The Impact of Public Charging Infrastructure Construction on Electric Vehicle Sales: An Empirical Study in China

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Abstract. The proliferation and advocacy of new energy vehicles play a crucial role in achieving carbon peak and carbon neutrality in China, effectively accelerating the decarbonization process within the transportation sector. This study focuses on the sales of pure electric vehicles in China. It constructs a panel fixed-effects model and a threshold-effects model using data from 31 provinces in China (excluding Hong Kong, Macao, and Taiwan) from January 2020 to December 2022, considering the number of charging piles and the sales of electric vehicles. The paper empirically examines the impact of public charging infrastructure on the purchase of pure electric vehicles, and analyzes the threshold effect of air quality on sales in different regions. The findings reveal that a 1% increase in the number of public charging stations leads to a significant 0.1574% increase in the purchase of pure electric vehicles. Additionally, regions with poorer air quality show a greater influence of public charging stations on pure electric vehicle sales, with significant dual thresholds of 67 and 77.

Keywords: new energy vehicle sales, public charging infrastructure, air quality, threshold effect

1 Introduction

As the global scientific and technological revolution and industrial transformation continue, the integration of automobiles with energy, transportation, information, and communication technologies is accelerating. The integration is driving the development of electrification, network connectivity, and intelligence. New energy vehicles have emerged as the primary focus of the global automobile industry's transformation and development, serving as a crucial driver for sustainable economic growth worldwide. Leading automobile nations have strengthened their strategic planning and policy support, while multinational automobile companies have increased their research and development investments and improved their industrial layout. Consequently, intense

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international competition and cooperation have emerged. China, being the world's largest auto consumer, with over 300 million cars, faces significant challenges related to energy consumption and environmental pollution caused by automobiles. With over 70% dependence on oil resources and vehicle emissions being a major contributor to urban air pollution, transportation emissions account for approximately 10% of China's total carbon emissions. In order to achieve energy security, environmental protection, carbon peaking, and carbon neutrality, China recognizes the development of electric vehicles as a crucial path forward. It is an inevitable choice to meet the growing expectations of its citizens for a better quality of life. China plays great importance in the electric vehicle industry for multiple reasons: as a strategic initiative to address climate change and promote green development, as a means to deepen supply-side structural reform, and as a driver for high-quality development on its path from being a major automobile nation to becoming a strong automobile nation. China has successively issued the Energy Saving and New Energy Vehicle Industry Development Plan (2012-2020) and the New Energy Vehicle Industry Development Plan (2021-2035). These plans clearly define the development goals, tasks, and measures of the EV industry and provide robust policy guidance and support for the industry's development.

Zhang Youguo [1] posited that the modernization of China's carbon governance system had gone through an evolutionary process from implicit to explicit. After the reform and opening up, China gradually formed an implicit carbon governance system under the leadership of energy saving strategy and the promotion of renewable energy strategy. As the problem of climate change has become more and more serious, China has formulated and implemented a series of strategic initiatives directly targeting the carbon intensity control goal, and the carbon governance system has entered the stage of explicit evolution dominated by carbon intensity control and is becoming more and more perfect. Zhang Xuemei [2] et al. discovered that energy "dual control" is closely related to the control of carbon emission growth and provided reference suggestions for the progress of energy "dual control" and carbon emission status in different regions. Xu Beiyao et al. [3] argued that reducing carbon emissions could achieve carbon neutrality and curb air pollution, O3, PM2.5, and CO2. Under strict regulation, temperatures might drop dramatically, and surface temperatures would continue to rise in the process of achieving carbon neutrality. In order to curb temperature rise, more rational planning of regional emission reduction paths and global emission reduction would be needed. Liu Tian-Le et al. [4] used the principal component analysis, the entropy evaluation method, and the coupled coordination degree model to explore the air quality of different cities, and the results showed that the scores of southern cities were significantly higher than those of the northern cities, showing that the coordination of pilot cities in the south was better than that of northern cities' local governments and that they should adopt low-carbon development policies.

The popularization and promotion of new energy vehicles can help China achieve carbon peak and carbon neutrality. Yu Yamei et al. [5] found that pure electric vehicles had significant GHG emission reduction potential compared with other vehicles. Zhao Xiaolei et al. [6] found that the promotion of new energy vehicles had a significant spatial spillover effect, and the promotion of local new energy vehicles not only reduced local carbon emissions but also reduced the carbon emissions of neighboring cities. Sun

Ying et al. [7] calculated the development trend of green GDP based on the scenario analysis technique and the green GDP accounting theory, and the results indicated that only under the low carbon emission scenario, China could achieve the carbon peak goal in 2030 and that the key to carbon emission reduction governance in the new era was to construct a new carbon emission control system, which would help China to achieve carbon peak and carbon neutral. Alan Jenn [8] argued that most of the emissions reductions from technology transformation in California's decarbonization strategy would come from vehicle electrification rather than grid decarbonization, and Ercan Tolga et al. [9] found that the adoption of self-driving electric vehicles could reduce greenhouse gas emissions by as much as 34% of total transportation emissions by 2050. The promotion of new energy vehicles has not only economic value but also health benefits. Pan Shuai et al. [10] demonstrated that widespread adoption of vehicle electrification could reduce oil consumption by 50%, cut CO2 emissions by about 75%, and prevent 5,500 premature deaths, which was equivalent to $58 billion in annual health benefits. Guo Jianfeng et al. [11] found a significant positive correlation between PM2.5 concentration and electric vehicle sales and pure electric vehicle sales.

However, range anxiety has become an important bottleneck constraining the development of the electrification of transportation in China. In the study of how range affected the sales of new energy vehicles, Wang Yuanyuan et al. [12] examined that the six pain points of negative consumer attitudes were inconvenient charging, charging dilemma, inability to install private charging piles, unsatisfactory charging modes, mileage anxiety, and limited range of purely electric vehicles, and at the same time, the more developed the city was, the higher the proportion of negative consumer attitudes, and negative attitudes played a more important role in the new energy vehicle. The more developed the city, the higher the proportion of negative attitudes, and negative attitudes play a more important role in the sales of new energy vehicles. Liu Yingqi et al. [13] argued that due to the government subsidies in the public and private sectors, the promotion of new energy vehicles was related to the degree of economic development in demonstration cities versus non-demonstration cities, and for demonstration cities, especially in areas with higher local government revenues, and further discussed the possibility of promoting the development of the new energy vehicle industry in China through increasing research and development (R&D) investment and building an industrial system under a competitive landscape. The study further discussed the possibility of improving the spatial spillover effect of the new energy vehicle market promotion in China through increasing R&D investment and building up the industrial system under the competitive pattern, thus promoting the development of the new energy vehicle industry. Yin Yarong et al. [14] found that the three factors that most influence purchasing attitudes are: battery replacement cost, low value retention, and battery spontaneous combustion, all of which negatively affect the choice of EVs. Zhang Zikai et al. [15] found that Macau residents' knowledge of EVs was relatively low by means of questionnaire surveys. The majority of respondents believed that EVs had environmental benefits, and only about 30% believed that EVs have short battery life, high safety, and low maintenance and repair costs. Kim Seiho et al. [16] found that the relative price, range, and number of models available in the market of EVs were correlated with EVs by conducting a panel data analysis on time series data from 2011 to

2015 for 31 countries where market share is correlated. They argued that policymakers needed to devote more resources to research and development to extend the range of electric vehicles when they entered the early stages of the market. Several scholars had planned strategies for stakeholders to plan infrastructure deployment with charging convenience and charging demand in mind [17,18]. Huang Youlin et al. [19] showed that new energy vehicle consumers in China's second and third-tier cities were very sensitive to range. Yang Xiong et al. [20] explored seasonal variations in electric vehicle (EV) charging demand and found that EV charging demand was higher in the winter months. Razi Faran et al. [21] argued that the construction of EV charging infrastructure could sustainably strengthen the EV industry across Canada in the long term. Jiang Ziyue et al. [22] designed a method for optimizing the layout of EV charging stations, taking into account EV charging behaviors as well as charging sequences and other relevant factors. Lv Ran et al. [23] found that direct current public charging posts had a much greater impact on the purchase of pure EVs than alternating current public charging posts, and also found heterogeneous impacts for different uses of EVs. In addition, the impact of public charging piles on pure EV purchases was greater in colder temperatures. Haidar Bassem et al. [24] found that the construction of fast charging facilities was positively associated with EV market share and that an increase in the price of gasoline had a positive effect on EV sales.

Existing literature has focused on exploring the negative sentiment affecting EV sales and seasonal changes in charging demand, with less attention paid to the impact of public charging facilities on EV sales. Therefore, based on the monthly panel data of public charging piles and pure EV sales in 31 provinces in China (excluding Hong Kong, Macao, and Taiwan) from January 2020 to November 2022, this paper utilizes the empirical analysis to explore the impact of the number of charging piles on the sales of pure EVs, and takes the air quality index (AQI) as the key factor to investigates the geographical differences in the relationship between charging pile construction and pure electric vehicles were studied. and analyzes in-depth the effects of the number of charging piles on the sales of pure EVs. The moderating effect and threshold effect of AQI on the relationship between charging piles and EVS is also deeply analyzed, and the construction targets of public charging piles in different regions based on AQI are also proposed, thus providing a reference for the rational planning of charging piles construction on the ground and realizing a win-win situation in terms of both economic performance and environmental performance.

The potential contributions of this study are threefold: firstly, the moderating effect of AQI on the impact of EV sales is explored when charging piles are constructed; secondly, a bidirectional impact relationship between public charging piles and EV sales is considered while the Granger causality tests are used to characterize the found bidirectional impact relationship instead of a unidirectional effect; and lastly, the empirical references are provided for the promotion of EVs through the construction of public EV charging piles for other densely populated countries as well as countries with heavy reliance on public charging piles for the deployment of charging pile constructions in the future.

The organization of this paper is as follows: A systematic review of how new energy vehicles contribute to China's carbon peak, carbon neutrality, and constraints to the development of electric vehicles is provided in Section 1, and data sources and model design are outlined in Section 2. An empirical analysis is conducted outlining the background of the problem and the corresponding hypotheses in Section 3, followed by the Granger causality tests in Section 4. Finally, Section 5 presents concluding remarks and potential research directions.

2 Research Design

2.1 Data Sources and Description of Variables

The public charging pile (*PCP*) data utilized in this study is sourced from the China Charging Alliance, and the total data timeframe is from January 2020 to December 2022, with a total of 36 time points, including 31 provinces and cities (excluding Hong Kong, Macao, and Taiwan). Pure electric vehicle purchase (*EVP*) data are from domestic passenger car sales data. In addition, this paper refers to previous studies [23,25] to select several factors that may affect the purchase of electric vehicles as control variables, including the consumer price index (*CPI)*, population size (*POP*), passenger capacity (*PC*), gross domestic product (*GDP*), per capita disposable income (*INC*)， *AQI*, and average annual temperature (*TEMP*).

POP data are from the annual data of the China Statistical Yearbook; *GDP* and I*NC* data are from the quarterly data of the China Statistical Yearbook; *CPI* data are from the monthly data of the China Statistical Yearbook; and *AQI* data are from the online monitoring and analyzing platform of air quality; *TEMP* data were obtained from 2345 Weather King. The descriptive statistics of each variable are shown in Table 1.

Table 1. Descriptive statistics for variables.

Variable	UoM	Mean	Std.dev.	Min	Max
EVP		8349.86	12051.3	0	87586
PCP		32988.44	43092.23	30	382960
CPI	/	101.7463	1.388587	98	106.9
POP	10,000	379.0762	250.8119	30.33333	1057
PC	10,000	2076.883	1601.596	93.16666	7109.167
GDP	100 Million CNY	6004.833	6624.037	81.5	41573.33
INC	CNY	6055.629	4301.768	886.5833	26009
AQI	$\mu g/m^2$	66.55108	20.5426	24	167
TEMP	°C	14.42115	10.53019	-20	33

Fig. 1 illustrates the trend of new energy vehicle sales volume. It indicates that the sales volume of new energy vehicles in different provinces has been increasing over time, but the trend of change is not the same as the timing. The differences in sales volume across provinces provide valuable insights into the factors influencing the sales volume of new energy vehicles.

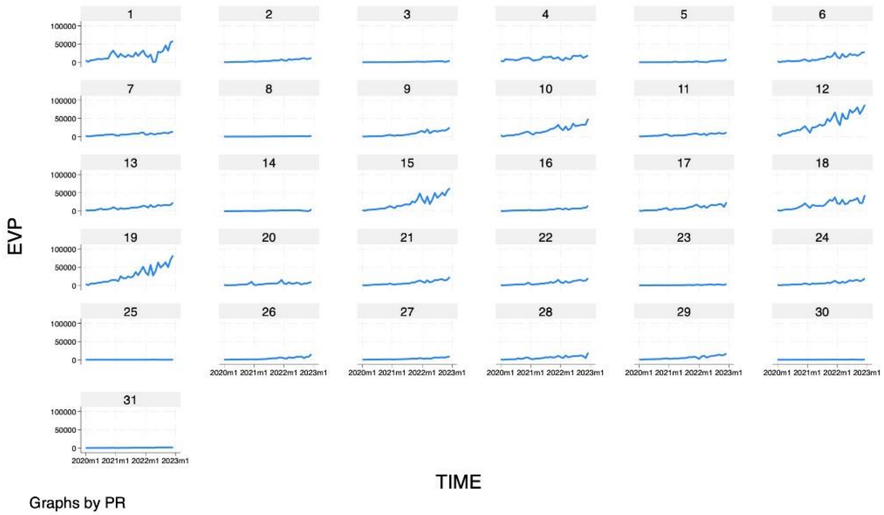

Fig. 1. Trends in sales of new energy vehicles.

2.2 Research Modeling

Benchmark Model of the Impact of Public Charging Piles on the Purchase of Pure Electric Vehicles. In order to study the impact of public charging piles on the sales of pure electric vehicles, this paper constructs the following panel fixed effects model:

$$EVP_{it} = \beta_0 + \beta_1 PCP_{it} + \sum_{j=1}^{n} \beta_j X_{ij} + \alpha_i + \lambda_t + \varepsilon_{it} \tag{1}$$

where EVPit is pure electric vehicle sales; PCPit is the number of public charging piles; Xit is the control variables, including CPI, POP, PC, GDP, per INC, AQI, and TEMP; n is the number of control variables; αi is an individual fixed effect that captures differences between individuals that do not vary over time; λt is a time fixed effect that allows for the problem of omitted variables that do not vary with the individual but do vary over time; εit is a random error term that incorporates unobserved demand shocks that vary over time and are specific to the province; and β is a coefficient.

Moderating Effects Test Model.

$$\begin{aligned} EVP_{it} = {} & \beta_0 + \beta_1 PCP_{it} + \beta_2 AQI_{it} + \beta_3 PCP_{it} \times AQI_{it} \\ & + \sum_{j=1}^{n} \beta_j X_{ij} + \alpha_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{2}$$

where AQI is the air quality index; $PCP_{it} \times AQI_{it}$ is the interaction term between the number of public charging piles and the average annual temperature.

Threshold Effects Model.

$$EVP_{it} = \beta_0 + \beta_1^{'} PCP_{it} I\left(AQI \leq \gamma\right) + \beta_2^{'} PCP_{it} I\left(AQI > \gamma\right) + \sum_{j=1}^{n} \beta_j X_{ij} + \varepsilon_{it} \tag{3}$$

where AQI_{it} are threshold variables; $I(\cdot)$ is the schematic function; λ is the threshold value.

3 Empirical Analysis

3.1 Impact of Public Charging Posts on Sales of Pure Electric Vehicles

The baseline model estimation results of the impact of public charging piles on the purchase of pure electric vehicles can be obtained using the panel fixed effects model, which are presented in Table 2. Column (1) of the regression results, which does not include control variables, indicates a significantly positive correlation between the number of public charging stations and the purchase of electric vehicles. Specifically, each additional public charging pile increases the purchase of pure electric vehicles by 0.233, which is significant at the 1% significance level, indicating that with the increase in the number of public charging piles, the willingness of residents to purchase new energy vehicles is significantly strengthened. Due to the different "provincial conditions" in each province, there may be omitted variables that do not change over time, and province-fixed effects and time-fixed effects are introduced in column (2). To mitigate the endogeneity problem caused by omitted variables, further control variables *CPI*, *POP*, *PC*, *GDP*, *INC*, *AQI*, and *TEMP* are added in column (3), and the regression results indicate that each additional public charging pile will increase the purchase of pure electric vehicles by 0.1574 units.

Table 2. Benchmark modeling of the impact of public charging piles on the purchase of pure electric vehicles.

Variable	$EVP_{(1)}$	$EVP_{(2)}$	$EVP_{(3)}$
PCP	0.2330^{***}	0.2085^{***}	0.1574^{***}
const	663.1481^{**}	-2088.269^{**}	-13255.42
Number of obs	1116	1116	1116
R^2	0.6942	0.6878	0.7588
Control variable	No	No	Yes
Province fixed effects	No	Yes	Yes
Time fixed effect	No	Yes	Yes

Note: $^*p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$

3.2 Moderating and Threshold Effects of Air Quality on Public Charging Piles and Sales of Pure Electric Vehicles

In a previous study [26], it was found that the construction of public charging piles had very distinct regional distribution differences. The construction speed of public charging piles in the eastern region led the country, while the construction speed of public charging piles in the western and central regions lags beheaded the national average. In addition to the difference in economic development level, the most obvious difference between regions was the regional air quality, which was mainly reflected in the difference in *AQI*. In order to study the relationship between charging piles and EV sales in different regions, this paper takes *AQI* as representative indicators of regional differences after controlling for the economic level of each region. This section will delve into the issue of *AQI* as an important moderating variable that affects the relationship between the two.

The Moderating Effect of Air Quality on Sales of Charging Piles and Pure Electric Vehicles. To investigate the moderating effect of the *AQI*, the moderating effect test model is constructed, and the test results are shown in Table 3. The moderating effect test results show that the interaction term between *AQI* and the number of public charging piles is significant and positive, which proves that the positive moderating effect of *AQI* on the relationship between public charging piles and the purchasing of pure electric vehicles is significant.

Table 3. Results of the test of the moderating effect of the air quality index on the relationship between public charging piles and the purchase of pure electric vehicles.

Explained Variable	*EVP*
PCP	0.2135***
PCP·AQI	0.0003***
AQI	-14.9629
const	1.6e+03**
R^2	0.6939

Note: *p<0.1, **p<0.05, ***p<0.01

Model Test of the Temperature Threshold Effect of Charging Piles and Electric Vehicle Sales. Although the above analysis has revealed the static effect of charging piles on EV sales, it is worth noting that the construction of charging piles is a long-term accumulation process, and there are dynamic changes in its impact on EV sales. Therefore, this study adopts a threshold model to verify the dynamic effect of charging piles on EV sales due to AQI changes.

Threshold effect tests are conducted assuming the existence of a triple threshold. A significant AQI threshold effect between charging piles and EV sales is demonstrated by 300 Bootstrap tests and *P*-value results through the self-sampling method. A significant double threshold for air quality at the 5% confidence level is seen in Table 4. The threshold and confidence interval estimates for the threshold effect model which is shown in Fig. 2 and Table 5, with threshold thresholds of 67 and 77 for air quality.

Table 4. A test of the threshold effect of temperature.

Threshold	Fstat	Prob	bootstrap
Single	15.69	0.1133	300
Double	29.59	0.0267	300
Triple	34.50	0.7067	300

Table 5. Estimated threshold.

model	Threshold	Lower	Upper
Th-1	77.0000	54.0000	78.0000
Th-21	77.0000	76.0000	78.0000
Th-22	67.0000	65.0000	71.5000
Th-3	54.0000	53.0000	55.0000

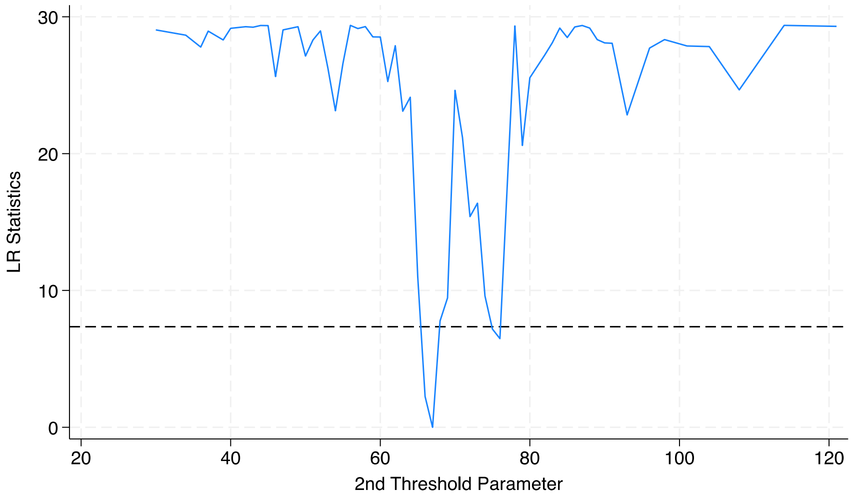

Fig. 2. Results of Double Threshold LR Statistic.

Table 6 displays the results of the threshold effect between the number of public charging stations and electric vehicle sales. When the result of AQI is lower than 67, the impact coefficient of public charging piles on the purchase of pure electric vehicles is 0.19, which is numerically close to the baseline regression results; when the result of AQI is higher than 67 and lower than 77, the impact coefficient of public charging piles on the purchase of pure electric vehicles is 0.15; when the result of AQI is higher than

77, the impact coefficient of public charging piles on the purchase of pure electric vehicles is 0.20. It can be seen that the worse the air quality, the greater the impact of public charging piles on the purchase of pure electric vehicles. Therefore, the worse the air quality is, the more important public charging piles are to the purchase of pure electric vehicles.

Lowering the external ambient temperature leads to an increase in the energy consumption of pure electric vehicles, which is even more variable in cold conditions. The lower the temperature, the wider the range gap between pure electric vehicles, and also the greater the need for public charging piles to extend their range. On the contrary, home charging piles can fully satisfy the daily range demand of pure electric vehicles when the temperature is higher, and the influence of public charging piles on the purchase behavior of pure electric vehicles decreases accordingly.

A higher percentage of new energy electric vehicle promotion and innovation can collaborate to get higher air quality improvement, weather economic benefits, and physical health economic benefits. There are two significant thresholds in the threshold model for the full *AQI* of 67 and 77. In areas where the *AQI* exceeds 77, the construction of public charging stations should be increased to better promote consumer purchases and the development and popularization of electric vehicles.

Table 6. Threshold effect model results.

Variable	*EVP*
$PCP(AQI<67)$	0.1900^{***}
$PCP(67<AQI<77)$	0.1519^{***}
$PCP(AQI>77)$	0.2048^{***}
const	13526.51^{***}
Number of obs	1116

Note: *$p<0.1$, **$p<0.05$, ***$p<0.01$

4 Granger Causality Test

The Granger causality test is conducted through *EVP* and *PCP*, and the results are shown in Table 7, which shows that there is a bi-directional Granger causality between the sales of electric vehicles and the number of public charging piles with a one-year lag at the 1% confidence level. In other words, the change of *EVP* is one of the causes of the change of *PCP*, while the change of *PCP* can explain the change of *EVP*.

The causes of this trend are examined from a demand perspective. Firstly, China's new energy vehicle countryside policy has spurred the incremental demand in the sinking market, leading to the growth in new energy vehicle consumption and an increase in the charging demand. This, in turn, has accelerated the development of new energy charging stations. Secondly, several policies have been introduced to promote the rapid growth of the domestic charging station industry. As public charging infrastructure construction continues to improve and achieve balanced deployment, it can alleviate the mileage anxiety of electric vehicle users and encourage the adoption of new energy vehicles.

Table 7. Results of the Granger causality test.

H_0	Lagorder	W-bar	Z-bar	Z-bartilde
EVP does not Granger-cause *PCP*	1	2.2820	5.0474***	4.2633***
PCP does not Granger-cause *EVP*	1	13.8136	50.4470***	44.7136***

Note: *p<0.1, **p<0.05, ***p<0.01

5 Conclusions

China's new energy vehicle industry is rapidly developing, with pure electric vehicles becoming the primary focus of new energy vehicle consumption and a key driver of ownership growth. The amount of supporting public charging infrastructure is closely related to the further promotion of pure electric vehicles. This paper establishes a panel fixed-effects model based on China's public charging pile data and pure electric vehicle sales from January 2020 to December 2022, and introduces *POP*, *AQI*, and *TEMP* as control variables for empirical analysis. The following main conclusions are drawn.

Firstly, the effect of the number of public charging piles on the purchase of pure electric vehicles is significantly positive. As the number of public charging piles increases, residents' willingness to purchase new energy vehicles is significantly strengthened.

Secondly, the empirical results show that the moderating effect of air quality in the relationship between public charging piles and the purchase of pure electric vehicles is significant and positive. The threshold effect model test found that the worse the air quality, the greater the impact of public charging piles on purchasing pure electric vehicles, a significant threshold value of 77. Therefore, it is necessary to increase the construction of public charging piles in areas with an annual air quality index higher than 77, which will not only promote the sales of pure electric vehicles but also improve air quality and achieve carbon peaks.

Lastly, analysis of *AQI* data reveals that areas with higher levels of air pollution are primarily concentrated in Henan Province, Shaanxi Province, Shandong Province, Shanxi Province, as well as the western region of Xinjiang Autonomous Region. These central regions are characterized by a greater concentration of heavy industries in China which contribute to increased air pollution levels. At the same time, in winter, the air pollution index in the Northeast region is also high, and the reason for this phenomenon may be that in cold weather, people need to heat up and the air quality is not good, and the battery efficiency of electric vehicles may be reduced due to low temperatures, which can lead to range anxiety among residents. Consequently, individuals residing in these areas tend to have a heightened awareness towards environmental protection. Furthermore, Henan and Shandong provinces are recognized as highly populated regions within China where insufficient public charging facilities may fail to meet people's mobility requirements adequately. As for Xinjiang province—a vast region—residents often have higher mileage demands compared to other areas. Therefore, improving the geographical distribution of charging stations within these specific regions could prove more effective in promoting electric vehicle sales.

Based on the empirical findings mentioned above, the corresponding policy recommendations are proposed: Firstly, the government should take significant steps to increase the availability of public charging stations to ensure that pure electric vehicles have access to reliable travel options, thereby promoting the adoption of electric vehicles. Then, in areas with poor air quality, the government can incentivize the creation of more public charging stations by providing subsidies, financing, and other forms of policy support. This will encourage the widespread use of pure electric vehicles in the community, while also providing safe and convenient travel options.

Considering the impact of the use of pure electric vehicles on achieving carbon peak and carbon neutrality, incentive measures will be considered to predict the sales of pure electric vehicles in the future. The aim of this study is to investigate the impact of promoting pure electric vehicles on GDP from a green economy perspective.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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