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Research on the Impact of Green Certificate Trading System on Regional Electricity Carbon Emissions

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Abstract

This paper utilizes the nationwide pilot implementation of China's Green Certificate Trading System in 2017 as a quasi-natural experiment. A generalized difference-in-differences model is constructed, and panel data from 31 provincial-level administrative regions from 2010 to 2023 are used to empirically examine the impact of the system on regional carbon emission intensity in the power sector. The study finds that the implementation of the Green Certificate Trading System significantly increased regional carbon emission intensity in the power sector. This finding remains robust after parallel trend tests, placebo tests, and various robustness checks. Mechanism analysis reveals that the main reasons for this policy effect contradicting the original emission reduction intention are: at the institutional design level, the separation between green certificates and carbon markets and the failure of the pricing mechanism; at the market mechanism level, the non-coverage of indirect emissions and insufficient liquidity; and at the technological pathway level, the existence of technological lock-in effects and energy rebound effects. This study provides new evidence on the potential unintended consequences of implementing environmental regulation policies and offers targeted policy insights for improving the green certificate trading system and collaboratively advancing the low-carbon transition of the power sector.

JEL classification numbers: P28.
Keywords: Green Certificate Trading System, Regional carbon emission intensity in the power sector, Generalized difference-in-differences.

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1. Introduction

With the growing severity of global climate change, reducing carbon dioxide emissions has become a critical challenge faced by all countries worldwide. On September 22, 2020, at the general debate of the 75th session of the United Nations General Assembly, China announced that "it will enhance its nationally determined contributions, adopt more vigorous policies and measures, and strive to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060." In the energy sector, the power industry, as one of the primary sources of carbon emissions, is crucial for its green and low-carbon transition. To promote the development of renewable energy and reduce carbon emissions in the power industry, China introduced the Green Electricity Certificate Trading System in 2017. This system uses market-based mechanisms to assign financial value to the environmental attributes of renewable energy, incentivizing enterprises to invest in clean power projects and promoting the transformation of the energy structure, thereby indirectly reducing carbon emissions in the power sector.

China's Green Certificate System has evolved through a dual-track exploration from "voluntary subscription" to "mandatory constraints". From 2011 to 2017, it was in an exploratory phase, trialing green certificate issuance and voluntary subscription, with supporting policies still under development. From 2017 to 2020, it entered a pilot reform stage, where the National Energy Administration issued the "Interim Measures for the Voluntary Subscription and Trading of Green Electricity Certificates," clarifying the scope of green certificate issuance and trading rules, and the Green Certificate Trading System began to be piloted nationwide. Since 2021, it has entered a mandatory constraint phase, with the implementation of the renewable energy consumption responsibility weight system, making green certificates a key tool for quota assessment. Theoretically, the Green Certificate Trading System, by creating additional green revenue through market-based trading, should enhance the competitiveness of renewable energy, reduce the proportion of traditional fossil fuel power generation, and thereby achieve emission reductions. However, the actual effectiveness of the policy is profoundly influenced by multiple factors such as institutional design, market environment, and technological pathways. Existing research has primarily focused on the mechanism design of the green certificate system or its theoretical synergy with carbon markets, with a lack of literature that systematically evaluates its emission reduction effects from a macro perspective using rigorous econometric methods.

The marginal contributions of this paper are threefold: First, from a research perspective, it is the first to utilize national provincial-level panel data, treating the Green Certificate Trading System as an exogenous policy shock, to systematically evaluate its net impact on regional carbon emissions from the power sector. Second, in terms of methodology, it employs a generalized difference-in-differences model, using green certificate trading volume as a continuous measure of treatment intensity, to more accurately identify the heterogeneous effects of the policy. Third, in terms of research depth, it not only verifies the overall policy effect but also delves into the underlying mechanisms from institutional, market, and technological dimensions that explain why the policy outcome contradicts its original intent, providing clear targets for subsequent policy optimization.

2. Literature Review and Theoretical Analysis

As a crucial policy instrument for promoting renewable energy development and reducing carbon emissions, research on the Green Certificate Trading System has accumulated substantial findings both domestically and internationally. Early studies primarily focused on theoretical foundations and institutional framework design. Theoretically, Fischer & Newell (2008) compared various climate policies, including renewable portfolio standards and emission pricing, evaluating their economic efficiency under different conditions, thereby providing theoretical support for understanding the cost-effectiveness of the Green Certificate Trading System. Academics generally agree that by using market-based approaches to assign financial value to the environmental attributes of renewable energy, green certificates can effectively correct their positive externalities. Fan & Xi (2017) systematically reviewed international experiences and noted that while the U.S. has considerable experience in promoting the green certificate trading system, Germany's situation is more comparable to China's in certain aspects, offering valuable insights for China. Ren (2019), through a comparison of the electricity markets in China and the U.S., identified significant institutional and policy differences, highlighting the profound impact of the institutional context on policy design. Gu (2019) focused more on the initial state of the green certificate market, analyzing China's green certificate market from the perspectives of pricing and market performance, and validated the feasibility and effectiveness of trading mechanisms and bidding strategies through simulations. Such research provides a solid theoretical foundation for understanding "why green certificates emerged" and "how they should be designed."

With the advancement of China's carbon market development and the introduction of the "dual carbon" goals, academic research has increasingly shifted toward the interactions between green certificates and other policies. Numerous studies have employed modeling and simulation methods to explore system operations and emission reduction effects under multi-market coupling. Peng et al. (2024) developed a low-carbon dispatch model for multi-regional power systems based on carbon-green certificate market mechanisms, analyzing the impact of different market signals on system operating costs. Li et al. (2024), from the perspective of power producers, constructed a bi-level game model to quantitatively analyze the incentive effects of green certificate and carbon emission trading systems on producers' optimal resource allocation structures. Zhang & Zhou (2020) built a system dynamics model involving the green certificate trading market, carbon emission trading market, generation rights trading market, and electricity market. Their findings demonstrated that the green certificate trading market significantly promotes renewable energy development. Subsequently, ALKHALAF (2021) integrating system dynamics theory, proposed an ET-based electricity market model, a TGC-based electricity market model, and an electricity market model under the combined effects of ET and TGC. The study analyzed the causal relationships among the three models and verified their validity. These studies deepen the academic understanding of the complexities of policy combinations but largely remain at the theoretical simulation stage, lacking empirical validation.

In recent years, some scholars have begun to focus on potential unintended consequences during the implementation of the system and have empirically tested them, providing the most direct theoretical reference for this paper. Li et al. (2023) indicated that the Green Certificate Trading System may lead to distorted calculations of the carbon emission factor for electricity, resulting in double counting of renewable energy's carbon reduction contributions and free-rider effects. This preliminarily demonstrates that institutional loopholes may offset emission reduction benefits. Zhang et al. (2024), based on graph database and graph computing technologies, established a quantitative measurement system for regional electricity carbon emission transmission, offering methodological support for monitoring changes in electricity carbon intensity across regions within the context of green electricity trading. In international research, scholars have revealed the inherent complexities in the energy transition process associated with green certificate trading from various perspectives. These complexities collectively pose practical challenges to the green certificate system achieving its theoretical emission reduction effects. Cheng et al. (2025) studied the lifecycle CO2 emissions of a typical 500 kV substation. The results showed that power facilities themselves also entail significant carbon costs. The Green Certificate Trading System can indirectly reduce the lifecycle carbon emissions of power facilities by promoting the application of renewable energy generation across the power industry. The green certificate system aims to alter the power supply structure, but its impacts are complexly transmitted through grid network effects. Vincenti & Valenti (2025) evaluated the avoided CO2 cost from well-to-wheel for zero-tailpipe-emission vehicles through a case study. The connection to regional electricity carbon emissions lies in the interplay between the energy transition in the transportation sector and renewable energy development in the power sector. The Green Certificate Trading System can incentivize the power industry to supply more renewable electricity to meet the electrification demands of the transportation sector, indirectly influencing regional electricity carbon emissions. Furthermore, external environmental factors profoundly constrain the effectiveness of the green certificate market. Ali et al. (2025) examined the impact of financial development on energy accessibility in the Middle East and North Africa (MENA) region, providing evidence from the perspectives of credit rationing and carbon emissions. The close link between financial development and the energy sector means that the Green Certificate Trading System, as a market mechanism, may be influenced by financial development, thereby affecting regional electricity carbon emissions. Meanwhile, Mebrek (2025)'s research on the impact of foreign direct investment (FDI) on carbon emissions also suggests that international capital flows in the energy sector may reinforce or undermine the investment structure that the local green certificate market seeks to guide.

In summary, existing domestic and international research on the Green Certificate Trading System, as a key market-based tool for promoting the low-carbon transition of the power industry, has extensively explored its emission reduction effects and mechanisms. Scholars generally agree that the system effectively fosters renewable energy development through economic incentives, thereby reducing carbon emissions in the power sector. However, despite the abundance of studies, there is a lack of empirical research based on diverse models.

The core efficacy of the Green Certificate Trading System lies in using market signals to correct the positive externalities of renewable energy, thereby driving the low-carbon transition of the power industry. However, the realization of this theoretical efficacy is strictly constrained in practice by the completeness of institutional design and the effectiveness of market mechanisms. In its initial stages, China's green certificate market faces multiple practical challenges, including, but not limited to: insufficient policy coordination due to poor integration between the green certificate market and the carbon emission trading system; undervaluation of environmental benefits caused by dysfunctional pricing mechanisms; impeded price discovery functions due to limited market liquidity; and evasion of indirect emission responsibilities resulting from ambiguous accounting boundaries. These structural deficiencies may collectively hinder policy transmission, not only diluting emission reduction incentives but also potentially causing adverse effects through specific channels. Based on this, this paper proposes the following competing research hypothesis:

H1: The implementation of the Green Certificate Trading System has a significant "policy paradox" effect on regional electricity carbon emission intensity, meaning that instead of achieving the theoretically expected emission reduction outcomes, it leads to an increase in carbon emission intensity.

3. Research Design

3.1 Sample Selection and Data Sources

To systematically evaluate the policy effects of the Green Certificate Trading System and obtain a relatively balanced panel dataset, this paper selects the period from 2010 to 2023 as the sample interval. The Green Certificate Trading System was officially piloted in 2017. This sample period covers a sufficiently long pre-policy implementation period, facilitating an effective policy impact assessment. The initial data were processed through the following screening steps: (1) Based on data availability and consistency, the research scope is limited to 31 provincial-level administrative regions in mainland China; (2) All province-year observations with missing key variables were excluded. After the above processing, a balanced panel dataset encompassing 31 provinces and municipalities across 14 years was finally obtained, totaling 434 valid sample observations.

The data in this paper are sourced from multiple authoritative channels. Provincial grid carbon emission factors are sourced from the "Research on CO2 Emission Factors for China's Regional Grids (2023)". Data on provincial electricity consumption are obtained from the statistical yearbooks of each province. Data on green electricity certificate trading volumes were acquired by accessing the China Green Electricity Certificate Trading Platform and manually compiling the information. The raw data for the remaining control variables primarily come from the "China City Statistical Yearbook", "China Regional Statistical Yearbook", and the CSMAR database. To mitigate the potential impact of outliers on the model estimation results, all continuous variables in this paper were winsorized at the 1st and 99th percentiles.

3.2 Model Specification and Variable Definitions

This paper treats the pilot implementation of the Green Certificate Trading System in 2017 as an external policy shock. A generalized difference-in-differences (DID) model is constructed using a panel dataset of 434 observations from 31 provincial-level administrative regions from 2010 to 2023 for policy evaluation. The specific econometric model is as follows:

$$LNCI_{it} = \beta_0 + \beta_1 (GREEN_{it} * TYPE_{it}) + \beta_2 Control_{it} + \theta_i + \varphi_t + \varepsilon_{it} \tag{1}$$

In Model (1), $LNCI_{it}$ is the explained variable, representing the carbon emission level from urban electricity consumption. This paper uses the carbon emission intensity of electricity consumption as a proxy variable. Electricity is regarded as a fundamental energy source for industrial development and a significant contributor to the increase in carbon dioxide emissions. In view of this, this paper focuses on the carbon emissions resulting from electricity consumption, using the carbon emission density of electricity consumption as the evaluation indicator. It is worth emphasizing that the total carbon emissions caused by electricity consumption are calculated by multiplying the total electricity consumption in a specific region by the carbon emission factor of the local power grid. In this process, the carbon emission factors for regional power grids can be referenced from the data provided in "China Regional Grid Research (2023)".

The explanatory variable $GREEN_{it} \times TYPE_{it}$ is the product of the implementation status and the implementation intensity of the Green Certificate Trading System, denoted as DID in the model, used to distinguish the implementation level of the system across different years and regions. $GREEN_{it}$ represents the implementation status of the Green Certificate Trading System, assigned a value of 0 before the policy introduction and 1 from 2017 onwards when implementation began. $TYPE_{it}$ indicates the implementation intensity of the Green Certificate Trading System. Drawing on the research of Ji et al. (2024) and considering the policy orientation, market influence, and practical operation of the system, provinces with annual green certificate trading volumes below one million are assigned a value of 0 (control group), and those with volumes of one million or above are assigned a value of 1 (treatment group).

X_{it} represents a set of control variables. To account for the influence of other potential factors on the carbon emission level from electricity consumption, this paper comprehensively analyzes the main influencing factors of electricity carbon emissions and, referencing the research of Chang et al. (2023), incorporates a series of control variables.These include industrial structure (IS), technological innovation (TECH), government involvement (GOV), population size (POP), and the level of government technology (GTECH).

i and t represent the city and year, respectively. μ_i and λ_t represent city fixed effects and year fixed effects, respectively, and ε_{tt} is the random error term. The coefficient of interest in this paper is β_1. If β_1 is negative and statistically significant, it implies that the Green Certificate Trading System significantly reduces the carbon emission level from electricity consumption. Detailed definitions of the variables are presented in Table 1.

Table 1: Variable Definitions and Measurement Methods

Variable Type	Variable Name	Variable Symbol	Definition
Explained Variable	Carbon Emission Intensity of Electricity Consumption	LNCI	Natural logarithm of the product of regional electricity consumption and the provincial grid CO2 emission factor.
Core Explana-tory Variable	Policy Interaction Term	DID	$GREEN_{it} \times TYPE_{it}$, where $GREEN_{it}$ is a policy dummy variable (equals 1 for the year 2017 and onwards), and $TYPE_{it}$ is the treatment intensity variable (equals 1 if the annual green certificate trading volume exceeds one million units).
Control Variables	Industrial Structure	IS	Industrial structure hierarchy coefficient (Proportion of secondary industry value-added to regional GDP).
	Technological Innovation	TECH	Number of patent applications per million people.
	Government Involvement	GOV	Proportion of general public budget expenditure to regional GDP (%).
	Population Size	POP	Natural logarithm of the year-end total population.
	Government Science & Technology Level	GTECH	Proportion of government science and technology expenditure to general public budget expenditure (%).

3.3 Descriptive Statistics

Table 2 presents the descriptive statistics of the variables. The mean value of LNCI is 6.7748, the median is 6.71, and the standard deviation is 1.051. The mean value of GREEN is 0.5000, the median is 0.50, and the standard deviation is 0.501.

Table 2: Results of Descriptive Statistical Analysis

Variable Name	Observations	Mean	Standard Deviation	Minimum	Median	Maximum
LNCI	434	6.7748	1.051	2.47	6.71	8.83
GREEN	434	0.5000	0.501	0.00	0.50	1.00
TYPE	434	0.4516	0.498	0.00	0.00	1.00
IS	434	0.2840	0.684	0.03	0.10	4.90
TECH	434	0.2171	0.242	0.01	0.13	1.46
GOV	434	0.2767	0.203	0.11	0.22	1.38
POP	434	8.1294	0.842	5.70	8.26	9.45
GTECH	434	0.0213	0.016	0.00	0.01	0.07

3.4 Multicollinearity Test

To prevent high correlation between variables and the presence of multicollinearity affecting subsequent model fitting, a Variance Inflation Factor (VIF) test was conducted for all variables. The results are shown in Table 3.

Table 3: VIF Test Results

Variable Name	VIF	1/VIF
TECH	4.61	0.217
GTECH	3.55	0.282
POP	2.40	0.417
GOV	2.36	0.425
IS	2.14	0.467
DID	1.30	0.770
VIF	2.73	-

As can be seen from Table 3, the VIF values for each variable range between 1.30 and 4.61, with a mean VIF of 2.73. It is generally accepted that when VIF values are less than 10, there is no severe multicollinearity problem. Therefore, the variables in this study do not exhibit multicollinearity and will not significantly impact the model estimation results.

4. Empirical Results and Analysis

4.1 Benchmark Regression Results

Table 4 presents the benchmark regression results of the impact of the Green Certificate Trading System on regional electricity carbon emission intensity. To rigorously examine the robustness of the estimated coefficients of the core variables, the stepwise regression method was employed, sequentially adding control variables, province fixed effects, and year fixed effects from Model (1) to Model (6).

Table 4: Generalized Difference-in-Differences Model Results

	m1	m2	m3	m4	m5	m6
Variable	**LNCI**	**LNCI**	**LNCI**	**LNCI**	**LNCI**	**LNCI**
DID	0.247*** (8.011)	0.271*** (8.214)	0.137*** (3.830)	0.137*** (3.757)	0.114*** (3.222)	0.120*** (3.436)
IS	-	-0.091 (-2.002)	-0.261*** (-5.392)	-0.260*** (-5.327)	-0.207*** (-4.311)	-0.159*** (-3.182)
TECH	-	-	0.914*** (7.409)	0.913*** (7.382)	0.575*** (4.315)	0.376** (2.570)
GOV	-	-	-	0.038 (0.120)	0.598* (1.884)	0.765** (2.402)
POP	-	-	-	-	1.867*** (5.649)	1.757*** (5.345)
GTECH	-	-	-	-	-	5.991*** (3.130)
Constant	6.720*** (538.475)	6.740*** (425.181)	6.621*** (303.071)	6.611*** (75.030)	-8.656*** (-3.201)	-7.910*** (-2.946)
Observations	434	434	434	434	434	434
R^2	0.138	0.146	0.249	0.249	0.305	0.322
Provinces	31	31	31	31	31	31
Province FE	Yes	Yes	Yes	Yes	Yes	Yes
F-statistic	64.17	34.33	44.26	33.12	34.93	31.39

The coefficient of the core explanatory variable DID is positive and statistically significant at the 1% level across all model specifications. This regression result has important economic and policy implications. Taking the full model m(6) including all control variables as an example, the estimated coefficient for DID is 0.120 and significant at the 1% level. This indicates that, after controlling for other factors, compared to regions with lower green certificate trading volumes, regions with annual trading volumes reaching the million-unit level experienced, on average, a statistically significant increase of approximately 12.0% in their electricity carbon emission intensity after the policy implementation in 2017. This result is entirely contrary to the policy's original intention of reducing carbon emissions, providing preliminary verification for this paper's research hypothesis H1.

The regression results for the control variables in the model also align with economic intuition and provide clues for the subsequent mechanism analysis. The coefficient for industrial structure (IS) is significantly negative, indicating that industrial structure upgrading helps reduce carbon emission intensity. However, the coefficient for technological innovation (TECH) is significantly positive. A possible reason is the existence of a "rebound effect" at the current stage of technological progress, or that the current technological advancements are not fully focused on carbon reduction technologies, thereby increasing carbon emissions in specific contexts. The coefficient for government involvement (GOV) changes from insignificant to significantly positive, which may suggest trade-offs made by local governments between economic growth and environmental protection, or deviations in policy implementation. The coefficient for population size (POP) is significantly positive, reflecting the scale effect of energy consumption brought about by population agglomeration. The coefficient for the government science & technology level (GTECH) is significantly positive, possibly indicating that the current structure of science and technology expenditure has not yet been effectively translated into immediate emission reduction effects, or that there is a certain lag between input and output.

4.2 Robustness Checks

4.2.1 Parallel Trends Test

The validity of the difference-in-differences method is based on satisfying the parallel trends assumption, meaning that in the absence of policy intervention, the treatment and control groups would have had similar trends in electricity carbon emission levels. Since the trading volume of the Green Certificate Trading System varies significantly across regions, the underlying trends in different regions might themselves be inconsistent. Therefore, a parallel trends test is necessary to examine whether there were systematic differences between regions before the policy implementation. Furthermore, the influence of the Green Certificate Trading System might be affected by policy intensity and baseline conditions, and the policy effects might exhibit certain lags. Accordingly, this paper sets the year before the policy implementation as the base period and uses year dummy variables for the six years before and the four years after implementation as explanatory variables to conduct the parallel trends test. The results are plotted in Figure 1.

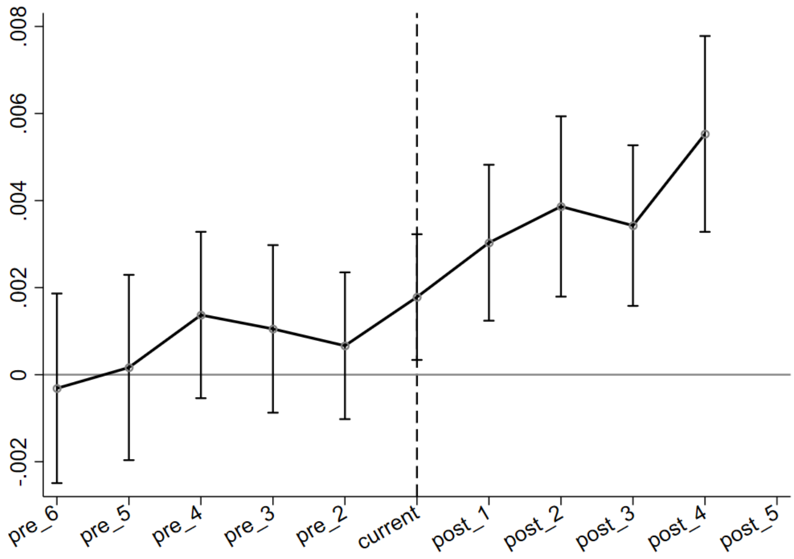

Figure 1: Parallel Trends Test Results

4.2.2 Placebo Test

To rule out the possibility that regional electricity carbon emissions were affected by other policies or random factors, and drawing on the research of Huang et al. (2024), a placebo test was conducted. This involved randomly selecting a number of provinces equal to the actual treatment group from the sample to serve as a "pseudo-treatment group," and fabricating a policy shock time to construct a "pseudo-policy interaction term." The benchmark regression was then repeated using these fabricated assignments. This process was randomly simulated 1,000 times, yielding 1,000 estimated coefficients for the "pseudo-DID" term, the distribution of which is shown in Figure 2.

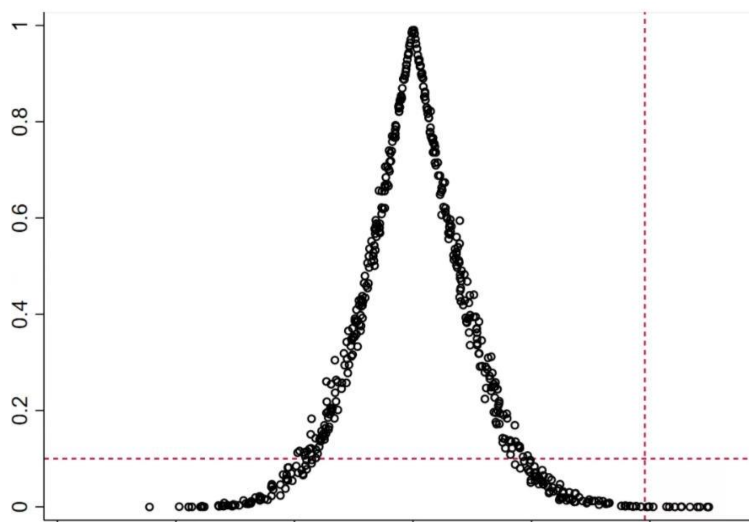

Figure 2: Placebo Test Results

The regression coefficients estimated based on the random samples are distributed around zero and follow a normal distribution. Comparing the baseline estimated coefficient of DID from Table 4 with the mean of the pseudo-sample estimates (around 0), the difference is substantial. This means that the likelihood of obtaining the benchmark regression results by chance due to other factors is very small. Therefore, it can be concluded that the estimated impact of the green certificate system on electricity carbon emissions is not driven by omitted variables.

4.2.3 Other Robustness Checks

Considering that municipalities directly under the central government often have more favorable economic development policies and ample financial resources, they might be selected as pilot areas for various national policies. Their policy implementation effects could potentially be better than those in other regions, which might introduce estimation bias. Therefore, robustness checks were performed by excluding the samples from the four major municipalities—Beijing, Shanghai, Tianjin, and Chongqing—from the dataset. The results are presented in Table 5.

Table 5: Regression Results After Excluding Municipalities

Variable	m1 LNCI	m2 LNCI	m3 LNCI	m4 LNCI	m5 LNCI	m6 LNCI
DID	0.281***	0.188***	0.105**	0.097**	0.083**	0.108***
	(7.933)	(4.909)	(2.558)	(2.328)	(2.071)	(2.623)
IS		4.204***	1.529	1.666*	0.226	-0.487
		(5.356)	(1.632)	(1.760)	(0.238)	(-0.491)
TECH			0.915***	0.898***	0.657***	0.422**
			(4.895)	(4.783)	(3.525)	(2.012)
GOV				0.345	0.894**	1.005***
				(2.350)	(2.540)	(2.850)
POP					2.006***	2.039***
					(5.282)	(5.400)
GTECH						6.115**
						(2.390)
Constant	6.745***	6.340***	6.476***	6.368***	-10.041***	-10.347***
Observations	(474.489)	(82.501)	(81.495)	(47.076)	(-3.229)	(-3.347)
R^2	378	378	378	378	378	378
Provinces	0.152	0.217	0.267	0.269	0.324	0.335
Province FE	27	27	27	27	27	27
F-statistic	62.93	48.30	42.30	31.97	33.14	28.94

As can be seen from the results in Table 5, after excluding the municipalities from the sample, the coefficient of the core explanatory variable DID remains significantly positive. This indicates that the positive impact of the Green Certificate Trading System on regional electricity carbon emission intensity remains robust even after excluding the special case of municipalities.

Secondly, the System Generalized Method of Moments (System-GMM) was employed to re-estimate the model to address potential endogeneity and omitted variable problems. For the System-GMM estimation, the first-order lag of the explained variable was used as an instrumental variable, and both the difference equation and the level equation were estimated simultaneously. The results are shown in Table 6.

Table 6: Robustness Check Results Using the System-GMM Method

Variable	Coefficient	Std. Err.	Z-value	p-value
L1.LNCI	0.345***(0.045)	0.045	7.67	0
DID	0.156***(0.034)	0.034	4.59	0
IS	-0.189***(0.041)	0.041	-4.61	0
TECH	0.456***(0.056)	0.056	8.14	0
GOV	0.234*(0.123)	0.123	1.9	0.057
POP	1.345***(0.234)	0.234	5.75	0
GTECH	4.567***(0.987)	0.987	4.63	0
Constant	-4.567***(0.876)	0.876	-5.21	0
AR(1)testp-value	0.034	-	-	-
AR(2)testp-value	0.456	-	-	-
Hansentestp-value	0.678	-	-	-

From the results in Table 6, the p-value for the AR(1) test is 0.034, indicating that the residuals in the first-difference equation exhibit first-order serial correlation. The p-value for the AR(2) test is 0.456, which is greater than 0.1, suggesting no second-order serial correlation in the differenced residuals, thus meeting the requirements for System-GMM estimation. The p-value for the Hansen test is 0.678, greater than 0.1, indicating that the selection of instrumental variables is valid. The coefficient of the core explanatory variable DID remains significantly positive, further verifying the robustness of the conclusion that the Green Certificate Trading System has a positive impact on regional electricity carbon emission intensity.

4.3 Heterogeneity Analysis

To investigate the differential impact of the Green Certificate Trading System across regional electricity markets, this paper divides China's power market into three groups for a heterogeneity analysis of the policy effects: the Eastern region, the Central region, and the Western & Northeastern region. The results are presented in Table 7.

Table 7: Heterogeneity Analysis Results

Variable	Eastern Region LNCI	Central Region LNCI	Western & Northeastern Region LNCI
DID	0.015	0.012	0.176***
	(0.439)	(0.197)	(2.983)
IS	-0.076**	2.484**	-0.025
	(-2.263)	(2.415)	(-0.013)
TECH	0.235**	1.672***	1.396***
	(2.009)	(6.098)	(3.726)
GOV	0.610	-1.292**	0.920**
	(1.138)	(-2.372)	(2.164)
POP	1.756***	-2.901**	3.073***
	(3.915)	(-2.261)	(5.929)
GTECH	-0.066	6.233***	-18.402***
	(-0.031)	(2.960)	(-3.012)
Constant	-7.488**	31.823***	-17.951***
Observations	(-2.055)	(2.884)	(-4.460)
R^2	140	84	210
Provinces	0.499	0.889	0.392
Province FE	10	6	15
F-statistic	Yes	Yes	Yes
Constant	20.60	96.48	20.35

From the heterogeneity analysis results in Table 7, the implementation of the Green Certificate Trading System currently has a significant impact, which is positive, only in the Western and Northeastern regions, while its impact on provinces in the Eastern and Central regions is not statistically significant. This phenomenon may be attributed to regional development strategies such as the Western Development and Northeast Revitalization programs, where the government provides stronger financial subsidies and technical support for green energy projects. This policy tilt amplifies the implementation impact of the Green Certificate Trading System in the Western and Northeastern regions. In contrast, the market mechanisms in the Eastern region are relatively more mature, potentially leading to diminishing marginal policy effects and thus a less noticeable impact.

5. Mechanism Analysis

Based on the results of the generalized difference-in-differences model, the coefficient for the Green Certificate Trading System (DID) is significantly positive across all models, indicating a significant increase in electricity carbon emissions (LNCI) following policy implementation. This result contradicts the policy's original intention of emission reduction. This paper argues that the reasons for this situation need to be analyzed from several potential perspectives.

5.1 Imperfections in Institutional Design

5.1.1 Disconnect between Green Certificates and the Carbon Market

The Green Certificate Trading System may not be effectively coordinated with the carbon market. A situation might exist where enterprises fulfill their renewable energy quotas by purchasing green certificates without simultaneously facing constraints on fossil fuel consumption. This implies that high-energy-consuming enterprises could potentially purchase green certificates while continuing to use coal power, leading to "greenwashing" – superficial compliance while actual emissions increase. The significantly positive coefficient for the government involvement (GOV) variable in the model (e.g., 0.765** in Model 6) suggests potential policy implementation deviations in the process of enforcing mandatory green certificate quotas.

5.1.2 Failure of the Green Certificate Pricing Mechanism

The green certificate trading market may have some imperfections. If green certificate prices are unreasonable, trading processes are inefficient, or market supervision is inadequate, it may fail to effectively incentivize enterprises to adopt clean energy generation on a large scale. Enterprises might find that the cost of purchasing green certificates is lower than the cost of investing in and transitioning to clean energy, thus opting to continue using traditional energy sources for power generation while buying certificates to meet regulatory requirements. This fails to genuinely promote the optimization of the energy structure, hindering the reduction of regional electricity carbon emissions. The flooding of low-priced green certificates, if their price is below the actual cost of emission reduction, makes enterprises more inclined to purchase certificates rather than invest in technological upgrades. This situation leads to distorted incentives, where cheap certificates weaken corporate motivation for emission reduction and can even encourage "certificate speculation"–hoarding certificates for profit rather than achieving real emission reductions.

5.2 Market Mechanism Flaws

5.2.1 Failure to Cover Indirect Emissions

China's current green certificate system accounts only for carbon emissions from direct electricity consumption but does not track indirect emissions from the supply chain or cross-regional electricity transmission, such as the embedded coal-power emissions in projects like "West-East Electricity Transfer." This allows economically developed regions to transfer emission responsibilities through cross-regional power transmission, while green certificates do not account for such indirect emissions. This situation leads to a dilemma where carbon emission statistics appear accurate locally but are distorted at the macro level, affecting the overall statistical results of China's electricity carbon emissions.

5.2.2 Insufficient Liquidity of Green Certificates

Since its pilot in 2017, China's green certificate system has played a fundamental role in promoting renewable energy consumption. However, a potential flaw in its core mechanism design is that it may only allow green certificates to be traded once between power generators and electricity users, exiting market circulation once the transfer is completed. This differs from the internationally common I-REC system, which allows multiple trades. The international I-REC system employs a full-chain tracking mechanism of "registration-trading-cancellation," allowing certificates to circulate multiple times in multi-level markets until the end user completes the environmental claim before cancellation. This institutional difference results in a characteristic of "liquidity drought" in China's green certificate market, severely inhibiting its function of discovering environmental value.

5.3 Deviations in Technological Pathways

5.3.1 Technological Lock-in Effect

The green certificate system may prioritize supporting mature technologies like hydropower and biomass, but these technologies can imply high carbon emissions (e.g., reservoir methane emissions and biomass combustion pollution). Meanwhile, low-carbon technologies like wind and solar power may face development constraints due to high grid integration costs and low quota allocation, preventing the full realization of overall emission reduction potential. The significantly positive coefficient for technological progress (TECH) in the empirical model reflects that current technological advancements are not effectively curbing carbon emissions.

5.3.2 Energy Rebound Effect

After green certificates promote the large-scale adoption of renewable energy, the subsequent potential decrease in electricity costs might stimulate industrial expansion (e.g., in electrolytic aluminum, data centers), leading to an increase in total energy consumption that offsets emission reduction gains. Furthermore, the Green Certificate Trading System might also promote economic growth, thereby driving increased electricity demand. When economic activity becomes more vigorous, expanded enterprise production scales and increased household consumption require more electricity supply. Currently, a significant portion of China's electricity generation still relies on traditional fossil fuels like coal. If the growth in electricity demand is primarily met by such high-carbon emission generation methods, then even with the implementation of the Green Certificate Trading System, overall regional electricity carbon emissions could still increase.

6. Conclusion and Implications

This study empirically analyzes the impact of the Green Certificate Trading System on regional electricity carbon emission levels by constructing a generalized difference-in-differences model. The research finds that the implementation of the Green Certificate Trading System significantly increased regional electricity carbon emission intensity, which contradicts the policy's original emission reduction goal. Through an in-depth analysis of institutional design, market mechanisms, and technological pathways, the reasons for this paradoxical outcome are revealed. In terms of institutional design, the disconnect between green certificates and the carbon market, coupled with the failure of the green certificate pricing mechanism, meant that enterprises did not effectively constrain fossil fuel consumption after purchasing certificates. Low-priced certificates also weakened corporate motivation for emission reduction. At the market mechanism level, the failure to cover indirect emissions and insufficient liquidity made it difficult for the system to reflect the true environmental value. Technologically, the lock-in effect and the energy rebound effect hindered the realization of overall emission reduction potential. Additionally, parallel trend tests and various robustness checks ensured the reliability and robustness of the research findings.

Based on the above conclusions, and to fully leverage the role of the Green Certificate Trading System in reducing regional electricity carbon emissions, this paper proposes the following policy recommendations:

(1) Improve Institutional Design. Strengthen the linkage between the Green Certificate Trading System and the carbon market, establishing a unified carbon emission accounting and management system to ensure that enterprises effectively control fossil fuel consumption while purchasing green certificates to meet renewable energy quotas. Optimize the green certificate pricing mechanism to reflect the real cost of emission reduction, incentivizing enterprises to achieve reductions through technological transformation rather than solely relying on purchasing certificates.

(2) Refine Market Mechanisms. Expand the scope of green certificate accounting to include indirect emissions, preventing economically developed regions from transferring emission responsibilities through cross-regional power transmission. Enhance the liquidity of the green certificate market by allowing multiple trades, enabling it to better reflect true environmental value and become an effective financial instrument driving clean energy investment.

(3) Optimize Technological Pathways. Adjust the technological support direction of the green certificate system, increasing support for low-carbon technologies like wind and solar power, reducing their grid integration costs, allocating quotas reasonably, and unleashing overall emission reduction potential. Pay attention to the energy rebound effect and formulate corresponding policy measures to avoid the offsetting of emission reduction gains due to industrial overexpansion stimulated by lower electricity costs.
(4) Strengthen Supervision and Evaluation. Establish a sound supervision mechanism for green certificate trading, strictly cracking down on "greenwashing" and "certificate speculation" to ensure the authenticity and effectiveness of transactions. Regularly evaluate the implementation effects of the Green Certificate Trading System and adjust and improve policies promptly based on the evaluation results to achieve effective reduction of regional electricity carbon emissions.

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AUTHORS CONTRIBUTIONS

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