compact 5-seat passenger vehicles, which were derived by taking the average of the selected best-selling comparable cars with the model year 2017 in our previous study[26] (summarized in SI 2).

We assume a nominal lifetime distance traveled of 150,000 kilometers for all vehicles. However, for EVs, battery lifetime could differ from vehicle lifetime; in this comparison, we assume EV battery replacement happens once during the vehicle lifetime. Estimated CO_2 emissions from vehicle and battery manufacture are provided in Table S1 and the related estimation methods are given in SI 6.6. Emissions from vehicle maintenance and end-of-life disposal are negligible compared to emissions from vehicle production and operation[32] and thus are neglected in this analysis.

2.2 Private vehicle fleet market

The car stock and sales model at the national level[33] is briefly described below, and the impacts of the dual-credit policy on national fleet size projection were shown in our previous study[24]. For fleet size projection, this study disaggregates the existing national-level model by provinces for higher granularity, develops a gravity-based migration model to capture the future people flows across provinces, but also incorporates the impacts of city-level car ownership restriction policies on China's provincial car fleet (SI 4).

Car sales were decomposed into new-growth purchases (associated with increases in car ownership due to rising income; also called first-time purchases) and replacement (for scrapped cars). The split between these two segments determines the maturity level of the auto market: in a mature car market, most car purchases are replacing retired vehicles.

2.3 Vehicle use intensity

Vehicle use intensity, expressed as vehicle kilometer traveled (VKT), is one of the key parameters determining the emissions of the vehicle fleet. In the absence of officially released data on VKT in China, we estimate vehicle use intensity trend as a function of car ownership level based on the historical nationwide gasoline consumption, on-road fuel consumption rate, and vehicle fleet breakdown by vehicle age in China (SI 5). We find that the annual VKT in provinces/province-level cities having higher per-capita ownership levels (usually with higher economic development) is lower than the others. This phenomenon could be explained by several aspects: firstly, multicar households are more and more common as the household income grows, causing VKT per vehicle to decrease assuming that their demand for vehicle use does not increase linearly with the number of vehicles in the household; secondly, multiple traffic control measures have been enforced in major cities across China; thirdly, public transportation has been promoted in big cities having severe traffic congestion, providing good alternatives to personal car travel.

2.4 Emission factors

This study calculates the impacts on oil consumption and emissions (including CO_2, CO, VOC, NO_x, SO_2, primary $PM_{2.5}$) due to EV policy implementation from 2017 to 2030. The year 2017 is chosen as the base year since this is the latest available data year for power grid emission factors (EFs). All the needed information to compute WTW emissions are summarized below and detailed in SI 6.

2.4.1 Electricity generation

To balance the electricity supply and demand in grid operation, there are daily electricity transmissions between regional grids in China—mainly from west to east and from north to south. Impacts of this inter-provincial transmission on the provincial grid carbon intensity are found to be non-negligible (Figure S7), especially for Beijing, Chongqing, Shanghai, and Guangdong. Thus, we take inter-provincial electricity transmission into account when examining the climate change mitigation potentials of vehicle electrification. For the future improvement in the carbon intensity of the electricity sector in *EV-REN SCENARIO*, we follow the expected decarbonization rates at the regional level that were documented in Shen et al.[5] (SI 6.1): at the national level, the carbon intensity of the power grid is projected to decrease from 604 to 464 gCO_2/kWh from 2017 to 2030.

Tang et al.[31] measured power plant emissions and found that China's power sector's emissions of SO_2, NO_x, and PM dropped substantially due to the introduction of ULE standards in 2014. Considering that Tang et al.[31] had access to an unprecedented wealth of emission data from continuous monitoring devices compared to any previous estimates[34–36], we take their 2017 estimated results as the base year EFs, and project future region-level thermal power plants' air pollutant EFs by modeling the relationship between emissions and ULE compliance rate for *EV-REN SCENARIO*. In addition to the increasing ULE compliance rate, we also take the expanding renewable energy into account when computing the future air pollutant EFs of electricity generation in *EV-REN SCENARIO* (SI 6.2). Note that all the EFs of electricity generation remain unchanged from 2017 to 2030 in *EV SCENARIO*.

2.4.2 Gasoline-powered vehicles

Based on China's "Technology roadmap for energy-saving and new energy vehicles", in *EV SCENARIO*, HEVs—belonging to energy-saving vehicles—are expected to start being adopted more widely, reaching a vehicle sales market share that is 50% more than that of ICEVs by 2030 (i.e., HEVs with a market share of 36% and ICEVs with a market share of 24%). The average on-road fuel consumption rate of new gasoline vehicles will be 5.0 L/100km by 2030. Driving conditions affect fuel consumption significantly; we apply the fuel consumption index[37] to capture the real-world differences in fuel consumption levels across provinces in our calculations (SI 6.4).

Tailpipe air pollutant EFs of gasoline-powered vehicles are affected by vehicle technology, climate, temperature, driving condition, fuel quality (e.g., sulfur content), and so on. This study derives provincial-level on-road air pollutant EFs based on a framework developed by Tsinghua University and the Chinese Academy of Environmental Sciences[38] (SI 6.5).

2.5 GEOS-Chem air quality model and health impact assessment

We model air quality and health impacts in each scenario following the approach described in Chossière et al.[39] and summarized in SI 7. For each scenario, monthly emissions derived from the MEIC[40] and CEDS[41,42] emissions inventories are input into the GEOS-Chem air quality model[43–46] and configured at run-time using the HEMCO module[47]. We use MERRA2 meteorology[48] for the year 2017 to drive the simulation (see SI 7). Health impacts are estimated using surface-level $PM_{2.5}$ and ozone concentrations. This study estimates changes in mortality and morbidity impacts. Surface-level concentration of $PM_{2.5}$ and ozone are combined with population data to estimate exposure.

2.6 Monetization of CO_2 emission reduction and avoided health damage benefits

The economic benefits of reduction in CO_2 emission are calculated based on *social cost of carbon* (SCC), a measure of the long-term damage done by a metric ton of CO_2 emissions in a given year. Considering that the country-level SCCs are more specific, this study applies the country-specific data—US$24 for China[49]. The economic benefits of reduction in premature death are computed based on *value of statistical life* (VSL), an indicator of *willingness to pay* (WTP) to avoid mortality risks. In the absence of sufficient local empirical studies for health cost estimation in China at the provincial level, we take the local VSL estimation in Chengdu, China in 2016 as the baseline[50] and apply a benefit-transfer approach[51] (SI 8.1). We estimate the uncertainty in monetary benefits of human health benefits and life-cycle CO_2 reductions by using different income elasticities of health cost (base case 0.8, ranging from 0.4[52] to 1[53]) and SCC (base case US$24, ranging from $4 to $50[49]).

3 Results and discussion

3.1 Current emissions for vehicles with different powertrains

Given the technical parameters of the reference vehicles shown in Table S1, we estimate CO_2 emissions per kilometer for vehicles with different powertrains based on the current (i.e., base year 2017) electricity generation and transmission in China. Figure 1(a) shows that EV emissions per km are approximately 71% of the emissions of comparable ICEVs. Increased emissions from battery and fuel (electricity) production are offset by increased powertrain efficiency. Second, HEV emissions per km, on average, fall between ICEVs and EVs. However, the carbon footprint benefits of EVs relative to ICEVs are uncertain, mainly depending on the power grids used to recharge the EVs. Error bars for EVs represent the variation among provinces in CO_2 intensity of electricity generation. Third, PHEVs and BEVs have similar carbon footprints under the current situation in China. In Figures 1 and 2, we use HEV emissions as the reference because in future scenarios with strong fuel-economy policies, we expect HEV to be the dominant vehicle type.

Figure 1(b) presents how the ratio of per-km BEV life cycle emissions to per-km HEV life-cycle emissions varies across major Chinese provinces. In the northern and northeastern provinces such as Inner Mongolia, Jilin, Hebei, and Shanxi, the carbon footprints of BEVs exceed those of HEVs by more than 10%; this is due to the fact that the power grids in these regions rely heavily on fossil fuels (mostly coal). On the other hand, BEVs driven in the southwestern provinces where hydropower accounts for a significant portion in the electricity mix, such as Yunnan, Sichuan, Hubei, Guizhou, and Qinghai, emit about 30% less CO_2 compared to HEVs. Importantly, in the provinces that currently lead in EV sales, we find that EVs do not have noticeably greater climate benefits than HEVs. Collectively, Beijing, Shanghai, Guangdong, Shandong, Zhejiang, and Tianjin accounted for 65% of the cumulative EV sales by the end of 2017 (with 24% of the total population in China), but the average carbon footprint of a BEV in these provinces is only 6% less than that of an HEV (the ratio ranges from 0.82 to 1.07). (Of course BEV, PHEV, and HEV all have significantly lower lifetime emissions than the conventional 2017 ICEVs.)

Unlike climate benefits, the potential for BEVs to reduce air pollutant emissions compared to ICEVs and HEVs is very clear, as shown in Figure 2. Note that Figure 2 is comparing fuel life cycle emissions (or WTW emissions) for vehicles with model year 2017, excluding emissions from vehicle production stage due to the local data availability. However, considering the fact that BEVs only have slightly higher aerial pollutant emissions from vehicle manufacturing stage than ICEVs[17], we expect the impacts of excluding vehicle manufacture emissions on the relative air pollutants reduction potentials among different types of vehicle technologies are small. WTW emissions of CO is primarily attributed to the TTW process for gasoline-powered vehicles; tailpipe exhaust contributes half of the WTW VOCs emissions of gasoline-powered cars. Vehicle electrification can significantly reduce CO and VOCs emissions, primarily due to lower emission factors for power generation relative to fuel life cycle of gasoline consumption. Unexpectedly, most of the NO_x, SO_2, and primary $PM_{2.5}$ emissions associated with gasoline are not being emitted from the tailpipe, but instead are WTT emissions, mostly from Chinese refineries which burn coal for process heat. Passenger car emissions are now tightly controlled by the stringent China 5 tailpipe emission standards implemented nationwide in 2017. Tighter emissions controls on refineries are needed to reduce air pollution in nearby cities. Given substantial emission reductions found in Chinese power plants after the introduction of ULE standards, EVs are estimated to reduce all types of criteria emissions compared to the gasoline counterparts, but this could change if the refinery emissions were better controlled.

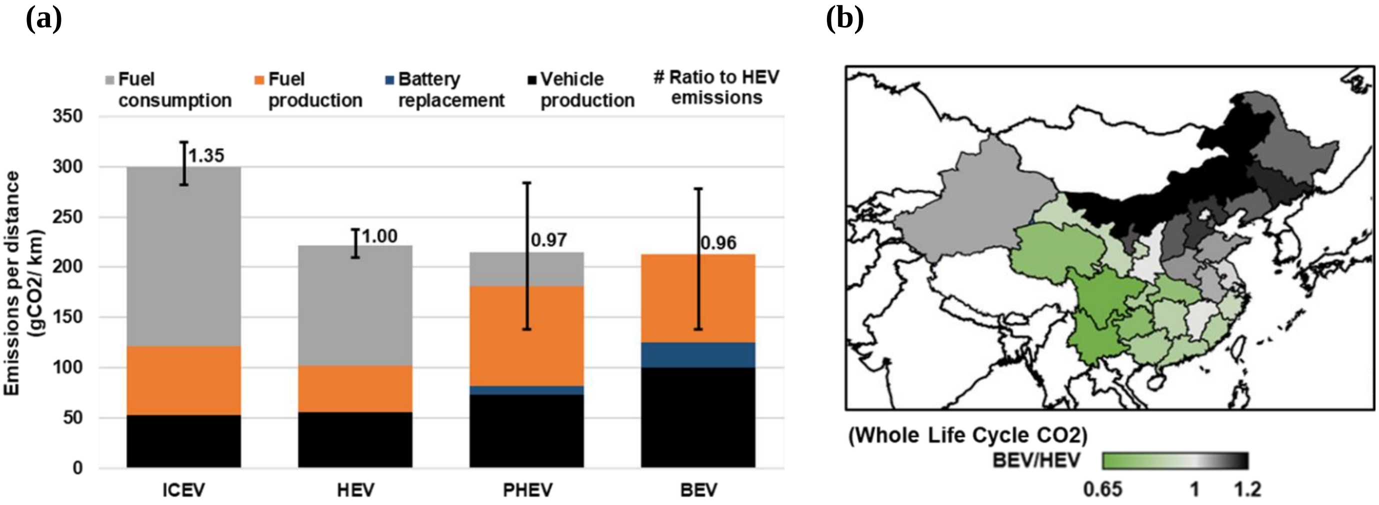

Figure 1. Whole life cycle CO_2 emissions comparison in 2017. (a) Per-kilometer CO_2 emissions for vehicles with different powertrains; (b) Provincial BEV-to-HEV ratios of CO_2 emissions

Note: Based on 150,000-km life for all powertrains; BEV emissions are based on the average carbon-intensity of China electricity (604 gCO2/kWh) in 2017; 76% of kilometers traveled by PHEV are powered by a battery[54]*; emissions from battery replacement are derived based on 2017 situation; error bars in (a) are from provincial differences in on-road fuel economy and electricity mix; interprovincial electricity transmission is considered when deriving BEV carbon footprints. GeoNames*[55] *is used for data visualization and only the provinces of China modeled in the present work are shown using colors in Figure 1(b).*

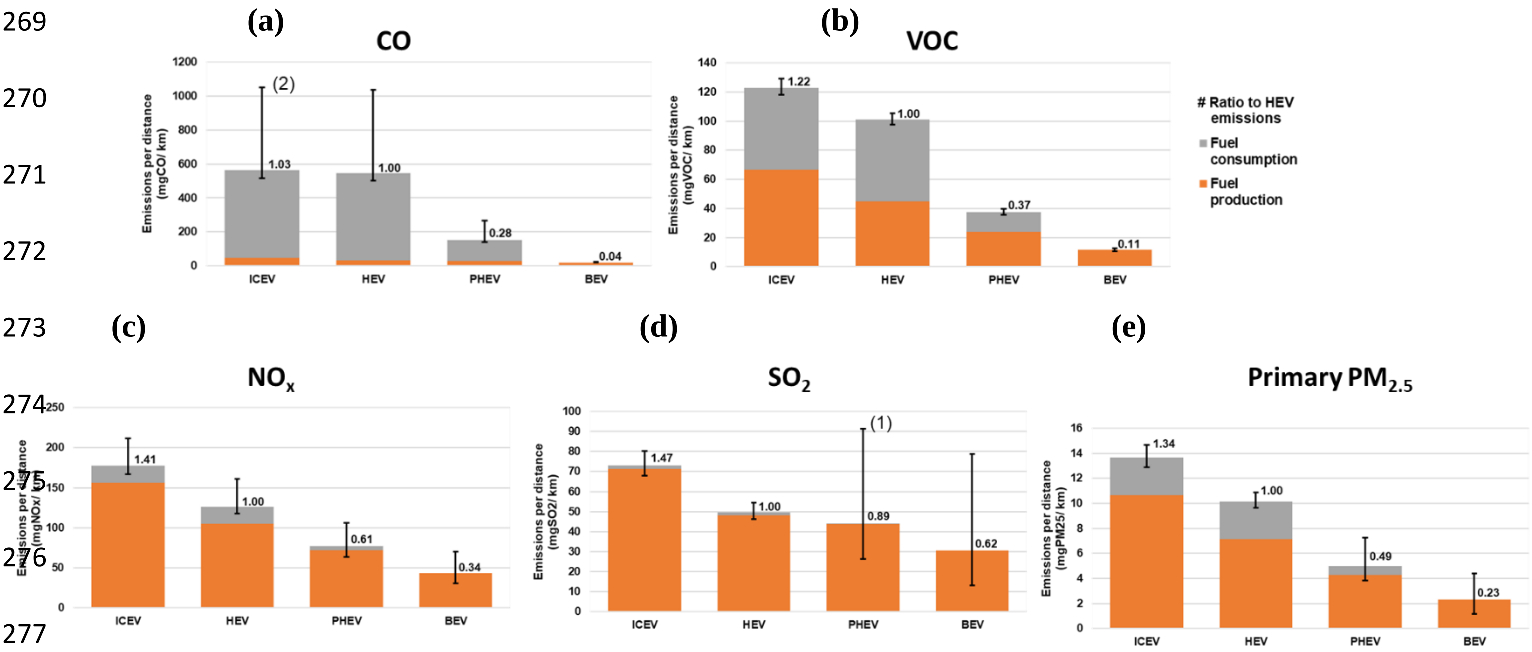

Figure 2. Air pollutants (a) CO (b) VOC (c) NO$_x$ (d) SO$_2$ (e) primary PM$_{2.5}$ emissions per kilometer for cars with different powertrains and with model year 2017

Note: This is well-to-wheel (WTW) emissions for vehicles; Error bars are from provincial differences in on-road emission factors (varying by temperature, altitude, and humidity) and power plant emissions (varying by compliance rate of ultra-low emissions (ULE) standards). [1]Power plants in Chongqing, Guizhou, Sichuan, and Yunnan have higher EF_{SO2}. *[2] On-road CO EF in Yunnan is more than double national average due to high elevation and steep terrain.*

3.2 Policy impacts on vehicle market and emissions

Compared to *NO EV POLICY COUNTERFACTUAL SCENARIO*, we estimate that the ongoing policy-driven EV penetration would reduce nationwide gasoline demand by 25 billion gallons/year in 2030 (Figure S11(a)-(b)), which corresponds to a reduction of 1.3 million barrels oil per day (i.e., more than 1% of the current world oil consumption). The overall trend of CO$_2$ is found to be similar to that of oil consumption (Figure S11(c)), and about 292 megatonnes (Mt) per year of CO$_2$ emissions would be avoided in 2030 in *EV SCENARIO*.

We break down the cumulative impacts on 2030 CO$_2$ emissions reduction: First, policies that are currently in place and would affect vehicle ownership demand include the national dual-credit policy (or EV mandate) and city-level car ownership restriction policies. At the national level, compared to the counterfactual scenario the dual-credit policy would diminish the nationwide vehicle demand by 18% and the cumulative effect of existing car ownership restriction policies would further reduce the vehicle stock by 4% (provincial-level reduction is displayed in Figure 3(a)). This vehicle stock reduction would cause CO$_2$ emissions per year to decrease by 143 million tonnes in 2030. Second, stringent fuel efficiency regulations (under EV mandates) would encourage the adoption of turbocharging/downsizing technology advances as well as HEV penetration, making the average on-road fuel consumption rate of new gasoline-powered passenger vehicles decrease to 5.0 L/100km by 2030 (compared to 7.3 L/100km in *NO EV POLICY COUNTERFACTUAL SCENARIO*); this fuel efficiency improvement would reduce CO_2 emissions significantly by 130 million tonnes per year. Third, mandating 40% EV sales market share would make the nationwide private EV stock in China reach 58 million by 2030, corresponding to 19% of the total stock; this EV adoption would lower CO_2 emissions by 19 million tonnes per year. Figure 3(b) depicts the EV adoption pattern by province in *EV SCENARIO* in 2030. From this breakdown analysis results (Figure 3(c)), we find that improved fuel efficiency of gasoline cars collectively reduces more CO_2 emissions than that of vehicle electrification, mainly because most of (~81%) the vehicle stock in 2030 are powered by gasoline.

Under *EV SCENARIO*, annual aerial pollutant emissions would be reduced by approximately 50% nationwide relative to *NO EV POLICY COUNTERFACTUAL SCENARIO* by 2030 (Figure S12): CO and VOC emissions share the similar trends: the total emissions would keep decreasing, mainly driven by the continued scrapping of the older polluting vehicles and their replacement with the cleaner cars. NO_x, SO_2 and primary $PM_{2.5}$ show a similar trajectory: the total emissions would start dropping noticeably after 2020; this is because less fuel is going to be produced and burned (i.e., oil consumption and the associated refinery emissions would peak in 2020) and tighter tailpipe emission standards are going to be enforced (i.e., from China 5 to China 6) after 2020.

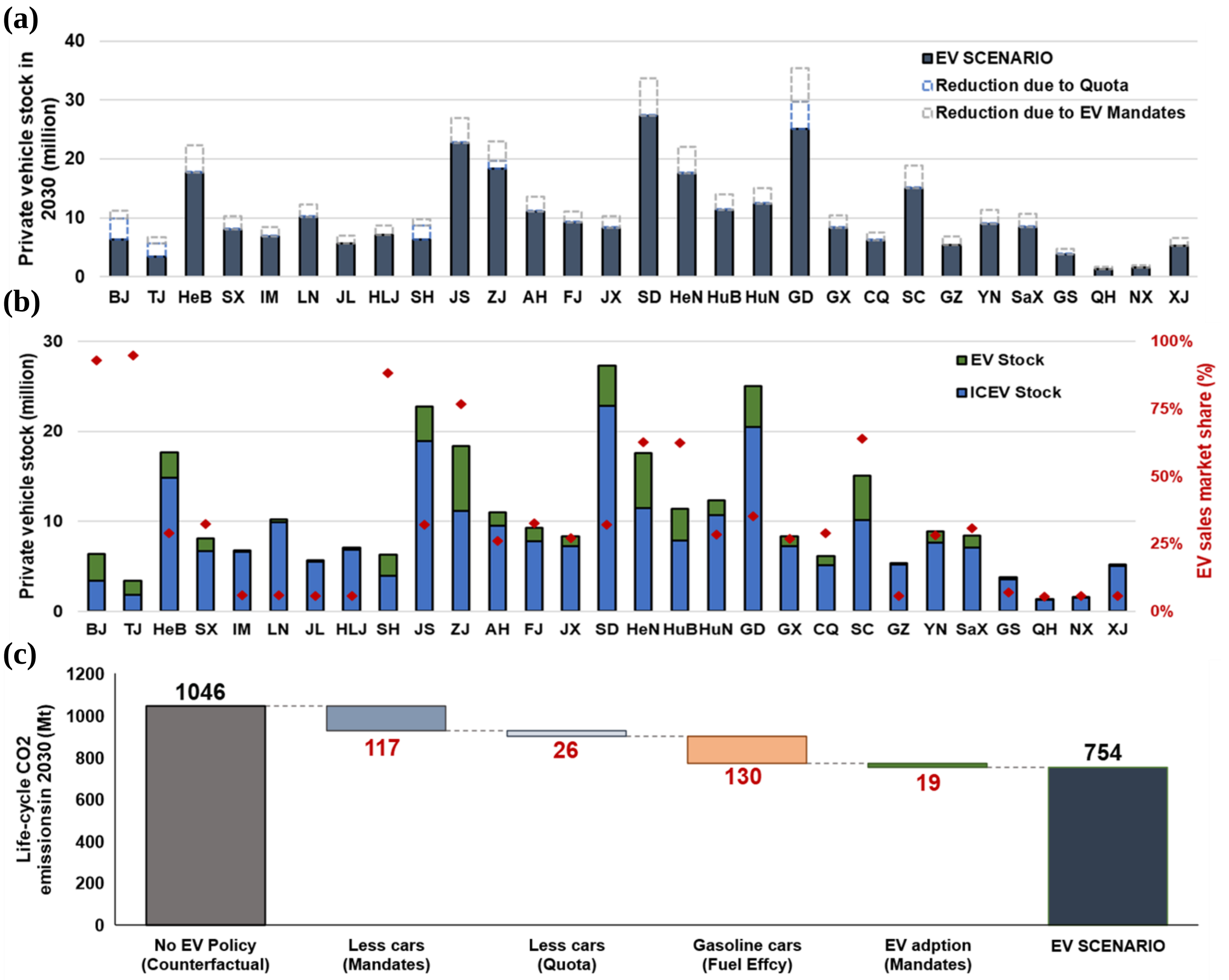

Figure 3. (a) The stock reduction amounts due to the city-level quota policy and national EV mandates; the solid dark-blue bar presents the projected vehicle stock at the provincial level in *EV SCENARIO*; (b) Provincial EV, ICEV stock (bar chart; left y-axis) and EV sales market share (red dot; right y-axis) in 2030 in *EV SCENARIO*; (c) Reduction in life cycle CO2 emissions of private vehicle sector in 2030 in *EV SCENARIO*, compared to the counterfactual scenario, broken down by different EV policies.

Note: We expect the private vehicle stock will reach 265 million and 302 million in 2025 and 2030 in EV SCENARIO, respectively. The private EV sales in 2030 will reach 11 million/year: EV sales in Beijing (BJ), Tianjin (TJ), and Shanghai (SH) are expected to achieve about 92% (in average) market share of the local new car sales; this is in stark contrast to the northeastern and northwestern provinces where EV market share will remain less than 10% even out to 2030.

3.3 Policy impacts on air quality and public health

Figure 4 (a) and (b) depict the differences between the changes of *EV SCENARIO* compared to *NO EV POLICY COUNTERFACTUAL SCENARIO* in surface-level $PM_{2.5}$ (primary + secondary) and O_3 exposure in 2030. The exposure maps are in people-micrograms per meter cubed for $PM_{2.5}$ and people-ppb per meter cubed for ozone. We estimate that by 2030, the new policy will lead to a consistent reduction in $PM_{2.5}$ concentration nationwide. Greater $PM_{2.5}$ concentration abatement (and thus health benefits shown later in Figure 4(c)) is found to occur in provinces with broader EV adoption, but also in provinces with larger refinery capacity. The countrywide, average population-weighted reduction in $PM_{2.5}$ concentration is 0.24 $\mu g/m^3$; this corresponds to the concentration change that the average person would experience. On the other hand, the EV penetration impacts on ozone concentration are more complicated. Ozone is very sensitive to the relative balance of changes in NOx and VOC emissions. In locations with very high NOx levels (dominant in most of China), the NOx contribution to ozone formation saturates, due to secondary reactions further increases in NOx reduce the ozone concentration, while a decrease in VOC emissions leads to a decrease in ozone concentration[56]. In this study (which includes the effects of EV penetration on emissions from refineries), we find that the VOC effect (i.e., decreases in VOC emissions from refineries) dominates, causing the countrywide, population-weighted ozone concentration slightly decreases in *EV SCENARIO* compared to the counterfactual scenario: the annual average of the daily 8-hour maximum ozone goes down 0.05 ppb.

Air pollution, particularly particulate, is known to be high correlated with mortality. Below we compute how many deaths would be avoided by replacing some ICEVs with EVs in 2030. According to our analysis, full implementation of current government EV policies (i.e., *EV SCENARIO*) will reduce the health impacts of exposure to air pollution. For example, in the year 2030 the new policy will avoid 15,534 premature deaths (95% C.I. = 14,474 to 16,602), 2,229 cases of hospital admission due to respiratory disease, 1,309 cases of hospital admission due to cardiovascular disease, 3,673 cases of chronic bronchitis, 3,909 cases of asthma attack, and 376 cases of emergency room visits for respiratory disease. For the avoided premature deaths, the reduced health endpoint of lower respiratory infection contributes the most—nearly 53%, followed by chronic obstructive pulmonary disease (20%) and stroke (16%). Figure 4(c) shows the avoided number of premature deaths per million people (on y-axis) at the provincial level. We find that nearly all the avoided premature deaths are attributable to reduction in exposure to ambient $PM_{2.5}$ concentrations (mainly driven by the reduction in secondary aerosol), so we only show the mortality effect of $PM_{2.5}$ in the figure. Note that we allocate the air pollutant emissions associated with the upstream gasoline production phase based on the capacity volume of China’s oil refineries and their locations. Additionally, we observe slight decreases in the ambient ozone under the policy scenarios, these changes however do not affect our mortality calculations since the health concentration-response functions that are used for ozone mortality calculations have a 35-ppb threshold and, in most cases, the annual average 8-hour daily maximum ozone is below this threshold. At the provincial level, the largest reductions in an individual’s mortality risk due to air pollution will occur in Guangxi (GX), Shandong (SD), and Hubei (HuB) provinces. In terms of the total number of premature deaths avoided (i.e., the rectangle area in Figure 4(c)), Shandong, Henan (HeN), and Guangdong (GD) provinces are the main beneficiaries of the EV policy; in each of these provinces more than 1,000 annual premature deaths may be avoided in 2030.

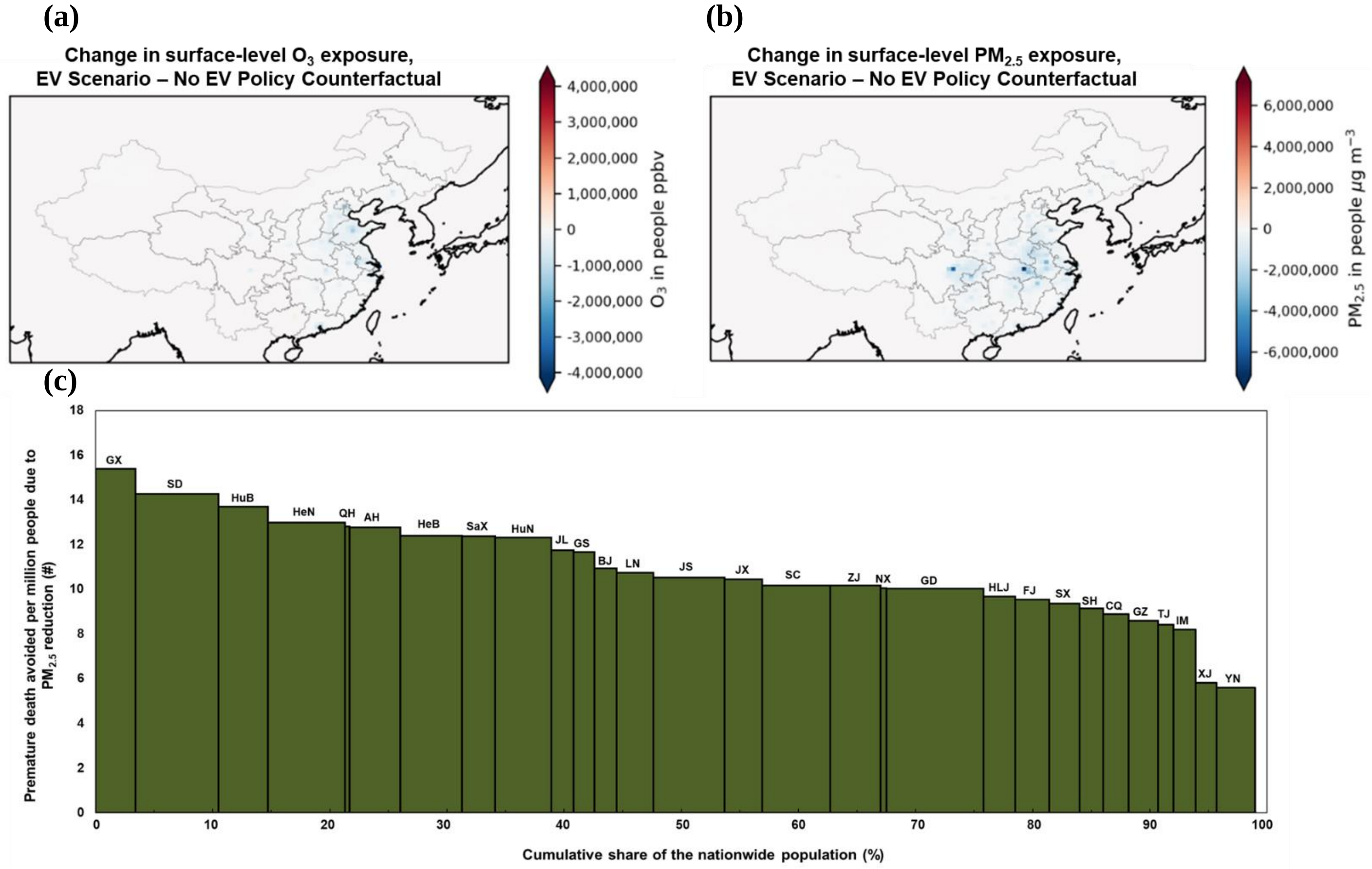

Figure 4. Air quality and health impacts of *EV SCENARIO* relative to *NO EV POLICY COUNTERFACTUAL SCENARIO*: (a)-(b) Change in surface-level O_3 and $PM_{2.5}$ exposure in the major Chinese provinces; (c) Avoided premature deaths to reduction in exposure to ambient $PM_{2.5}$ concentrations by province in 2030, in descending order. Greater $PM_{2.5}$ concentration abatement (and thus health benefits) is found to occur in provinces with broader EV adoption, but also in provinces with larger refinery capacity.

Note for (c): Per million premature deaths avoided in each province on y-axis; percentage share of mainland China's total population (1.42 billion) on x-axis; the area of each rectangle times the total population is the total deaths avoided in that province. This study captures 99% of the nationwide population in mainland China (Hainan and Tibet are not included).

3.4 Cost-benefit analysis

This section compares the economic values of health and climate benefits with the published[26] transition cost to China of switching from ICEVs to EVs in a single year of 2030. Both the costs and benefits are computed based on the direct economic costs and the emission reductions corresponding to the on-road passenger vehicle distance driven in 2030. More details about the definitions of "economic benefits" and "transition costs" can be found in SI 8.

Combining the quantified benefits with the costs, we examine the cost-effectiveness of the EV policy in 2030—at both national and provincial level (Supplementary Figure S13). The nationwide benefits from implementing EV policy in Chinese passenger vehicle sector are valued between 70 and 170 billion (base case 116 billion) Yuan at a cost of 152 billion Yuan in the year 2030, with a benefit-to-cost ratio of 0.46-1.12 (base case 0.76). The expected benefit due to avoided premature deaths and reduced climate change is comparable (i.e., having the same order of magnitude) to the expected direct economic cost. It is important to keep in mind that all of these projections have significant uncertainties, e.g. there is about a factor of 2 uncertainty in the true cost to society of emitting a tonne of CO_2 in 2030[49], the models for predicting numbers of premature deaths due to air pollutant emissions have large uncertainties, the Yuan value of avoiding a premature death is debatable, and the cost of producing batteries and BEVs in 2030 is also significantly uncertain. We hope that this study, albeit with significant uncertainties, will foster more intensive impact analysis of this important new policy to improve vehicle/transportation policies in China and elsewhere in the coming decades.

For health benefits: while Guangxi has the largest reduction in the individual's mortality risk (Figure 4(c)) and Shandong collectively benefits the most from China's movement to electric mobility (the rectangle area in Figure S14(a)). Beijing will obtain the largest health benefits in terms of per capita economic value. This is because individuals in Beijing, who on average have higher incomes, are expected to be willing to pay 132% and 83% more than those in Guangxi and Shandong to avoid health-related risks. For CO_2 benefits: while we expect climate change mitigation would impact different provinces differently, we do not know how to apportion the actual climate benefits amongst the regions correctly. As a result, instead of reporting "climate benefits to province", in Figure S14(b), we report "contribution to global climate change mitigation by province." These contributions are expected to benefit everyone in the world by slowing climate change. For Transition Costs (Figure S14(c)): we first compute the national-level transition costs by following the methodologies given in the previous study[26], and then apportion these costs to each province based on the projected EV sales in each province. Many of these costs are expected to be shared across China, not to be borne by the individual provinces, but in Figure S14 we do not include that likely cost-sharing because we do not have enough information.

Overall, we find that current EV policies can substantially contribute to climate change mitigation and improve air quality, with associated public health benefits. But these benefits are not distributed equally across provinces given differences in socioeconomics, electricity generation and transmission, and local-level car ownership policies. As more energy-efficient vehicles account gradually account for greater share of vehicle activity, the benefits will continue to increase long past 2030.

3.5 Sensitivity Analysis

We test the sensitivity of *EV SCENARIO* to variations in the underlying assumptions (scenarios are well-defined in Table S9); the main findings are as follows (Figure 5):

(1) *Fewer Car Scenario*: All the conditions are the same as the counterfactual scenario except for car market size—302 million cars on road in 2030 here (same size as *EV SCENARIO*). As expected, vehicle stock reduction would significantly reduce CO_2 emissions and also reduce air pollution leading to premature mortality (i.e., fewer cars, less emissions), even if the cars are no different than those on the road today.

(2) *Cleaner ICEV/HEV Scenario*: All the conditions are the same as *Fewer Car Scenario* except for the improvements in vehicle fuel economy and emissions; all the cars out to 2030 are powered by gasoline, same as those in *EV SCENARIO*. We find that supporting HEVs and cleaner ICEVs deployment would significantly lower CO_2 emissions but have a smaller effect on premature deaths. While the climate benefits of *Cleaner ICEV/HEV Scenario* are comparable to *EV SCENARIO*, the health benefits of cleaner ICEVs and HEVs are much less than EVs. The results suggest that China's benefits from electrifying private vehicle sector are more significant for public health than for climate change. The tight China 6 and fuel economy standards as well as the carbon-intensity of China's electricity grid combine to make CO_2 emissions relatively insensitive to vehicle type. However, there are noticeable local air pollution improvements associated with vehicle electrification, due primarily to reduced particle pollution in densely populated regions near oil refineries as those are turned down.

(3) *EV-Homo Scenario*: All the conditions are the same as *EV SCENARIO* except for the geographical patterns of future EV population growth—EV sales market share by 2030 across provinces is homogeneous here. The uncertainties in future geographical patterns of EV purchases have only minor effects on the greenhouse gas and air pollution predictions. The provincial contribution to the total number of avoided premature deaths and the reduced CO_2 emissions are similar between *EV SCENARIO* and *EV-Homo Scenario* (Figure S15): greater contributors are the provinces with larger refinery capacity (like Shandong) and those with larger vehicle market (like Guangdong).

(4) *EV-Double Scenario*: All the conditions are the same as *EV SCENARIO* except for the EV population growth rate—EV penetration rate is doubled here. While doubling EV penetration rate would further avoid additional 2,129 (14%) premature deaths relative to *EV SCENARIO*, it would cause life cycle CO_2 emission to increase by 2%. This is because EV-leading provinces do not necessarily have less carbon emissions associated with EVs relative to HEVs (Figure 1), due to the high carbon-intensity of their electricity.

(5) *EV-REN Scenario*: All the conditions are the same as *EV SCENARIO* except for the future emission intensity of the power grid which gets improved as a result of the *expected* increasing ULE standard compliance rate and expanding renewables. While vehicle electrification combined with an expected reduction in grid emission intensity would only reduce CO_2 emissions by additional 4% per year, it could greatly reduce premature mortality by 93% compared to *EV SCENARIO* thanks to implementation of the ULE standards.

(6) *EV Scenari*o *with X% of power grid EFs*: All the conditions are the same as *EV SCENARIO* except for the future EFs of the power grid—2030 EFs (including CO_2, SO_2, NO_2, and $PM_{2.5}$) are reduced by 20%, 40%, and 60% (*=1–X %*) compared to *EV SCENARIO*. Because predicting the exact extent of renewables penetration and future EFs is uncertain, we here examine the sensitivity of the CO_2 emissions and health impact results to the EFs of the electricity generation. Avoided premature deaths are much more sensitive with respect to the power grid EFs than that of climate change benefits.

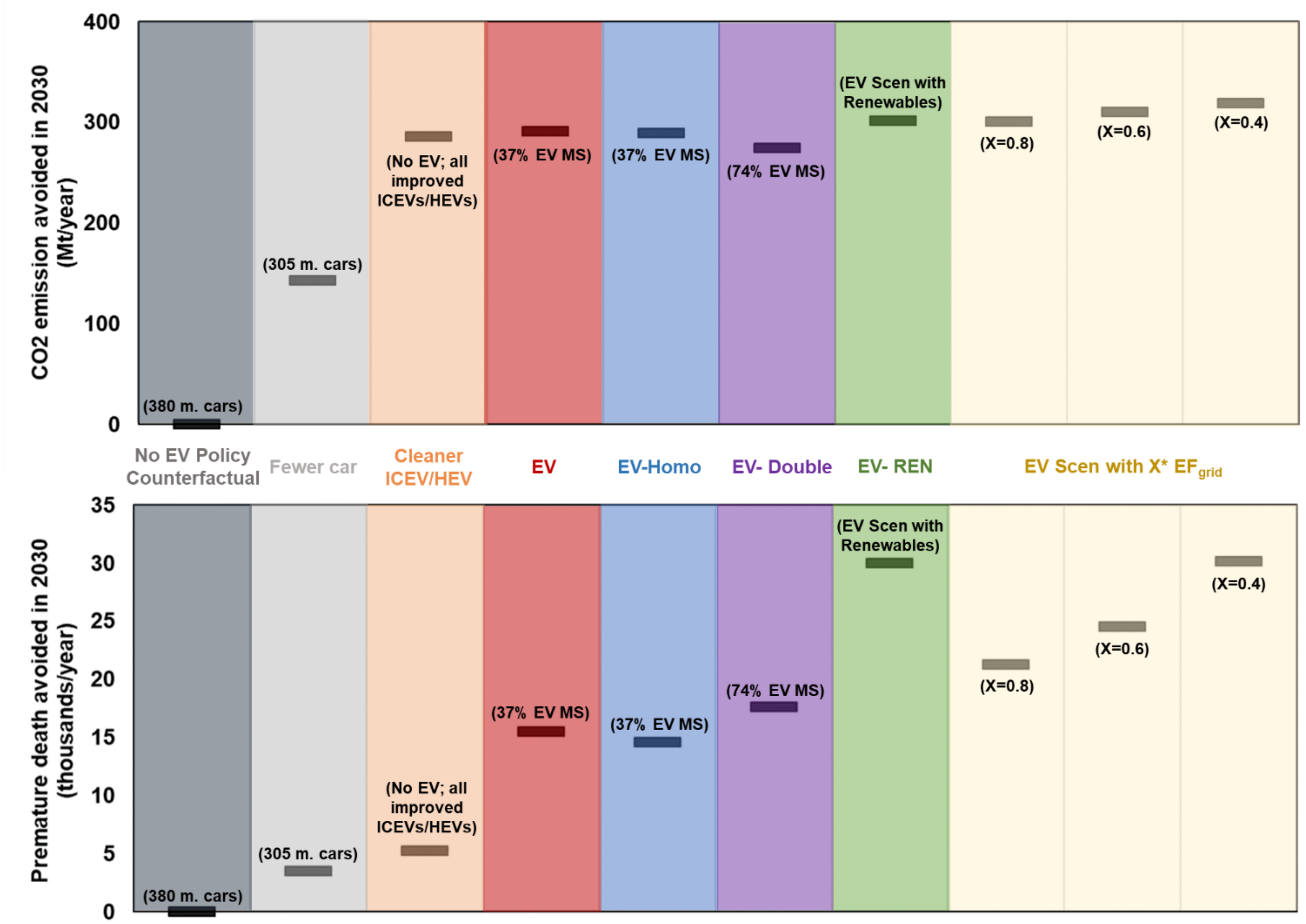

Figure 5. Avoided CO_2 emission and premature deaths in 2030 under different scenarios relative to *NO EV POLICY COUNTERFACTUAL SCENARIO*.

3.6 Limitations and future research

Despite the advances made in understanding provincial variations in the impacts of EV policies, this work still has some limitations that require further investigation. First, when we investigate BEV carbon footprints with the consideration of the interprovincial electricity transmission, in theory we should use the marginal grid mix at the time of day when the vehicle is charged instead of the average grid mix to determine the impacts of adding new loads to a utility grid owing to EV charging. However the needed information (e.g., electrical load profile, charging times[57], charging rates, and marginal electricity source in each province at each time) about the current electrical system is unavailable, and there is high uncertainty about how that grid (and its dispatch policies) will change out to 2030 as BEV charging becomes a significant fraction of the total load. Second, we exclude manufacturing-related air pollutant emissions in the air quality and health impact assessment due to lack of data. Although the bias might not be significant, this part of the work is worthy of investigation. Thirdly, we do not consider the substitution effects between private and public transport modes: the reduction in private vehicle purchases might increase the demand for other public transport modes, and thus increase (or slow the decline) in public transit emissions. While this study only focuses on the private vehicle sector, the policy impacts on the whole transportation sector emissions are interesting to examine further. Lastly, this study does not attempt to quantify all of the impacts of the new policy (e.g. other effects of pollutants, energy security, balance of trade, manufacturing policy). We hope this study prompts future work to better understand and predict the benefits of proposed EV policies, and to reduce the uncertainties in the predictions, to provide better information to decision-makers.

Conflicts of interest

There are no conflicts to declare.

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Supporting Information

The Supporting Information is available, including emissions data for current and future years, China-specific vehicle fleet modeling, air quality modeling, key parameters for health impacts evaluation and quantification, and the details of the additional scenarios.

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