

The Impact of Electricity Supply and Demand on Carbon Prices: Evidence from China

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Abstract: China, the world's largest emitter of greenhouse gases, aims to achieve carbon neutrality by 2060, having already established a unified carbon market in 2021 following regional pilot markets that provided insights into carbon pricing mechanisms. This study addresses gaps by analyzing the impact of national electricity generation and industrial electricity consumption on carbon prices before the national market was established, using data from six provinces and applying multivariate regression models to explore the influence of electricity variables, GDP, and regional factors. Key findings indicate that both national electricity generation and industrial electricity consumption are positively correlated with carbon prices. Significant regional disparities are observed, with first-tier cities such as Beijing and Shanghai showing a stronger link between electricity generation and carbon prices compared to non-first-tier cities. Additionally, the influence of GDP on carbon prices varies across different models. These findings provide important insights for optimizing China's national carbon market, especially considering the 2060 carbon neutrality goal. This study contributes to the literature by filling the gap in understanding how electricity demand and supply impacted carbon pricing in China's pilot markets, offering valuable lessons for policymakers to enhance the national carbon trading system.

Keywords: carbon prices, carbon trading, electricity supply and demand.

1. Introduction

As the largest emitter of greenhouse gases, the Chinese government has implemented multiple policies to achieve the 2060 carbon neutrality goal, including establishing a unified carbon market in 2021 to manage greenhouse gas emissions. To construct and improve the national unified carbon trading market, China established several regional pilot carbon markets before 2021. These pilots were spread across various provinces, each with different economic and industrial development levels, providing valuable insights for developing a national unified carbon trading system. Despite these advances, coal accounted for approximately 73% of China's total energy supply as of 2010, with coal-fired power generation playing a significant role. [1] This has led to fluctuations in electricity supply and demand, directly impacting carbon prices and reflecting changes in industrial activity and related emissions. The pilot carbon markets in regions such as Beijing, Shanghai, and Guangdong served as testing grounds for carbon pricing strategies. However, the lack of consistency in trading rules and market liquidity across these markets resulted in varying degrees of effectiveness. [1] Understanding

how electricity supply and demand affected carbon prices during this period is crucial for the future development of a more comprehensive carbon market in China.

This paper aims to contribute to the current literature on carbon markets by analyzing how electricity supply and demand influenced carbon prices before 2021, with a particular focus on the impact of national electricity generation and industrial electricity consumption on carbon prices. This study provides valuable insights for optimizing China's national unified carbon market and advancing the 2060 carbon neutrality goal."

2. Literature Review

The implementation of carbon markets has become a core initiative in China's efforts to reduce greenhouse gas emissions and work towards the 2060 carbon neutrality goal. The literature on China's carbon market development emphasizes the importance of regional pilot programs as testing platforms for the establishment of the unified carbon market in 2021. These pilot programs, implemented in provinces with different economic conditions and industrial structures, provide essential insights into the complexities of carbon trading and its impact on greenhouse gas reduction.

Hua and Dong [2] provide a review of China's carbon market development, highlighting the significant role of the pilot programs in the transition to a unified market. Pilot markets in regions like Beijing, Shanghai, and Guangdong played a crucial role in testing carbon pricing mechanisms and revealed the challenges in policy implementation. However, the inconsistency in trading rules and market liquidity led to varying levels of success in these regions. Understanding these discrepancies is essential for designing a more stable and effective national carbon market. Hua and Dong further point out that the experience gained from these pilots is critical for optimizing the integration of carbon pricing mechanisms across different regions.[2]

In addition to the regional pilots, the literature highlights the significant role of coal and electricity production in the dynamics of the carbon market. For instance, Wang et al. [1] analyze the long-term trends in China's energy structure and carbon emissions. Despite efforts to diversify energy sources, coal remained the dominant energy source, accounting for 73% of China's total energy supply in 2010. Coal-fired power generation significantly affects carbon pricing, as fluctuations in electricity supply and demand directly influence emissions. Wang et al. indicate that industrial electricity consumption in energy-intensive industries is closely linked to carbon emissions, thereby impacting the volatility of carbon prices. [1]

Several studies have explored the economic impacts of carbon pricing and its interaction with regulated electricity prices. Li et al. [3], using a computable general equilibrium (CGE) model, assessed the economic impact of carbon pricing in China, focusing on regulated electricity prices. The study found that carbon pricing is an effective policy for reducing emissions. Still, it noted that regulated electricity prices might limit the long-term effectiveness of carbon pricing by distorting market signals. This finding is significant for understanding the interaction between China's carbon and electricity markets, especially in the context of coal-dominated power generation.

Jia and Lin [4] further explored policy choices between carbon taxes and carbon trading in China, concluding that carbon trading is more suitable given China's economic structure and energy profile. They emphasize the need for flexibility in carbon market design to accommodate regional differences in industrial activity and electricity consumption patterns. This is consistent with the findings of Fan et al. [5], who explored the impact of carbon pricing on the electricity market, highlighting how electricity reforms and carbon pricing strategies can complement each other in reducing emissions. However, they also warned that inconsistencies in policy implementation, such as differential pricing and market liquidity across regions, could hinder the effectiveness of the national carbon market.

The distributional impacts of carbon pricing have also been explored in the literature. Wang et al. [6] examined the regional disparities in the distributional effects of carbon pricing across China,

noting that provinces reliant on coal and energy-intensive industries face greater economic burdens from carbon pricing. The study stresses the importance of designing carbon pricing policies that account for regional differences in energy consumption and industrial structure, particularly in provinces where coal plays a dominant role in electricity generation.

Finally, Wu et al. [7] analyzed the economic impact of combining carbon pricing with renewable energy policies, noting that while renewable energy subsidies can promote the transition to cleaner energy, they also increase the economic costs of carbon pricing. The study suggests that a carefully balanced policy mix is needed to ensure both emissions reductions and economic stability. This is particularly relevant for China, where coal continues to dominate the energy landscape, and renewable energy subsidies must be carefully integrated into the carbon market framework.

In conclusion, the literature highlights several key themes essential for understanding the development of China's carbon market. The role of regional pilot programs, the dominance of coal in electricity production, and the interaction between carbon pricing and electricity market reforms are all crucial factors influencing the effectiveness of the carbon market. As China advances its national unified carbon market, addressing these challenges will be critical for achieving the 2060 carbon neutrality goal.

2.1. Data

All the data used in this study comes from the CSMAR database, which is currently the largest, most accurate, and most comprehensive economic and financial research database in China. The dataset used in this paper covers factors that may influence the variation in carbon prices in the Chinese market, including national power generation, industrial electricity consumption, provincial GDP, regions, and years. Due to the scarcity of data in some provinces in China, data from six provinces from 2014 to 2021 were used to ensure the completeness and accuracy of the regression analysis, forming a cross-sectional dataset. Given the scarcity of effective trading days and proportions in the carbon markets of Chinese provinces, this study only includes data from provinces with the highest number of effective trading days. These provinces include three first-tier cities (Guangdong, Shanghai, Beijing) and three non-first-tier cities (Tianjin, Hubei, Chongqing). Due to data scarcity, using annual data could lead to low data utilization and potential sample bias. Therefore, this study uses quarterly data, considering that quarterly data can better reflect the trends and changes in carbon prices and the impact of policies. Recognizing that quarterly data may still lead to significant volatility, this study processes GDP and carbon price data into weighted values to handle extreme values and data imbalance, thereby reflecting the actual impact. This paper uses national and industrial power generation as the core explanatory variables, measured in hundred million kilowatt-hours. Additionally, provincial GDP is used as a control variable to measure the impact of GDP differences in each province on the market carbon prices. Both region and time variables are clearly defined as fixed effects to detect factors that do not change with these two factors in different times and regions. Regional data must only be classified in the initial data processing stage, while time data does not require additional processing. The summary statistics for the variables in this study are presented as follows in Table 1.

Table 1: Descriptive Statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
carbon pw	171	29.365	18.595	2.5	87.333
gdpw	174	9289.204	6556.213	2874.35	30479.801
national elc	168	12146.661	4555.667	4779	21720
industrial use	166	9063.114	2402.435	5481	14086

Table 1: (continued).

prov	174	3.5	1.713	1	6
year	174	2017.138	2.102	2014	2021

The total sample size in this study is 171. The maximum value of the carbon price is 87.333, the minimum value is 2.5, and the average value is 29.365, indicating that the maximum carbon price in the database from 2014 to 2019 is 87.333 CNY, the minimum is 2.5 CNY, and the average is 29.365 CNY. The national power generation and industrial power generation have maximum and minimum values of 21,720 and 14,086 billion kilowatt-hours and 4,779 and 5,481 billion kilowatt-hours, respectively, with averages of 12,146.661 and 9,063.114 billion kilowatt-hours. The regions are numbered from 1 to 6, where 1 is Shanghai, 2 is Beijing, 3 is Tianjin, 4 is Guangdong, 5 is Hubei, and 6 is Chongqing. The next step is establishing a model to further analyze the factors influencing the carbon price and their statistical significance.

3. Econometric model

Since industrial electricity consumption is an important part of national electricity generation, the two are highly correlated. In Table 2, it is clear that the correlation coefficient between national electricity generation and industrial electricity consumption is 0.960, indicating a very high positive correlation between these two variables. Including both variables in the same model would lead to multicollinearity, resulting in large errors in the regression results. The common strategies to address multicollinearity are either to exclude one variable or to create a composite variable. Since both variables are core research variables in this paper, we decided to include the two variables in separate Ordinary Least Squares (OLS) models for regression analysis to better understand the relationship between China's carbon prices and various variables. Below is the model (1) and model (2).

$$Carbon_pw_{it} = \alpha + \beta_1 National_elc_t + \beta_2 GDPw_t + e_{it} \quad (1)$$

$$Carbon_pw_{it} = \alpha + \beta_1 Industrail_use_t + \beta_2 GDPw_t + e_{it} \quad (2)$$

Firstly, in model (1), the carbon price is used as the dependent variable, national electricity generation is the core independent variable, and China's GDP is the control variable. The regression results are shown in result (1) of Table 3. In model (2), the carbon price is used as the dependent variable, industrial electricity consumption is the core independent variable, and China's GDP is the control variable. The regression results are shown in result (1) of Table 4. The above two models can simply analyze the relationship between China's electricity supply and demand and the carbon price. Still, they overlook the fixed effects of regional exchanges and national policies. Since China established a unified carbon trading market in 2021, the carbon market before that had insufficient trading liquidity, inadequate response from market participants, and the emergence of information bubbles that limited the effectiveness of the carbon market.

Additionally, the trading rules varied across different exchanges, leading to heterogeneous volatility in carbon prices across different exchanges, which directly affects the accuracy of the carbon price data before and after 2021.[8]This could impact the accuracy of the regression analysis results and may lead to regression results that do not reflect the true relationship between carbon prices and core variables. Therefore, it is necessary to consider the changes brought about by the unified carbon market in 2021.

Thus, in model (3) and model (4), regions and years are included as fixed effects in the analysis models to further mitigate omitted variable bias, reduce the impact of time and specific regional

characteristics on the regression results, and ensure the accuracy and authenticity of the regression analysis results.

$$Carbon_pw_{it} = \alpha + \beta_1 National_elc_t + \beta_2 GDPw_t + \delta_t + \gamma_i + e_{it} \quad (3)$$

$$Carbon_pw_{it} = \alpha + \beta_1 Industrail_use_t + \beta_2 GDPw_t + \delta_t + \gamma_i + e_{it} \quad (4)$$

In models (3) and (4), fixed effects δ_t and γ_i are included to control for changes in carbon market trading rules and government policies, thereby reducing the error in the regression results. The regression results for the core variables, national electricity generation, and industrial electricity consumption are shown in results (2) of Table 3 and (2) of Table 4, respectively. Finally, considering the possibility of heteroskedasticity in the model, this paper will consider whether to introduce a weighted least squares estimation model after analyzing the results of the above model.

4. Result

Table 2: Matrix of correlations.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) carbon_pw	1.000					
(2) gdpw	-0.104	1.000				
(3) national_elc	0.157	0.083	1.000			
(4) industrial_use	0.168	0.090	0.960	1.000		
(5) prov	-0.498	0.129	-0.014	0.003	1.000	
(6) year	0.109	0.227	0.077	0.204	0.025	1.000

Based on the correlation table (Table 2), national electricity production and carbon prices exhibit a positive correlation (0.157), indicating that carbon prices tend to rise as electricity production increases. This also highlights the crucial role that power generation companies play in the carbon trading market. [9] Similarly, industrial electricity consumption positively correlates with carbon prices (0.168). These two data points are sufficient to demonstrate a significant correlation between carbon prices, national electricity production, and industrial electricity consumption, warranting further study. At the same time, carbon prices are negatively correlated with regions (-0.498), indicating the strong regional nature of the carbon trading market. This explains the need to establish a unified national carbon market. Additionally, the low correlation between the explanatory variables helps avoid multicollinearity in the regression, ensuring the accuracy of the analysis.

This study constructs two regression models, using national electricity production and industrial electricity consumption as the core independent variables, while controlling for GDP and other fixed effects (such as region and year), to examine their impact on carbon prices. The corresponding regression results are shown in Table 3 and Table 4, which will be analyzed and summarized respectively in the following sections.

5. Electricity Generation Regression Results

First, consider the results of model 1, which does not include fixed effects and is shown in the first column of Table 3. The regression analysis shows that for every increase of 100 million kilowatt-hours in national electricity generation, the carbon price rises by an average of 0.058%. This indicates that as electricity generation increases, the carbon price also rises. This is understandable, as power generation companies and other industrial sectors must manage their carbon emissions within the allocated quota. If emissions are below the cap, they can trade excess quotas; if emissions exceed the cap, they must purchase additional quotas. [9] However, GDP is not significant in this model.

Additionally, the R-squared value is relatively low, at 0.028, indicating that the model only explains a small portion of the variation in carbon prices, likely due to the exclusion of time and regional factors.

Thus, the explanatory power of model 2, which introduces fixed effects for year and province, is significantly improved, with the R-squared rising to 0.739. According to result 2, the impact of national electricity generation on carbon prices has changed, decreasing from 0.058% to 0.045%. The results also show that for every unit increase in GDP, carbon prices decrease by 0.098%. In the early stages of China's carbon trading market, the system was a pilot scheme, and trading data were quarterly, so the introduction of fixed effects addressed potential unobserved heterogeneity related to time and location, providing a more comprehensive understanding of the relationship between electricity generation and carbon prices. [8]

To gain a deeper understanding of the relationships between variables, heterogeneity analysis was conducted for the periods before and after 2020, to observe the impact of different policies implemented in China before and after the COVID-19 pandemic and to improve the robustness of the model results. Now, let's look at models 3 and 4. Model 3 focuses primarily on the period before 2020. The results indicate that for every unit increase in national electricity generation, the carbon price increases by 0.031%, while GDP has a negative impact on carbon prices, decreasing them by 0.084%. In the results of model 4, which focuses on the period after 2020, we find that, due to the scarcity of the sample, both national electricity generation and GDP are not significant variables, but the province of Beijing has a significant impact on the dependent variable. Since China's carbon market was a pilot system before 2021, different provinces may have had different economic policies, resource allocation, industrial structures, or infrastructure, all of which can significantly affect carbon prices.

Lastly, in models 5 and 6, the analysis considered the heterogeneity between different provinces. The results show that the relationship between electricity generation and carbon prices varies significantly across different regions. In first-tier cities like Shanghai, Beijing, and Guangdong, the correlation between electricity generation and carbon prices is significantly higher than in other provinces. Additionally, the R-squared value in model 5, which includes first-tier cities, is 0.838, significantly higher than the 0.380 in model 6, indicating that electricity production in more developed regions has a more significant impact on carbon prices.

6. Industry electricity consumption regression results

Next, we will analyze the regression result of industrial electricity consumption. The results from model 1, which does not include fixed effects, as shown in the first column of the table. The regression analysis indicates that for every unit increase in industrial electricity consumption, the carbon price increases by 0.126%. This suggests a positive correlation between industrial electricity consumption and carbon prices, which aligns with expectations. Increased industrial electricity consumption typically correlates with heightened production activity, leading to higher carbon emissions and, consequently, an increased demand for carbon allowances. However, the GDP variable is insignificant in this model, and the R-squared value is relatively low at 0.038, indicating that the model explains only a small fraction of the variation in carbon prices. This is likely due to the exclusion of regional and temporal factors.

Second, introducing fixed effects for both year and province in model 2 significantly enhances the model's explanatory power, with the R-squared increasing to 0.760. The positive relationship between industrial electricity consumption and carbon prices remains, and it is statistically significant, although the effect size is slightly smaller at 0.08. Meanwhile, the effect of GDP becomes marginally significant, with a negative impact on carbon prices of -0.07%, suggesting that accelerated GDP growth is associated with a slight reduction in carbon prices. This is consistent with the relationship

observed between GDP and carbon prices in the national electricity generation models discussed earlier. Including fixed effects addresses potential unobserved heterogeneity related to time and region, providing a more nuanced understanding of how industrial electricity consumption interacts with carbon pricing in China's carbon market.

To further explore the relationships between variables, heterogeneity analysis was conducted before and after 2020 to examine the impacts of differing policies implemented before and after the COVID-19 pandemic. Model 3 focuses on the period before 2020, and the results show that for each unit increase in industrial electricity consumption, carbon prices rise by 0.061%, while GDP exerts a slightly negative influence of -0.057%. In contrast, model 4, which examines the period after 2020, highlights some data limitations. Both industrial electricity consumption and GDP become insignificant, but the province-level variable (Beijing) has a significant impact on carbon prices. Given that China's carbon market was still in the pilot phase before 2021, these results suggest that provinces experienced significant variations in economic policies, resource allocation, and industrial structure, contributing to differential impacts on carbon pricing.

Finally, models 5 and 6 analyze the heterogeneity across different provinces. The results demonstrate substantial regional variation in the relationship between industrial electricity consumption and carbon prices. In first-tier cities such as Shanghai, Beijing, and Guangdong, the correlation between industrial electricity consumption and carbon prices is significantly stronger than in other provinces. The R-squared value in model 5, which includes first-tier cities, is 0.841, much higher than the 0.409 observed in model 6, indicating that industrial electricity consumption in more developed regions has a greater impact on carbon prices. This finding suggests that the link between industrial activity and carbon pricing is more pronounced in economically advanced regions, likely due to stricter environmental regulations, more developed economies, and higher levels of industrial activity.

So far, the optimal regression results of this paper are results (2) in Table 3 and Table 4. A test for homoscedasticity was conducted to further assess the validity of the model. The Breusch-Pagan test results show that for the result (2) in Table 3, the chi-square statistic is 8.14 with a p-value of 0.0043, and for the result (2) in Table 4, the chi-square statistic is 13.51 with a p-value of 0.0002. This indicates the presence of significant heteroscedasticity in the model, which suggests that the significance of the previous estimates might be incorrect (as heteroscedasticity affects the accuracy of the standard errors of the coefficients).

To address this, the paper adopts the STATA robust command method and re-estimates model (2) using heteroscedasticity-robust standard errors, obtaining result (7). The regression results after correcting for heteroscedasticity show that the coefficients of the variables remained largely unchanged. For example, the coefficient for "national electricity generation" remained at 0.00045 both before and after the correction. Overall, despite the presence of heteroscedasticity, the regression coefficients themselves did not change, indicating that the model's basic structure and estimates are robust. Therefore, this paper selects the model corresponding to result (6) as the final model, with the equation as follows:

$$Carbon_pw_{it} = \alpha + \beta_1 National_elc_t + \beta_2 GDPw_t + \delta_t + \gamma_i + e_{it} \quad (5)$$

$$Carbon_pw_{it} = \alpha + \beta_1 Industrail_use_t + \beta_2 GDPw_t + \delta_t + \gamma_i + e_{it} \quad (5)$$

Table 3: National Electricity Generation Regression Results.

	OLS (1)	FE (2)	HA (3)	HA (4)	HA (5)	HA (6)	Robust (7)
VARIABLE	carbon_p	carbon_p	carbon_p	carbon_p	carbon_p	carbon_p	carbon_p
S	w	w	w	w	w	w	w
national_elc	0.001* (0.000)	0.000** (0.000)	0.000* (0.000)	0.001 (0.001)	0.001*** (0.000)	0.000 (0.000)	0.000** (0.000)
gdpw	-0.000 (0.000)	-0.001** (0.000)	-0.001* (0.000)	-0.001 (0.002)	-0.002*** (0.000)	-0.000 (0.001)	-0.001* (0.001)
Constant	25.189*** (4.450)	40.217*** (3.975)	41.227*** (4.069)	43.045** (17.004)	45.118*** (4.198)	24.320*** (5.047)	40.217*** (4.423)
FE	N	Y	Y	Y	Y	Y	Y
Observations	162	162	134	28	84	78	162
R-squared	0.028	0.739	0.761	0.685	0.838	0.380	0.739

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4: Industrial Electricity Consumption Regression results.

	OLS (1)	FE (2)	HA (3)	HA (4)	HA (5)	HA (6)	Robust (7)
VARIABLES	carbon_pw	carbon_pw	carbon_pw	carbon_pw	carbon_pw	carbon_pw	carbon_pw
industrial_use	0.001** (0.001)	0.001** (0.000)	0.001* (0.000)	0.002 (0.001)	0.001** (0.000)	0.000 (0.000)	0.001** (0.000)
gdpw	-0.000 (0.000)	-0.001* (0.000)	-0.001 (0.000)	-0.001 (0.002)	-0.002*** (0.001)	-0.000 (0.001)	-0.001 (0.001)
Constant	20.628*** (5.752)	37.179*** (4.337)	38.681*** (4.312)	35.902* (17.774)	40.743*** (4.991)	23.585*** (5.658)	37.179*** (4.198)
FE	N	Y	Y	Y	Y	Y	Y
Observations	160	160	132	28	82	78	160
R-squared	0.038	0.760	0.792	0.687	0.841	0.409	0.760

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

7. Conclusion

This study highlights the significant impact of China's electricity supply and demand on carbon pricing. Both national electricity generation and industrial electricity consumption are positively correlated with carbon prices, indicating that increased electricity generation and industrial electricity consumption lead to greater demand for carbon emission allowances. Historically, coal has been China's primary energy source, accounting for a large portion of the country's total energy consumption. [1] As of 2010, coal accounted for approximately 73% of total energy supply. However, it is projected that this proportion will decline to around 43% by 2050. Despite the decline, coal will continue to play a key role in China's energy supply, remaining above 50% of total energy consumption around 2042. [1] Even though the coefficient of national electricity generation is 0.00045, the mean national electricity generation is 12,146.66 billion kWh (Table 1), which implies that the impact of national electricity generation on carbon prices is substantial each quarter, as the mean carbon price is only 29.36. The mean industrial electricity consumption is 9,063, which similarly indicates a strong impact on carbon prices. Interestingly, GDP is insignificant in the model where industrial electricity consumption is the core independent variable, but it has a negative impact

in the model where national electricity generation is the core independent variable. This may be the result of China's shifting economic structure. Additionally, since China's carbon market was still in the pilot phase before 2021, this study introduces fixed effects to improve the explanatory power of the model, emphasizing the role of regional and temporal differences.

The heterogeneity analysis reveals significant differences across different periods and provinces. While national electricity generation and industrial electricity consumption were statistically significant before 2020, the results become insignificant after 2020, likely due to data scarcity caused by the COVID-19 pandemic. Moreover, first-tier cities like Beijing, Shanghai, and Guangdong showed significant results compared to non-first-tier cities, where the results were mostly statistically insignificant in the heterogeneity analysis. These findings suggest that economically developed regions have more active environmental regulations and industrial activities.

In conclusion, China's electricity demand and supply play a crucial role in shaping carbon prices in the country's carbon market. Government agencies should consider the industrial and economic disparities across provinces, especially when establishing a unified carbon trading market.

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