# Regional Disparities of Electric Vehicle Marginal Emissions - Evidence from China Market

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***Abstract*—Recent years have witnessed a surge in Electric Vehicle (EV) sales in China due to a combination of reasons ranging from government incentives in purchasing (subsidies, tax cuts, etc.), lowered costs of EVs, as well as an increase in environmental awareness among Chinese citizens. This paper intends to uncover the regional disparities in EV cars' marginal emissions in China. Using data from 2010 through 2017, with a focus on carbon dioxide ($CO_2$), we find substantial variation in metric tons of $CO_2$ emissions per EV sold among geographic regions in China (denoted as marginal emissions of EV). We define the term "e_ratio" as the ratio of electricity consumption over electricity generation. A region with a high e_ratio indicates that its electricity generation is larger than its electricity consumption. We find that in provinces with the highest e_ratio, 1% increase in the sales of EVs results in a 0.105% decrease in $CO_2$ emission from the electric power industry (10% significance); 1% increase in the sales of Battery EVs (BEVs) is related to 0.12% decrease in $CO_2$ emissions from the electric power industry (10% significance). In comparison, the effect of additional EV sales on reducing $CO_2$ emission is not significant in provinces with the lowest e_ratio.**

***Index Terms*—China energy market, electric vehicles, marginal emissions, regional heterogeneity**

## I. Introduction

The transportation sector has contributed to a significant part of air pollution in China, producing 917 metric tons of carbon emissions in 2018 [1]. Climate policies designed to reduce carbon emissions include the electrification of the transportation sector. While these policies increase the demand for electricity, which is the largest contributor to carbon emissions in China, it is claimed that the electricity consumed by electric vehicles (EVs) will generate less carbon dioxide ($CO_2$) emissions than conventional gasoline vehicles. As the sales of EVs grew exponentially in the past few years in the China market (Fig. 1), it is clear that the design of EV policies matter in the near future.

When it comes to making EV policies for different regions, it is often complicated to determine the optimal subsidy policy. If there is spatial heterogeneity in marginal emissions (metric tons of $CO_2$ per EV sale), would policies differ according to that? The key is to establish a mechanism linking EV sales with power plant emissions. Nonetheless, it is hard to estimate the marginal emissions of EVs in one region for several reasons. First, China has a mixture of thermal, hydro, wind, and nuclear power plants. In 2018, thermal power accounted for 71% of electricity production, hydropower accounted for 17%, wind and nuclear power accounted for 5% and 4% respectively [2]. These power plants could have different emissions per unit of electricity generation. Second, the regional imbalance of population and natural resources is present noticeably in China. As a result, the government has made interconnection of power possible between regions, such as the "west to east power transmission" project. Because the consumption and generation of power are so different between regions, the true emissions associated with electricity consumption in one region are hard to estimate. Third, different models of EVs might have different electricity consumption per kilometer driven. Thus, the marginal emissions might vary between different brands of EV.

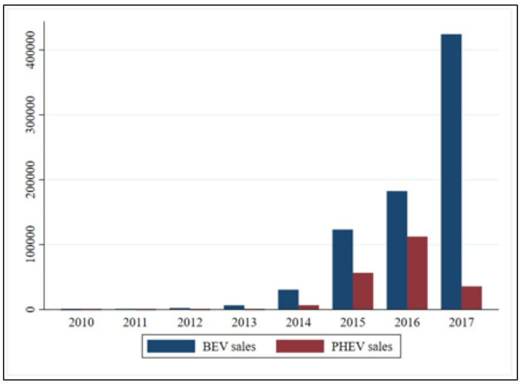


Figure 1. EV sales in China from 2010 to 2017

Attempting to overcome these challenges, this paper makes the following contributions. We develop and implement a methodology for estimating marginal emissions of EVs across China. Our method focuses on regions that matter the most for policymaking: regions that

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are heavily populated and more economically developed, and the regions with abundant resources for electricity generation. The result will be essential for improving current EV policies in China.

Our approach for estimating the marginal emissions of EV exploits several datasets on pollution, EV sales, and socioeconomic information across China. We create dummy variables for the provinces with the highest and lowest electricity consumption to generation ratio (which we define as "e_ratio"). We then regress the EV sales on $CO_2$ emissions related to electricity generation, interacting with the two regional dummy variables and controlling for social-economic variables.

The results indicate that in provinces with the highest e_ratio, 1% increase in total sales of EVs results in a 0.12% decrease in $CO_2$ emission from the electric power industry (10% significance). 1% increase in the sales of BEV results in a 0.128% decrease in $CO_2$ emission from the electric power industry (10% significance). In comparison, the results suggest that the effect of additional EV sales on reducing $CO_2$ emission is not significant in provinces with the lowest e_ratio. These results have important implications for future EV policies in China.

## II. Background

### A. Relevant EV Policies

We begin with a brief summary of the major EV incentives programs in China in recent years. The past decade has witnessed a surge in EV sales (Fig. 1) due to various incentive policies. In 2009, China launched the "Ten Cities Thousand Vehicles" program in 13 major cities in China[1]. This program has lasted three years, and the central government was reported to provide subsidies of over 1 billion yuan for public sector EVs, such as buses and taxis, driving private investment worthy of 8.5 billion yuan in the large-scale productions of motors and batteries [3]. A policy to provide subsidies for the private purchase of EVs was announced in 2010. Five pilot cities (Beijing, Shanghai, Shenzhen, Chongqing, Wuhan) were selected with maximum subsidies of 50,000 yuan ($7,900) for Plug-in Hybrid EVs (PHEVs) and 60,000 yuan ($9,500) for Battery EVs (BEVs). As for more recent policies, it's noticeable that stricter EV qualifications are required, and subsidies are decreasing. Following this trend, monetary incentives are shifting towards other forms of incentives, such as the dual-credit policy issued in 2017. Overall, these policy incentives on EVs led to the exponential increase in EV purchases over recent years in China.

### B. Electricity Generation and Pollution in China

Coal has always been the main source of electricity supply in China. In 2010, coal accounted for 76.85% of China's total electricity production. Although this percentage decreased to 66.44% in 2018, it remained significant [4]. Since the burning of coal leads to various air pollution (including sulfur dioxide ($SO_2$), nitrogen oxides (NOX), $CO_2$...), electricity generation in China leads to substantial air pollution. In 2010, electricity and heat production emitted 44.53% of all $CO_2$ emissions. This figure increased to 49.71% in 2017 [4].

### C. Resource Imbalance in China

There is a spatial imbalance in the distribution of coal and water-powered electricity in China. Coal and water resources are more distributed in north and west areas and less in south and east areas [5]. To resolve this resource imbalance between regions, the Chinese government proposed and implemented electricity transmission from the inland resource-abundant regions to coastal provinces that are in high demand for electricity since the 1980s. The "west to east power transmission" project has three main corridors. The north corridor transmits electricity from Shanxi, Shaanxi, and Inner Mongolia to northern China, such as Beijing, Tianjin, and Hebei. The central corridor transmits hydropower primarily from the Three Gorges on the Yangtze River to eastern China, such as Shanghai, Jiangsu, and Zhejiang. The south corridor transmits electricity from Yunnan, Guizhou, and Guangxi to Guangdong.

In 2014, China's National Energy Administration of China announced twelve additional "west to east power transmission" lines. These twelve proposed lines would transmit electricity from provinces in the west part[2] to provinces on the eastern coast[3]. Consequently, this regional imbalance of electricity generation results in the imbalance of air pollution associated with electricity production.

## III. Relevant Literature

A lot of studies suggest that replacing traditional internal combustion engine vehicles (ICEVs) with EVs could provide environmental benefits through effectively reducing $CO_2$, $SO_2$, and other pollutant emissions [6, 7, 8]. However, other scholars support the idea that the benefits of EVs are less clear when it comes to $CO_2$ emissions [9, 10]. The main reason is that the net effect on $CO_2$ emissions of switching to EVs is partly dependent on the carbon intensities of the power plants supplying the electricity for charging. The environmental benefit might only be obtainable in areas with low-carbon power [11, 12]. Therefore, it is important to take regional disparity into consideration when examining the environmental benefits of EVs.

Reference [13] estimates the geographic variation in the environmental benefits of driving EVs in the United States. They find the second-best EV purchase subsidy ranges from $2,785 in California to -$4,964 in North Dakota, with a mean of -$1,095. 90% of the local environmental externalities from driving EVs in one state are exported to

[1] Including Beijing, Shanghai, Chongqing, Changchun, Dalian, Hangzhou, Jinan, Wuhan, Shenzhen, Changsha, Kunming, Nanchang, and Hefei. In early 2010, Guangzhou, Haikou, Suzhou, Tangshan, Tianjin, Xiamen, and Zhengzhou were added to the program, and the third batch of cities including Chengdu, Hohhot, Nantong, Shenyang, and Xiangfan were added at the end of 2010

[2] Including Liaoning, Shanxi, Shaanxi, Inner Mongolia, Yunnan, Anhui, and Ningxia

[3] Including Beijing, Tianjin, Hebei, Shandong, Zhejiang, Jiangsu, Shanghai, and Guangdong

others. EVs have substantial environmental benefits in California, the opposite occurs in the upper Midwest where gasoline vehicle damages are small (low population densities) but EV damages are large (due to the prevalence of coal-fired generation in the region and the temperature adjustment to EV range).

When it comes to EVs in China, it is reasonable to also expect spatial heterogeneity in the environmental benefits of driving EVs. There are two studies worth mentioning because they are most closely relevant to our analysis in this paper. Reference [14] uses a well-to-wheel model to $SO_2$ and NOX emission reductions from EV by provinces in China. Unlike their analysis, we define our marginal emission to be the amount of carbon emission created associated with electricity generation with one additional sale of EV. Moreover, we find the difference in marginal emission through running regression analysis for each province. We also account for the resource imbalance of different provinces by considering the electricity consumption and generation ratio in our model. Another relevant paper is [15]. They investigated the pollution imbalance between three major cities (Beijing, Shanghai, and Shenzhen) and their surrounding cities. However, they only looked at imbalances in a small geographic area around the major cities, neglecting the regional imbalances between larger geographic areas (e.g., Eastern and Western, Northern and Southern China). We aim to fill this gap by looking at the regional disparities of EV benefits at the country level. On this basis, we propose hypothesis 1 and 2:

**H1.** The use of EVs in China generates environmental benefits.

**H2.** The environmental benefits generated by EVs are heterogeneous among different regions in China.

## IV. DATA

We create a novel and comprehensive dataset by merging several datasets, including administrative vehicle registration records, carbon emissions related to the power sector, and province-level socioeconomic conditions. The final dataset is of panel format from 2010 to 2017 containing 30 provinces in China.

### A. EV Sales Data

The administrative vehicle registration data contains records on every new vehicle sold in each city from 2010 to 2017. We are interested in EV car sales at the province-by-year level (to be matched with the $CO_2$ data). The EV sales data includes two types of EV: BEV and PHEV.

### B. $CO_2$ Data

Our pollution data is collected from China Emission Accounts and Dataset (CEADs [4]), which regularly publishes the latest $CO_2$ emission inventories by using the IPCC Sectoral Emission Accounting Approach (in the format of 45 production sectors and 2 residential sectors) for China and its 30 provinces and cities. All emission inventories are compiled based on the latest energy data revision (2015) by the National Bureau of Statistics of China. We specifically aim to look at the total amount of $CO_2$ generated by the electric power industry in different provinces in China.

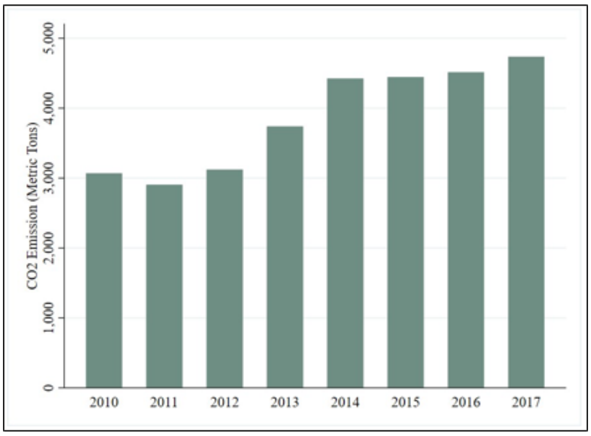


Figure 2. $CO_2$ Emissions from Electricity Generation in China From 2010 to 2017

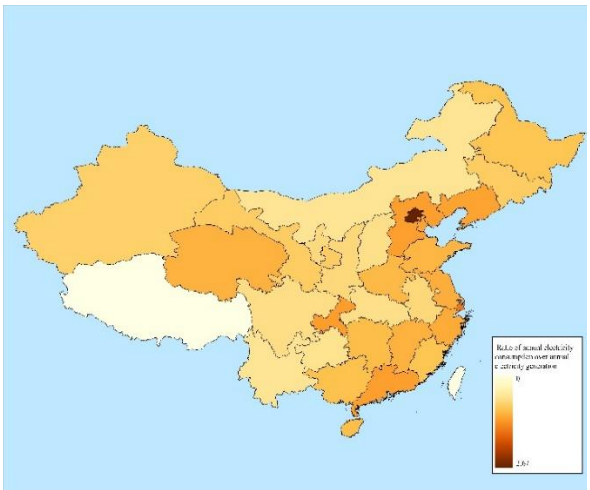

Figure 3. Ratio of Annual Electricity Consumption Over Annual Electricity Generation by Province

### C. Additional Socioeconomic Control:

We obtained some additional socioeconomic control variables from the National Bureau of Statistics of China. We gathered the GDP per capita, population, annual electricity consumption, and annual electricity generation at the provincial level. For each province *i*, we took the ratios of annual electricity consumption over annual electricity generation, and rank provinces according to their average ratio over the years (denote as e_ratio). We considered e_ratio as the property of each province. E_ratio is large if a province is using more electricity transported from other provinces than the electricity generated by itself. The top 5 provinces with the highest e_ratio (abbreviated as "Top 5" below) are Beijing, Shanghai, Chongqing, Hebei, and Guangdong. The bottom

[4] All datasets published by CEADs are the results of current research projects funded by National Natural Science Foundation of China, Ministry of Science and Technology of China, Chinese Academy of Sciences, Science and Technology Research Council UK, Newton Fund

5 provinces with the lowest e_ratio (abbreviated as "Bottom 5" below) are Yunnan, Inner Mongolia, Guizhou, Hubei, and Shanxi. We will present some regional socioeconomic differences in the Summary Statistics.

### D.Summary Statistics

Table I summarizes the dataset. Panel A describes variables related to EV sales. While the average annual sales of EVs are 4,961, the figure is almost 7,000 higher if we only focus on "Top 5" provinces. If we narrow it down to "Bottom 5" provinces, the average annual EV sales become 2,259. It's reasonable to interpret that provinces with high electricity imports (high e_ratio) tend to have higher EV sales, and vice versa. This is probably due to the fact that the provinces with high e_ratios are the ones that are more economically developed.

TABLE I. SUMMARY STATISTICS, 2010 - 2017

| VARIABLES | MEAN | SD | MIN | MAX |
|---|---|---|---|---|
| *Panel A: EV Sales Variables* | | | | |
| Annual EV Sales (Sum of PHEV and BEV sales) | 4,961 | 10,980 | 1 | 58,715 |
| Annual EV Sales (top 5 provinces) | 11,845 | 18,449 | 1 | 58,715 |
| Annual EV Sales (bottom 5 provinces) | 2,259 | 4,069 | 1 | 17,867 |
| Annual PHEV Sales | 1,070 | 4,166 | 0 | 34,344 |
| Annual BEV Sales | 3,886 | 8,933 | 0 | 54,291 |
| *Panel B: Pollution Variables* | | | | |
| $CO_2$ Emissions from Electricity Generation (in *Mt*) | 156.3 | 114.1 | 12.40 | 477.9 |
| $CO_2$ Emissions from Electricity Generation (Top 5 provinces) | 138.3 | 102.8 | 27.73 | 290.8 |
| $CO_2$ Emissions from Electricity Generation (Bottom 5 provinces) | 184.8 | 133.2 | 27.07 | 467.7 |
| *Panel C: Electricity Variables* | | | | |
| Electricity consumption (100 million kWh) | 1,933 | 1,327 | 185.3 | 5,959 |
| Electricity generation (100 million kWh) | 1,923 | 1,195 | 172.9 | 5,329 |
| E_ratio* | 1.069 | 0.393 | 0.627 | 2.673 |
| E_ratio (top 5 provinces) | 1.629 | 0.538 | 1.280 | 2.673 |
| E_ratio (bottom 5 provinces) | 0.666 | 0.0329 | 0.627 | 0.701 |
| *Panel D: Social-economic Variables* Population (in %) | 3.461 | 2.052 | 0.422 | 8.035 |
| Population (top 5 provinces) | 3.942 | 2.586 | 1.463 | 8.035 |
| Population (bottom 5 provinces) | 2.997 | 0.856 | 1.819 | 4.272 |
| Real GDP per capita (in 1,000 Yuan) | 49.55 | 22.51 | 15.75 | 120.0 |
| Real GDP per capita (top 5 provinces) | 66.33 | 25.02 | 28.67 | 116.11 |
| Real GDP per capita (bottom 5 provinces) | 39.65 | 18.98 | 15.75 | 83.10 |

*E_ratio is denoted as the ratio of electricity consumption over electricity generation.

*Note*: A total of 198 province-level observations.

Annual sale trends of BEV and PHEV are shown in Fig. 1. BEV sales had experienced exponential growth since 2013. Similarly, PHEV sales shared this growth pattern prior to 2016. Despite that the PHEV sales experienced a decrease in 2017, there is an overall upward trend of the sales of the two types of EVs from 2010 to 2017.

Panel B in Table I reveals the characteristics of the pollution variable we used, specifically $CO_2$ emissions from electricity generation. It's noticeable that the average $CO_2$ emissions of "Bottom 5" are higher than the overall average $CO_2$ emissions, and the average CO2 emissions of "Top 5" provinces are lower. The "Bottom 5" are provinces with relatively high electricity production and export, which means they are likely to emit more $CO_2$. Similarly, since the Top 5 are mainly dependent on electricity import from other provinces, it's reasonable that their $CO_2$ emissions associated with electricity are lower. Fig. 2 presents the evolution of overall $CO_2$ emissions from 2010 to 2017. According to this figure, the only noticeable increase is from 2012 to 2014. For the rest of the years, $CO_2$ emissions have been steady thanks to a series of climate policies dedicated to reducing greenhouse gas, including the promotion of EVs. Overall, $CO_2$ emissions from electricity generation have increased by around 1,500 metric tons during these eight years.

Panel C provides the characteristics of the electricity data. The average e_ratio of all provinces is around 1, meaning there's a balance between electricity consumption and generation at the national level. Yunnan has the lowest e_ratio of 0.627, and Beijing has the highest e_ratio of 2.673. Besides Beijing and Shanghai, all the provinces have uniformly distributed e_ratios in the range of 0.6 to 1.3. Fig. 3 shows the distribution of e_ratio by province on the map of China. The east part of China evidently has a darker color than the west part. This pattern indicates that provinces in the east part of China generally exhibited higher electricity consumption than electricity generation, and thus, they're in high demand of electricity and require electricity import. Provinces in the west part of China generally have excess electricity, suggesting that they are mostly electricity exporting provinces. In fact, this pattern of distribution is indicative of the electricity transmission policies proposed by the Chinese government as mentioned in the Background section. The power importing provinces and power exporting provinces are highly consistent with the "Top 5" and "Bottom 5" provinces in our study. Thus, the e_ratio pattern is partly a result of the "west to east power transmission" project.

Panel D presents the characteristics of social-economic variables. It's evident that both the population and real GDP per capita of "Top 5" provinces are higher than the national average. Conversely, the population and real GDP per capita of "Bottom 5" provinces are relatively lower than the national average. The statistics imply that not only do "Top 5" and "Bottom 5" provinces stand on the opposite ends of the e_ratio spectrum but they are also positioned at the opposite ends of the spectrum in terms of provincial economic and population levels.

## V. Empirical Methods / Econometric Model

We created two province-specific time-invariant dummy variables $D_i^{top}$ , $D_i^{bottom}$:

$$D_i^{top} = \begin{cases} 1, \text{ if province } i \text{ ranks as top five provinces with the highest e\_ratio} \\ 0, \text{ otherwise} \end{cases}$$

$$D_i^{bottom} = \begin{cases} 1, \text{ if province } i \text{ ranks as bottom five provinces with the lowest e\_ratio} \\ 0, \text{ otherwise} \end{cases}$$

Regression specifications are given by:

$$\log Y_{it} = \beta_1 \log X_{it} + \gamma_{1i} D_i^{top} + \theta_1 \log X_{it} \cdot D_i^{top} + \eta_1 Z_{it} + e_{it}$$
$$\log Y_{it} = \beta_2 \log X_{it} + \gamma_{2i} D_i^{bottom} + \theta_2 \log X_{it} \cdot D_i^{bottom} + \eta_2 Z_{it} + e_{it}$$

where,

$Y_{it}$ : Carbon emissions related to production and supply of electric power in province $i$, year t

$X_{it}$: EV sales in province $i$, year t

$Z_{it}$: Social-economic control variables such as GDP per capita, population

$e_{it}$ : Error terms

We are interested in both $\widehat{\beta_1} + \widehat{\theta_1}$ and $\widehat{\beta_2} + \widehat{\theta_2}$, whether being the province with large electricity imports or exports (as denoted by $D_i^{top}$ = 1 or $D_i^{bottom}$ = 1) affect the estimated marginal carbon emissions of EVs. We expect to find that being the province with large electricity imports lowers down the marginal carbon emissions of EVs since the pollution related to electricity generation happens outside of the province.

## VI. Results

Table II reports the estimation of the effects of EV sales on $CO_2$ emissions from electricity generation. Column (1) to (4) displays the regression result when the dependent variables are the log-transformed total EV sales, sales of BEV, and sales of PHEV. Column (1) shows the overall effect of total EV sales on $CO_2$ emissions related to electricity generation. 1% increase in total sales of EVs would lead to about 0.105% decrease in $CO_2$ emissions related to electricity generation. Even if China is thought to be a country with coal-intensive electricity generation, the benefits of EVs are still evident. The promotion of EVs, as a series of climate policies aimed to reduce carbon emission, does seem to take effect. Therefore, hypothesis 1 is verified.

TABLE II. Effect of EV Sales on CO2 Emissions Related to Electricity Generation (Interaction with Cities with the Highest e_ratio)

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Log Sales | -0.1047*** | -0.0756** | | |
| | (.0324) | (0.0324) | | |
| Log Sales × Top | | -0.0439* | | |
| | | (0.0265) | | |
| Log BEV | | | -0.0822*** | |
| | | | (0.0287) | |
| Log BEV × Top | | | -0.0455* | |
| | | | (0.0271) | |

| | | | | |
|---|---|---|---|---|
| Log PHEV | | | | -0.0655<br>(0.0487) |
| Log PHEV × Top | | | | -0.000421<br>(0.0366) |
| Top | | -0.227<br>(0.191) | -0.224<br>(0.187) | -0.552**<br>(0.234) |
| Real GDP per Capita | 0.0103***<br>(.00261) | 0.0131***<br>(0.00264) | 0.0133***<br>(0.00252) | 0.0119***<br>(0.00334) |
| Population | 0.2974***<br>(.02440) | 0.301***<br>(0.0231) | 0.312***<br>(0.0233) | 0.283***<br>(0.0258) |
| Constant | 3.506***<br>(.180) | 3.410***<br>(0.176) | 3.199***<br>(0.174) | 3.564***<br>(0.204) |
| Observations | 198 | 198 | 183 | 153 |
| R-squared | 0.424 | 0.472 | 0.509 | 0.432 |
| Yearly Fixed | X | X | X | X |
| Social-economic controls | X | X | X | X |
| Interaction with Top | | X | X | X |
| BEV Sales | X | X | X | |
| PHEV Sales | X | X | | X |

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

TABLE III. EFFECT OF EV SALES ON CO2 EMISSIONS RELATED TO ELECTRICITY GENERATION (INTERACTION WITH CITIES WITH THE LOWEST E_RATIO)

| | (1) | (2) | (3) |
|---|---|---|---|
| Log Sales | -0.103***<br>(0.0304) | | |
| Log Sales × Bottom | -0.00353<br>(0.0504) | | |
| Log BEV | | -0.104***<br>(0.0264) | |
| Log BEV × Bottom | | 0.0102<br>(0.0504) | |
| Log PHEV | | | -0.113***<br>(0.0414) |
| Log PHEV × Bottom | | | -0.0987<br>(0.0802) |
| Bottom | 0.459<br>(0.284) | 0.350<br>(0.274) | 0.917**<br>(0.366) |
| Real GDP per Capita | 0.0117***<br>(0.00247) | 0.0118***<br>(0.00237) | 0.0118***<br>(0.00365) |
| Population | 0.305***<br>(0.0236) | 0.315***<br>(0.0237) | 0.303***<br>(0.0284) |
| Constant | 3.329***<br>(0.184) | 3.147***<br>(0.214) | 3.339***<br>(0.214) |

| | | | |
|---|---|---|---|
| Observations | 198 | 183 | 153 |
| R-squared | 0.457 | 0.486 | 0.431 |
| Yearly Fixed | X | X | X |
| Social-economic controls | X | X | X |
| BEV Sales | X | X | |
| PHEV Sales | X | | X |

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Nonetheless, the overall effect of EV promotions does not tell us the whole story. It's necessary to probe into the effect of EV at the provincial level. Columns (2) to (4) are regressions with sales variables interacting with the dummy variable $D_i^{top}$. According to Column (2), for provinces with the highest e_ratio, 1% increase in total sales of EVs results in a 0.12% decrease in $CO_2$ emission from the electric power industry (result is significant at 10% level). Column (3) shows the estimated results for BEV sales. For provinces with the highest e_ratio, 1% increase in the sales of BEV is related to 0.128% decrease in $CO_2$ emissions from the electric power industry (result is significant at 10% level). Column (4) indicates that while negative coefficients are present, PHEV sales have no significant effect on $CO_2$ emissions related to electricity production. Overall, there is a benefit in driving EVs in provinces that have electricity generation much lower than consumption. This might be due to the fact that carbon emissions related to EVs are generated somewhere else (possibly in provinces with large electricity generations).

Table III displays the effect of EV sales on $CO_2$ emissions related to electricity generation for provinces with the lowest e_ratios. The coefficients of interaction terms are not significant for all three sales variables. This indicates that the marginal emissions associated with EV sales do not depend on whether or not the region belongs to the lowest e_ratios group. In other words, provinces with electricity generations higher than consumption have less significant effects on reducing EV marginal emissions compared to the provinces with electricity consumption higher than generations. Based on the analyses above, we can claim that there is enough evidence to validate hypothesis 2.

## VII. Conclusions and Discussions

While the hypothesis regarding the environmental benefits of EVs in reducing carbon emission is proven in our analysis, we found varied benefits for different geographic areas. For provinces with relatively high electricity import and low export, it's reasonable that EV sold is associated with a higher degree of carbon emission reduction compared to the overall effects in China (0.12% compared to 0.105%). As for provinces with relatively high electricity export and low import, EVs sold in these provinces appear to have insignificant effects on reducing carbon emissions. This corresponds to our hypotheses. Provinces with relatively high electricity imports and low exports, such as Beijing and Guangdong Province, are typically more economically advanced provinces (or municipalities). Environmental benefits of EVs are therefore more prominent in those provinces because pollution related to EV driving is generated elsewhere. Nonetheless, these environmental benefits are likely based on electricity generated from provinces with high electricity exports. EVs tend to export air pollution to provinces with high electricity exports. For those provinces, we've shown that the environmental benefit of EVs is less significant, likely offset by the carbon emissions related to electricity generation.

These findings on the geographic heterogeneity of EV marginal emissions have important implications for EV policies in China. Questions can be raised regarding the one-size-fits-all nature of the uniform national subsidy. As of 2021, a national subsidy of 13,000 yuan ($2,020) is given for purchasing BEV with a range from 300 km to 400 km; a national subsidy of 18,000 yuan ($2,800) is given for purchasing BEV with a range over 400 km; as for purchasing PHEV, a national subsidy of 6,800 yuan ($1,060) is provided [16]. Though there are variations between different types of EV, the national subsidy should also take geographic heterogeneity into consideration. Our results suggest that the minority of people living in those "bottom" provinces are suffering from environmental externalities generated by EVs. Appropriate subsidy policy for EVs should be at the national level but differentiated by location.

In addition, better technology support to electricity plants in the "Bottom" provinces is necessary to accommodate the growing demand for EVs. Specifically, the current power structure should be switching to one that uses clean renewable energy. Clean energy power plants including wind, hydro, solar photovoltaic (PV), and nuclear power plants are preferable to the existing majority of coal-based thermal power plants. Provinces with high electricity generation should aim to develop clean energy making use of their natural resources advantages. Inner Mongolia and Shanxi Province, for example, are "Bottom 5" provinces that are mainly dependent on thermal power generation (84% and 89% of total power generation in 2019 [2]) but with substantial potential in developing solar and wind power plants as replacements for thermal plants. Granted, an important factor of consideration is the cost-effectiveness of shifting the existing energy mix towards one that contains a higher proportion of clean energy. The fact that coal-based thermal power plants have been so popular is because of the low cost of coal. Nonetheless, the future of renewable energy power plants is still promising in China. According to [17], utility-scale solar PV and onshore wind have the lowest levelised cost of electricity (LCOE) in China. Nuclear energy also exhibits lower levelised generation costs compared to coal. As the transition of the power structure is taking place, the government will play an indispensable role in providing incentives and technology supports, especially to the "Bottom" provinces with underdeveloped but high potential for clean energy power.

Overall, this study provides empirical evidence for assessing the regional disparity of EV marginal emissions. The findings would help design the future EV policies and contribute to addressing the environmental externalities of EVs. Though focusing on vehicles, the econometric model might have broader applications for determining marginal emissions from other forms of electrification in the transportation sector. There are two main limitations to our research. On one hand, we have not considered the different energy consumption (kWh every 100 km) of different models of EV. We assume that all types of BEV and PHEV have the same contribution to electricity generation. On the other hand, limited by the data accessibility, our comparison of marginal emissions is merely conducted on the province level. The regional disparity might be more apparent if the analysis is conducted on the city or county level.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

Tinghan Ye conducted the research, proposed a model, and analyzed the data; Hanyi Wang determined the direction of the topic, provided the experimental ideas, and checked the results of the final data analysis; All authors had approved the final version.

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