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Analysis of the Impact Mechanism of Carbon Emission Trading Policy on Carbon Emissions and Measurement of Operational Efficiency in Pilot Markets

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Abstract

Based on data from 30 provinces in China from 2010 to 2021, this study employs the super-efficiency SBM model to assess the operational efficiency of pilot carbon trading markets and the carbon reduction efficiency across provinces. A multiple time points DID approach evaluates the effectiveness of the carbon trading pilot policy on carbon reduction efficiency and emissions. Additionally, a mediation model is utilized to explore the mechanisms through which carbon trading policies influence carbon reduction efficiency and emissions. The results indicate that: (1) there are disparities in the operational efficiency of pilot carbon trading markets, with Beijing, Guangdong, and Shenzhen demonstrating high efficiency, followed by Shanghai and Tianjin, while Hubei and Chongqing exhibit the lowest; (2) compared to the control group, the carbon trading pilot policy significantly improves carbon reduction efficiency in the experimental group by 11.3% and reduces carbon emissions by 3%; (3) the carbon trading policy enhances carbon reduction efficiency and achieves emissions reductions through upgrading industrial structures, increasing foreign direct investment, and improving levels of openness; (4) regional heterogeneity exists in the carbon trading policy's effects, showing an imbalance with western regions > central regions > eastern regions. The study reveals that carbon trading policies significantly contribute to achieving emissions reductions, but further improvements in carbon trading markets and enhancements in green innovation are necessary to advance carbon neutrality goals.

JEL classification numbers: P28.
Keywords: Carbon Trading Policy, Super-efficiency SBM, Carbon Trading Market, Multiple Time Points DID, Mediation Effect.

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1. Introduction

Climate change represents a major global challenge for humankind. According to the IPCC's Sixth Assessment Report (2021), the Earth has already warmed by 1.1 °C on average - rising by 1.6 °C over land areas. Further temperature increases are expected to accelerate glacier retreat, sea-level rise, and ecological degradation, posing serious threats to human survival and development. In 2020, President Xi Jinping announced that China would peak its carbon-dioxide emissions before 2030 and strive to achieve carbon neutrality before 2060. Emissions Trading Schemes (ETS) are a key market-based instrument for achieving emission reductions.

In 2011, the National Development and Reform Commission (NDRC) authorized carbon-trading pilots in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen. Shenzhen launched the nation's first ETS in 2013, followed the same year by Beijing and Shanghai; Fujian and Sichuan initiated local markets in 2016. Since their inception, the pilot markets have expanded continuously, now covering multiple industries and more than 3,000 compliance entities. In 2017, the NDRC released the National Carbon Emissions Trading Scheme Development Plan (Power Sector), formally initiating the construction of a nationwide ETS. The Interim Measures for Carbon Emissions Trading Management issued by the Ministry of Ecology and Environment (MEE) in 2020 marked the start of the first national compliance cycle. The national carbon market officially commenced trading in 2021 with the power sector as its entry point, encompassing 2,225 key emitting power companies. By February 2024, Vice-Minister Zhao Yingmin of the MEE reported that the national ETS was operating smoothly, covering 5.1 billion tonnes of CO_2 annually and becoming the world's largest carbon market. By the end of 2024, cumulative trading volume had reached 630 million tonnes, with a transaction value of roughly 43.03 billion yuan.

To deepen research on China's ETS, this study focuses on pilot provinces and municipalities and employs panel data from 2010-2021. Carbon-reduction efficiency is measured using a super-efficiency SBM (Slack-Based Measure) model. A multi-period Difference-in-Differences (DID) framework combined with mediation analysis is then used to identify the mechanisms through which the ETS affects carbon-reduction outcomes.

The potential marginal contributions of this paper are twofold. (1) It applies a super-efficiency SBM approach to determine input – output indicators for assessing ETS efficiency. Inputs include total allocated allowances, the carbon-control rate, and the number of covered industries, while outputs comprise trading volume, transaction value, carbon-price stability, and market liquidity. (2) It explores the mediating roles of industrial structure, foreign direct investment, and openness to trade in enhancing carbon-reduction efficiency under the ETS, thereby enriching the literature on the pathways through which emissions trading influences carbon abatement.

2. Literature review and theoretical hypotheses

2.1 Literature Review

2.1.1 Impacts of Emissions Trading Schemes (ETS)

Whether covered enterprises can achieve an environmental and economic "win-win" outcome by undertaking carbon emission reduction responsibilities is a key criterion for evaluating the effectiveness of carbon emissions trading scheme (ETS) implementation. Numerous scholars have assessed the energy-saving and emission-reduction impacts of ETS policies from various perspectives. At the micro-enterprise level, multiple empirical studies demonstrate that ETS policies effectively stimulate corporate innovation (Lv and Bai, 2021; Li, et al, 2019), reduce carbon dioxide emission intensity, promote carbon abatement (Xuan, et al, 2020), and significantly enhance corporate carbon emission performance (Zheng, et al, 2021). This impact is particularly pronounced for high-energy-consumption enterprises (Sun, et al, 2022). At the macro-regional level, compared to non-pilot cities, cities participating in the ETS pilot program have experienced a 22.8% reduction in energy consumption (Hu, et al, 2020) and an average annual decline in carbon emission intensity of approximately 0.026 tonnes per ¥10,000 GDP (Zhou, et al, 2019). The carbon mitigation effect of ETS policies becomes more substantial alongside industrial restructuring and shifts in energy-saving methodologies (Feng, 2020). However, ETS implementation has also led to carbon leakage, exacerbating inter-provincial imbalances in carbon emission transfers (Gao, et al, 2020).The enactment of ETS policies mitigates economic and social welfare losses and exerts a positive impact on employment, generating an "employment dividend". It concurrently increases gross industrial output value while reducing industrial carbon dioxide emissions (Wu and Tang, 2015; Yu and Li 2021; Zhang, et al, 2020). Furthermore, ETS implementation significantly improves air quality, reduces mortality attributable to both acute and chronic exposure to pollution, and delivers substantial health co-benefits (Chang, et al, 2020).

2.1.2 Efficiency Measurement Models

The Data Envelopment Analysis (DEA) model is employed not only to evaluate the operational efficiency of carbon emissions trading markets and assess the impact of carbon trading policies on carbon emission reduction efficiency, but also to measure the emission reduction effectiveness of these policies (Cheng and Mu, 2017; Wang and Zhao, 2019). Research indicates that optimization models based on DEA reveal that carbon trading policies offer cost savings in emission reduction and carbon abatement potential. These models can further evaluate the impact of carbon trading policies on economic output and CO_2 reduction within China's industrial sector. However, findings suggest that such policies primarily reduce carbon emissions without concurrently increasing product output (Wang, et al, 2017; Zhang, et al, 2020; Tan and Lin, 2022). The Super-Slacks-Based Measure (Super-SBM) model is widely applied in efficiency assessment studies across various sectors and regions in China and internationally. Researchers have utilized the Super-SBM-DEA model to conduct comparative analyses of: Regional energy efficiency in China, Energy-environmental efficiency across different sectors, CO_2 emission reduction efficiency in coastal areas of China. Furthermore, this model has been applied to evaluate: Environmental efficiency in Turkey's cement industry, Total-factor industrial eco-efficiency across Chinese provinces, Total-factor energy efficiency, and Environmental efficiency of coastal ports (Tang, et al, 2014; Xiao, et al, 2018; Gan, et al, 2018; Dirik, et al, 2019; Wang and Yang, 2019; Cheng and Bai, 2019; Zhou and Gao, 2022). These studies demonstrate the versatility and applicability of the Super-SBM model in assessing efficiency and environmental performance. The Difference-in-Differences (DID) model, grounded in a counterfactual framework, is primarily utilized for policy impact evaluation. Scholars have adopted the Propensity Score Matching-Difference in Differences (PSM-DID) method and standard DID models to: Analyze the carbon reduction effects of carbon trading policies on pilot enterprises, Examine the impact of emissions trading policies on carbon emission reduction, and Investigate carbon abatement pathways via mediating variables. Additionally, the DID model has been employed to analyze: Liquidity, volatility, and effectiveness in carbon market operations, The influence of carbon trading policies on carbon reduction efficiency within the steel industry, and The emission reduction effectiveness of carbon trading policies from both price and scale perspectives (Shen, et al, 2020; Yong, et al, 2021; Wang and Wang, 2022; Wu, 2022).

2.1.3 Implementation Pathways of Emissions Trading Schemes (ETS)

An Emissions Trading Scheme (ETS) is a market-based environmental economic instrument that utilizes economic incentives to promote carbon emission reduction. Research demonstrates that ETS policies not only directly enhance carbon abatement efficiency but also indirectly improve carbon reduction efficiency through industrial structure upgrading and adjustments in energy consumption patterns. Furthermore, ETS implementation exhibits synergistic emission reduction effects on sulfur dioxide (SO_2) emissions.

The achievement of carbon reduction targets under ETS policies can be realized through the enhancement of technological capabilities, where strengthening green technological capacity serves as a primary strategy for enterprises responding to policy implementation. Additionally, ETS policies influence emissions of carbon and air pollutants through three key mediating pathways: industrial structure optimization, technological progress, and foreign direct investment (FDI) (Hou, et al, 2024; Feng, et al, 2024; Xian, et al, 2024).

In summary, extensive research indicates that Carbon Emissions Trading Policies (CETP) facilitate carbon abatement through multiple mechanisms and have achieved significant outcomes in environmental improvement.

However, challenges such as carbon leakage persist. Current research employs refined DEA and Super-SBM models to measure the efficiency of carbon emissions trading markets and utilizes DID models to evaluate the implementation effectiveness of CETP.

2.2 Theoretical Hypotheses

2.2.1 Carbon Emissions Trading Policy and Carbon Emission Reduction

Firstly, according to Property Rights Theory (Shang, 2021), an Emissions Trading Scheme (ETS) internalizes the previously unpriced external costs (environmental damage) into firm-specific costs (quota prices). This compels firms to incorporate the true social cost of carbon emissions into their decision-making, thereby incentivizing carbon abatement. Secondly, under pressure to reduce carbon emissions, local governments are motivated to strengthen non-market-based mechanisms, such as traditional command-and-control instruments, to promote carbon reduction (Wu, et al, 2021). This encourages firms to place greater emphasis on environmental benefits during production processes. Furthermore, the trading mechanism facilitates cooperation and competition among firms. Through this market-based approach, resource allocation becomes more efficient (Wang and Li, 2024), collectively enhancing carbon emission reduction efficiency.

Finally, the successful experience gained from the pilot policies provides critical practical foundations for subsequent larger-scale carbon market development, further advancing nationwide carbon emission reduction efforts.

Based on the above analysis, this study proposes the following hypothesis:

Hypothesis H1: The carbon emissions trading pilot policy enhances carbon emission reduction efficiency and reduces carbon emissions.

2.2.2 Pathway Mechanisms for Carbon Emission Reduction under Emissions Trading Schemes (ETS)

The carbon trading mechanism effectively incentivizes high-energy-consumption, high-emission traditional industries to undertake transformation and upgrading, shifting towards low-carbon and green industries. Under policy guidance, firms seeking to reduce emissions drive technological progress and industrial optimization (Zhang, et al, 2024), effectively mitigating the negative ecological impacts arising from unreasonable energy consumption structures and persistently increasing total energy consumption (Xu and Liu, 2024). This fosters a more sustainable economic structure, ultimately achieving aggregate carbon emission reduction. Furthermore, a well-functioning carbon market mechanism attracts foreign investment, particularly from environmentally conscious firms willing to invest in green technologies. Foreign enterprises often possess advantages in technology and management expertise. By introducing advanced low-carbon technologies and management practices, they can enhance the green development capabilities of domestic firms (Xian, et al, 2024) while simultaneously promoting overall carbon emission reduction. Concurrently, the establishment and development of carbon markets facilitate international cooperation and exchange. By incorporating international standards and best practices, they further stimulate green development among domestic enterprises. Increased openness facilitates the inflow of international resources and technologies, supporting the widespread adoption of low-carbon technologies and thereby improving carbon emission reduction efficiency. Finally, the ETS mechanism creates innovation incentives for firms, prompting them to pursue green innovation in products and processes (Yu, et al, 2024). This generates the "Porter Effect", whereby environmental regulations compel innovation and improve corporate environmental performance (Li, et al, 2024). By providing clear market signals, firms invest more actively in R&D for low-carbon technologies and products, not only advancing their own sustainable development but also exerting a positive influence on emission reduction across the entire industry.

Based on the above analysis, this study proposes the following hypotheses:

Hypothesis H2a: The carbon emissions trading policy enhances carbon emission reduction efficiency and promotes carbon reduction by upgrading the industrial structure.

Hypothesis H2b: The carbon emissions trading policy enhances carbon emission reduction efficiency and promotes carbon reduction by increasing foreign direct investment (FDI).

Hypothesis H2c: The carbon emissions trading policy enhances carbon emission reduction efficiency and promotes carbon reduction by increasing the degree of openness.

Hypothesis H2d: The carbon emissions trading policy enhances carbon emission reduction efficiency and promotes carbon reduction by elevating the level of green innovation.

2.2.3 Regional Heterogeneity of Carbon Emissions Trading Policy Effects

This study primarily examines the impact of the ETS policy on carbon emissions in the seven pilot provinces and municipalities. However, considering spatial interdependence, Chinese provinces are not independent entities; regional spillover effects exist (He, 2024).

Firstly, disparities in regional economic development levels constitute a primary factor contributing to the heterogeneity of ETS policy effects (Chen, et al, 2022). Economically developed regions typically possess stronger technological innovation capabilities and greater capital accumulation, enabling more effective implementation of emission reduction measures. Conversely, less developed regions may face constraints in technology and funding, thereby impeding policy effectiveness. Secondly, differences in industrial structure also lead to disparate impacts of the ETS policy (Feng, et al, 2024). Regions dominated by high-energy-consumption, high-emission industries face greater emission reduction pressure.

In contrast, regions with more developed green industries may exhibit different reduction potential and actual outcomes.

These structural divergences present distinct challenges and opportunities during policy implementation across regions. Furthermore, the strength of policy support and administrative capacity of local governments are significant factors influencing regional ETS policy effectiveness. Some regions may prioritize and strongly support carbon reduction, actively promoting relevant measures, while others may experience slower progress in emission reduction due to insufficient effective policy guidance. Finally, variations in societal awareness and public participation also affect policy implementation. In regions with stronger public environmental consciousness, active participation can facilitate policy enforcement. Conversely, regions with weaker public awareness may encounter obstacles to policy implementation.

Based on the above analysis, this study proposes the following hypothesis:

Hypothesis H3: The impact of the carbon emissions trading policy exhibits regional heterogeneity, resulting in spatially differential effects.

3. Research Methodology

3.1 Data Sources

This study utilizes annual panel data spanning from 2010 to 2021. Due to data availability constraints, the analysis encompasses 30 Chinese provinces, autonomous regions, and municipalities, excluding Hong Kong, Macao, Taiwan, and Tibet. Data are sourced from the National Bureau of Statistics of China, the China Energy Statistical Yearbook, the China Statistical Yearbook, and the China Emission Accounts and Datasets (CEADs), among others.

The data underwent preprocessing, including logarithmic transformations of fundamental variables and winsorization of relevant variables to mitigate the influence of outliers. Samples containing missing values for primary variables were excluded. For samples with minimal missing values, interpolation methods were employed.

3.1.1 Dependent Variables

Carbon Emission Reduction Efficiency (CE): Calculated using the Super-Slacks-Based Measure (Super-SBM) model. This metric not only evaluates the comprehensive performance of regions in balancing economic development with carbon emission reduction but also identifies regions with higher and lower efficiency, providing a scientific basis for improving resource utilization and carbon mitigation strategies.

Carbon Dioxide Emissions (CO2): Measured using apparent consumption-based CO2 emission inventory data provided by CEADs. Apparent consumption-based CO2 emissions refer to emissions generated from energy combustion. The logarithm of apparent CO2 emissions is used to represent CO2 emissions.

3.1.2 Core Explanatory Variable

The core explanatory variable is a dummy variable representing the Carbon Emissions Trading Policy (CETP), constructed using a Difference-in-Differences (DID) framework: DID = Treated × Time.

Treated is assigned a value of 1 if the province is part of the CETP pilot program (based on the official list of pilot regions released by the National Development and Reform Commission (NDRC)) and 0 otherwise (non-pilot provinces).

Time is assigned a value of 1 for years after the policy implementation and 0 for years before the policy implementation.

3.1.3 Control Variables

Gross Domestic Product (GDP): Economic growth is a significant driver of increased carbon emissions. The logarithm of GDP serves as a proxy for provincial economic growth.

GDP per Capita (PGDP): Measures the economic output per person within a region, reflecting the average living standards and economic welfare of residents. Measured by the logarithm of GDP per capita.

Population (P): Measured by the year-end total population of each province. A larger population generally correlates with higher energy consumption, leading to increased carbon emissions.

Energy Consumption Structure (ES): Measured by the ratio of coal consumption to total energy consumption. A smaller ES value indicates a reduced reliance on coal within the energy mix, which contributes to lowering CO2 emissions.

Energy Consumption Intensity (EI): Measured by the ratio of total energy consumption to regional GDP. A smaller EI value signifies lower energy consumption per unit of economic output, facilitating the development of a green economy and reducing CO2 emissions.

3.1.4 Mediating Variables

Industrial Structure (IS): Measured by the ratio of the value-added of the secondary industry to the value-added of the tertiary industry. Industrial structure is a crucial factor in carbon emission reduction. CETP policies can promote resource reallocation towards more efficient sectors, stimulate demand for environmentally friendly products, drive progress in technology-intensive industries, and support low-carbon production.

Foreign Direct Investment (FDI): Calculated as the total investment by foreign-invested enterprises divided by GDP. FDI brings not only capital but also advanced technologies and management practices. This influx of external resources helps enhance the green production capabilities and environmental management proficiency of local enterprises. Moreover, foreign firms often adhere to higher environmental standards, prompting local firms to elevate their own environmental standards, thereby further contributing to carbon emission reduction.

Degree of Openness (OPEN): Calculated as the total value of imports and exports by business entities within the province divided by GDP. Opening up facilitates the inflow of advanced technologies and management experience and integrates domestic firms into global markets, improving their environmental management practices. Regions with a higher degree of openness are often better positioned to rapidly absorb and apply international green technologies, leading to effective carbon emission reduction.

Green Innovation Level (GI): Measured by the logarithm of the number of green patent grants in each province. Green innovation promotes technological progress, thereby enhancing energy efficiency and reducing carbon emissions. The CETP policy incentivizes enterprises to pursue technological innovation to achieve higher economic returns and environmental benefits. Consequently, the level of green innovation is a significant pathway through which the CETP policy influences emission reduction outcomes.

3.2 Model Building

3.2.1 Super-efficient SBM Model

When conducting efficiency evaluations, conventional DEA models may encounter the issue where multiple decision-making units (DMUs) exhibit identical maximum efficiency values (1), rendering effective ranking infeasible. To address this limitation, this study employs the Super-Slacks-Based Measure (Super-SBM) model.

This model is applied to a production system comprising n DMUs. Each DMU utilizes m inputs to produce S1 desirable outputs and S2 undesirable outputs. The input vector, desirable output vector, and undesirable output vector for each DMU can be represented as:

$$x \in R^m \text{，} y^g \in R^{S_1} \text{，} y^b \in R^{S_2}$$

The corresponding input, desirable output, and undesirable output matrices are defined as:

$$X = [x_1, x_2, \ldots, x_n] \in R^{m\times n}$$
$$Y^g = \left[y_1^g, y_2^g, \ldots, y_n^g\right] \in R^{S_1\times n}$$
$$Y^b = \left[y_1^b, y_2^b, \ldots, y_n^b\right] \in R^{S_2\times n}$$

Assuming $X>0$，$Y^g>0$，$Y^b>0$, the production possibility set (PPS) can be defined as:

$$P = \{(x, y^g, y^b) | x \geq X\theta, y^g \geq Y^g\theta, y^b \geq Y^b\theta, \theta \geq 0\}$$

In many efficiency evaluation studies, it is common for multiple DMUs to achieve the 100% efficiency frontier (efficiency score = 1). To obtain more discriminative efficiency scores and enable the ranking of these efficient DMUs, this study adopts the Super-SBM model proposed by Tone(2001). The mathematical formulation of the model is given below:

$$\rho^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}_i}{x_{i0}}}{\frac{1}{S_1+S_2}\left(\sum_{r=1}^{S_1}\frac{\bar{y}_r^g}{y_{r0}^g}+\sum_{r=1}^{S_2}\frac{\bar{y}_r^b}{y_{r0}^b}\right)}, s.t. \begin{cases} \bar{x} \geqslant \sum_{j=1,\neq k}^{n} \theta_j x_j \\ \bar{y}^g \leqslant \sum_{j=1,\neq k}^{n} \theta_j y_j^g \\ \bar{y}^b \geqslant \sum_{j=1,\neq k}^{n} \theta_j y_j^b \\ \bar{x} \geqslant x_0, \bar{y}^g \leqslant y_0^g, \bar{y}^b \geqslant y_0^b, \bar{y}^g \geqslant 0, \theta \geqslant 0 \end{cases} \quad (1)$$

Where:
ρ^* represents the efficiency score of the DMU under evaluation (DMU_k).
The value of ρ^* can exceed unity (1), allowing for the differentiation of DMUs lying on the conventional efficiency frontier.

3.2.2 Multi-Period Difference-in-Differences (DID) Model

In 2011, the General Office of the National Development and Reform Commission (NDRC) issued the Circular on Launching Pilot Emissions Trading Schemes, initiating the Carbon Emissions Trading Policy (CETP). Subsequently, starting from 2013, eight provinces and municipalities - Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, Shenzhen, and Fujian (with later inclusion) - commenced pilot operations.
This study utilizes panel data from 30 Chinese provinces and municipalities spanning 2010 to 2021. The treatment group consists of the pilot provinces and municipalities, while the control group comprises the remaining provinces.
Crucially, the implementation start dates of the carbon trading markets varied across the pilot regions. Consequently, conventional DID models are inadequate for accurate policy evaluation due to the staggered treatment adoption. To effectively address this issue and mitigate potential endogeneity arising from the policy rollout, this study employs a multi-period DID model as the baseline regression framework. This approach effectively controls for unobserved heterogeneity inherent in panel data and accounts for time-invariant unobserved confounding factors.
The baseline regression model is specified as follows:

$$Y_{it} = \alpha_0 + \alpha_1 Treated_i * Time_t + \sum \alpha_j X_{jit} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

Where:
i denotes the province/municipality (individual unit).t denotes the year (time period).Y_{it} represents the dependent variable for province i in year t, namely Carbon Emission Reduction Efficiency (CE) or Carbon Dioxide Emissions (CO_2).$Treated_i * Time_t$ is the core policy dummy variable, indicating whether province i had implemented the CETP policy by year t ($Treated_i * Time_t$ = 1 for treated provinces post-implementation, 0 otherwise).X_{jit} denotes the set of control variables j for province i in year t that may influence the dependent variable. μ_i captures province fixed effects, controlling for time-invariant

unobserved characteristics specific to each province. δ_t captures year fixed effects, controlling for common time trends and shocks affecting all provinces in a given year. ε_{it} is the idiosyncratic error term.

3.2.3 Mediation Effect Model

To examine the pathways through which the Carbon Emissions Trading Policy (CETP) achieves carbon emission reduction, this study employs the "Two-Step Approach" proposed by Jiang Ting (2022) in China Industrial Economics (Jiang,2022). Traditional three-step mediation analysis faces limitations such as high collinearity between explanatory and mediating variables, potential omitted variable bias, and unresolved endogeneity issues. The two-step approach strengthens causal inference by addressing these methodological concerns.

In this study, we adopt the two-step method to investigate carbon reduction pathways under the CETP framework. From the dual dimensions of economic development and technological advancement, four mediating variables are selected:

Industrial Structure (IS)
Foreign Direct Investment (FDI)
Degree of Openness (OPEN)
Green Innovation Level (GI)

$$M_{it} = \alpha_0 + \alpha_1 Treated_i * Time_t + \sum \alpha_j X_{jit} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

4. Results and Analysis

4.1 Operational Efficiency Measurement of Carbon Trading Markets in Seven Pilot Regions

Using carbon quota allocation totals, carbon control rates, and number of covered industries from policy documents as input variables, alongside trading volume, transaction value, carbon price stability, and market liquidity data publicly available from carbon markets as output variables, this study applies the Super-Slacks-Based Measure (Super-SBM) model to evaluate the operational efficiency of carbon trading markets across seven pilot regions.

The resulting operational efficiency scores for the pilot carbon markets are presented in Table 1, with a corresponding efficiency heatmap shown in Figure 1.

4.1.1 Analysis of Efficiency Measurement Results

As shown in Table 1 and Figure 1, the operational efficiency of China’s pilot carbon markets exhibited significant regional disparities between 2014 and 2021. Beijing and Shenzhen demonstrated consistently high efficiency, with average scores of 0.909 and 0.891, respectively. Guangdong’s market efficiency surged notably to 2.125 in 2021 but displayed substantial volatility overall, averaging 0.747. In contrast, Hubei, Shanghai, Tianjin, and Chongqing registered lower efficiency with pronounced fluctuations, averaging 0.266, 0.445, 0.460, and 0.265, respectively.

Overall, the performance divergence across regional carbon markets highlights significant variations in policy effectiveness and market mechanisms. Beijing, Guangdong, and Shenzhen achieved the highest efficiency, followed by Shanghai and Tianjin, while Hubei and Chongqing ranked lowest.

4.1.2 Problem Diagnosis

Despite observable achievements in China's pilot carbon markets between 2014 and 2021, persistent challenges warrant critical attention. Significant regional efficiency disparities reveal uneven policy adaptation and implementation effectiveness. While Beijing and Shenzhen demonstrate robust performance, Hubei, Shanghai, Tianjin, and Chongqing exhibit persistently low efficiency with pronounced volatility, necessitating strengthened carbon market frameworks and governance. Guangdong's abrupt efficiency surge in 2021 reflects a dramatic increase in market activity; however, this volatility may indicate underlying market mechanism instability, requiring scrutiny into its drivers and sustainability. Markets such as Shanghai and Hubei display transient peaks followed by declining trajectories, signaling concerns regarding operational continuity and stability. Notably, excessive market volatility - particularly evident in Chongqing and Tianjin - undermines long-term expectations and investor confidence. Consequently, intensified policy formulation and regulatory oversight are imperative to enhance market transparency and stability, ensuring the long-term, stable, and efficient operation of carbon trading mechanisms.

4.1.3 Causality Analysis

Disparities in carbon market performance across regions are fundamentally attributed to three interconnected dimensions. Regarding policy enforcement, Beijing, Guangdong, and Shenzhen - as economically advanced regions - demonstrate robust governmental support manifested through comprehensive policy frameworks, stringent regulatory oversight, and effective implementation, collectively ensuring standardized market operations. In contrast, Shanghai and Tianjin exhibit substantive policy backing but deficiencies in operational implementation details and regulatory consistency, resulting in suboptimal enforcement. Hubei and Chongqing suffer from inadequate policy commitment, insufficient local prioritization, and lax compliance mechanisms, culminating in diminished market participation and impaired operational efficiency. Economic development constitutes another critical determinant: The high-income economies of Beijing, Guangdong, and Shenzhen feature elevated corporate engagement in carbon trading, substantial transaction volumes, and vibrant market activity that undergird effective operations. Shanghai and Tianjin, despite comparable economic development, display moderated participation that constrains efficiency gains. Conversely, Hubei and Chongqing's economic constraints correspond to limited corporate awareness, minimal trading activity, and market stagnation. Finally, infrastructural and technical capabilities critically shape outcomes. Cutting-edge trading infrastructure, advanced technical systems, and sophisticated management protocols in top-performing regions ensure operational excellence. While Shanghai and Tianjin maintain adequate physical infrastructure, they lag in technical modernization, utilizing outdated trading platforms with limited management innovation. Underperforming regions confront deficient technical frameworks and obsolete operational systems. Concurrently, the professional expertise of market participants varies significantly: Mature markets benefit from seasoned professionals with specialized knowledge, whereas emerging markets in Shanghai and Tianjin contend with knowledge gaps despite technical competence, and underdeveloped markets suffer from acute expertise shortages. These multidimensional factors collectively shape regional performance differentials in China's carbon markets.

Table 1: Operational efficiency of the pilot carbon trading market

Region	2014	2015	2016	2017	2018	2019	2020	2021	Average
Beijing	1.058	0.854	1.042	0.846	1.000	1.053	0.613	0.803	0.909
Guangdong	0.334	0.468	0.420	0.358	0.568	1.095	0.609	2.125	0.747
Hubei	0.148	0.298	0.253	0.288	0.244	0.195	0.424	0.280	0.266
Shanghai	0.698	0.367	1.103	0.270	0.246	0.260	0.379	0.235	0.445
Shenzhen	1.004	1.078	1.111	0.644	0.383	0.329	1.016	1.566	0.891
Tianjin	0.469	0.500	0.454	0.282	0.252	0.217	0.588	0.921	0.460
Chongqing	0.135	0.240	0.305	0.502	0.278	0.247	0.204	0.209	0.265

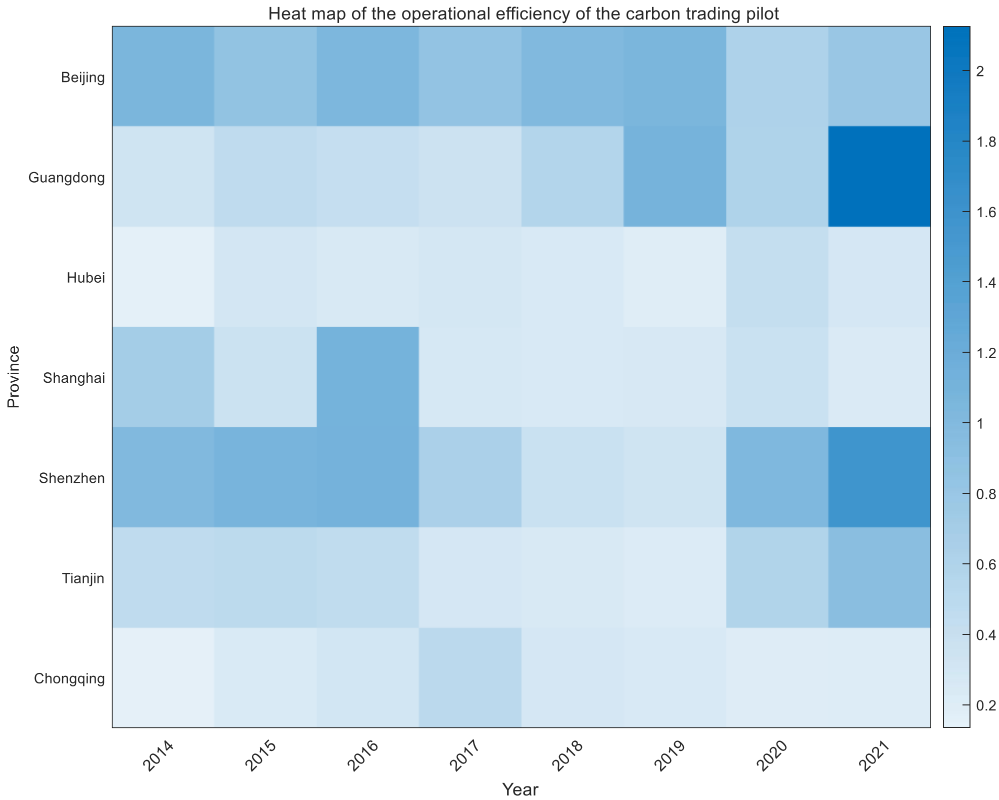

Figure 1: Heat map of the operational efficiency of the carbon trading pilot

4.2 Measurement of National Carbon Emission Reduction Efficiency

Using capital stock, employed population, and energy consumption as input indicators, regional GDP as the desirable output, and carbon dioxide emissions as the undesirable output, this study applies the Super-Slacks-Based Measure (Super-SBM) model to measure carbon emission reduction efficiency across China. The resulting national carbon emission reduction efficiency heatmap is shown in Figure 2, with focused analysis on emissions trading pilot regions.

4.2.1 Analysis of Efficiency Measurement Results

The national efficiency heatmap reveals significant regional disparities in carbon emission reduction efficiency across China from 2010 to 2021. Beijing and Shenzhen demonstrated consistently high efficiency during 2014-2021. Beijing maintained relatively high levels despite fluctuations after peaking in 2014, while Shenzhen's efficiency progressively increased from 2014, reaching its zenith in 2021. Guangdong exhibited a substantial efficiency surge in 2021, aligning with Table 1 data. Conversely, Hubei, Shanghai, Tianjin, and Chongqing showed lower efficiency with pronounced volatility. Shanghai's efficiency rapidly declined after its 2016 peak, remaining at low levels thereafter. Hubei registered modest improvements but remained inefficient overall. Tianjin and Chongqing displayed high volatility coupled with persistently low efficiency, highlighting challenges in carbon market development and management.

4.2.2 Problem Diagnosis

Notwithstanding incremental progress in carbon emission reduction efficiency across select regions, persistent challenges demand critical resolution. Pronounced interregional efficiency disparities underscore uneven policy implementation efficacy and differential market mechanism adaptability. While Beijing and Shenzhen demonstrate comparatively robust performance, the suboptimal efficiency observed in Hubei, Shanghai, Tianjin, and Chongqing necessitates substantial refinements in carbon market architecture and regulatory frameworks. Guangdong's marked efficiency surge in 2021, though indicative of accelerated market dynamism, potentially signals underlying institutional instability, warranting rigorous investigation into its causal drivers and long-term sustainability. Furthermore, transient efficiency peaks followed by declining trajectories in regions such as Shanghai and Hubei reveal systemic concerns regarding market continuity and operational stability. Collectively, these patterns indicate imperative needs for enhancing operational efficiency in underperforming carbon markets and optimizing the functional effectiveness of prevailing policy-market mechanisms.

4.2.3 Causality Analysis

Regional disparities in carbon emission reduction efficiency stem primarily from a tripartite causal framework. Foremost, the stringency of policy enforcement and sophistication of market mechanisms directly shape efficiency outcomes, evidenced by Beijing and Shenzhen's mature institutional frameworks that underpin their stable, high-efficiency performance. Concurrently, divergent economic and energy structures across regions constitute critical determinants; Guangdong's 2021 efficiency surge likely reflects its accelerated industrial restructuring and energy mix optimization. Market dynamics - particularly participant engagement and liquidity - further exert substantial influence, wherein flexible market architectures and robust participation (exemplified by Shenzhen) enable superior carbon control efficacy. Finally, technological advancement and managerial proficiency positively contribute to efficiency gains. Collectively, enhancing regional carbon efficiency necessitates integrated optimization across policy support systems, market mechanisms, economic restructuring, and technological innovation.

Nationally, carbon emission reduction efficiency demonstrates an upward trajectory. China's proactive promotion of industrial upgrading - particularly through restricting energy-intensive sectors and transitioning toward cleaner production modes - has driven systemic improvements. Parallel implementation of energy conservation policies, including the dual control mechanism (regulating aggregate consumption and intensity) and energy-saving target accountability systems, has further catalyzed efficiency gains. Strategic energy mix diversification toward hydropower, wind, and solar power progressively reduces coal dependency while elevating energy utilization efficiency and curbing carbon emissions.

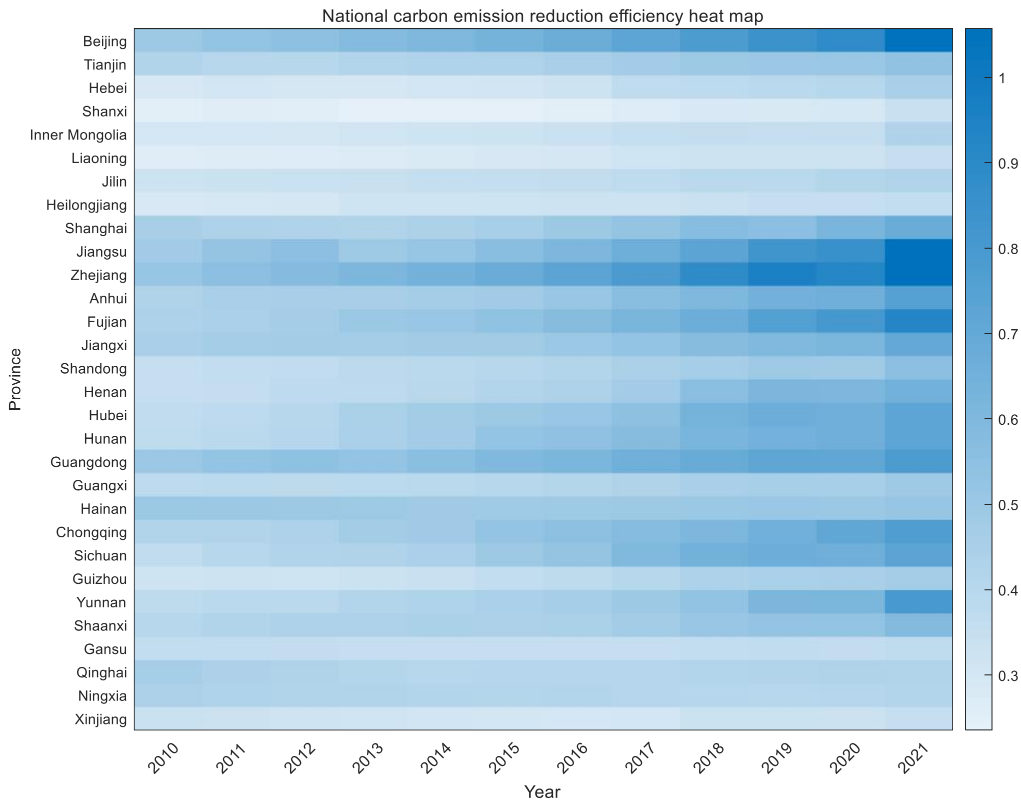

Figure 2: National carbon emission reduction efficiency heat map

4.3 Baseline Regression

Regression analysis employing a multi-period Difference-in-Differences (DID) framework was conducted with carbon emission reduction efficiency (CE) and carbon dioxide emissions (CO_2) as dependent variables, while controlling for gross regional product (GDP), GDP per capita (PGDP), population (P), energy consumption structure (ES), and energy consumption intensity (EI). Table 2 presents the estimated effects of China's Carbon Emissions Trading Policy (CETP) on these outcomes. Columns (1) and (4), excluding control variables, show statistically significant DID coefficients at the 1% level, indicating that the CETP significantly enhances carbon efficiency and curbs excessive carbon emissions in pilot regions relative to non-pilot areas - thereby validating Hypothesis H1. The results remain robust upon inclusion of control variables (Columns (2) and (5)). In economic magnitude, CETP implementation corresponds to an 11.3% average increase in carbon efficiency (0.053/0.468, where 0.468 denotes mean CE) and a 3% reduction in CO_2 emissions (0.172/5.641, where 5.641 is the logarithmic mean of CO_2) for the treatment group versus the control. Columns (3) and (6), incorporating quadratic and cubic terms of log GDP, reveal a monotonic trend under current data constraints: carbon emissions decline while efficiency rises with economic development, exhibiting no inverted-U or N-shaped patterns. This phenomenon likely stems from technological and economic development approaching a developmental threshold, concurrently reinforced by China's dual carbon goals policy elevating public and corporate focus on emission reduction, thereby constraining excessive production and associated emissions.

Table 2: Benchmark regression results

	(1)	(2)	(3)	(4)	(5)	(6)
VAR	**CE**	**CE**	**CE**	**lnCO2**	**lnCO2**	**lnCO2**
DID	0.077***	0.053***	0.031***	-0.133***	-0.172***	-0.181***
	(5.54)	(4.11)	(3.46)	(-3.77)	(-5.03)	(-5.30)
lnGDP		0.334***	0.855		-0.083	-8.881***
		(3.25)	(1.29)		(-0.30)	(-3.53)
lnGDP_2			-0.127*			0.915***
			(-1.92)			(3.62)
lnGDP_3			0.007***			-0.033***
			(2.99)			(-3.72)
lnPGDP		-0.012	0.003		0.059	0.277
		(-0.11)	(0.05)		(0.21)	(0.99)
lnP		-0.320**	-0.340***		1.184***	1.964***
		(-2.17)	(-2.91)		(3.02)	(4.42)
ES		-0.338***	-0.021		0.707***	0.755***
		(-4.96)	(-0.42)		(3.91)	(3.87)
EI		0.175***	0.041*		0.244***	0.243***
		(5.68)	(1.82)		(2.98)	(2.83)
Constant	0.456***	-0.065	0.442	5.662***	-4.348	16.046**
	(128.37)	(-0.05)	(0.25)	(632.33)	(-1.34)	(2.36)
Observations	360	360	360	360	360	360
R-squared	0.885	0.914	0.960	0.975	0.979	0.980
Year FE	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. t-statistics are reported in parentheses. This convention applies to all subsequent tables.

4.4 Robustness Checks To ensure the robustness of the baseline regression results, a series of robustness tests was conducted

4.4.1 Parallel Trends Test

The parallel trends assumption requires that the treatment and control groups exhibit comparable characteristics (e.g., follow similar development trajectories) in the pre-treatment period. This is a prerequisite for implementing the multi-period DID model. Accordingly, an event study approach was employed to examine whether parallel trends exist in the impact of CETP on carbon emissions. The model is specified as follows:

$$Y = \eta_0 + \eta_1(Treat_i * Time_t)^{-4} + \eta_2(Treat_i * Time_t)^{-3} + \cdots + \eta_8(Treat_i * Time_t)^{4} + \sum\eta_j X_{jit} + \mu_i + \delta_t + \varepsilon_{it} \quad (4)$$

Where: k denotes the k-th year relative to policy implementation. The year immediately preceding policy implementation (Year -1) serves as the reference group. The estimation window spans four pre-treatment years, the implementation year, and four post-treatment years.

As shown in Figures 3 and 4, statistically insignificant coefficients prior to policy exposure indicate no significant divergence in carbon emission trajectories between treatment and control groups among pilot regions, which satisfies the parallel trends assumption.

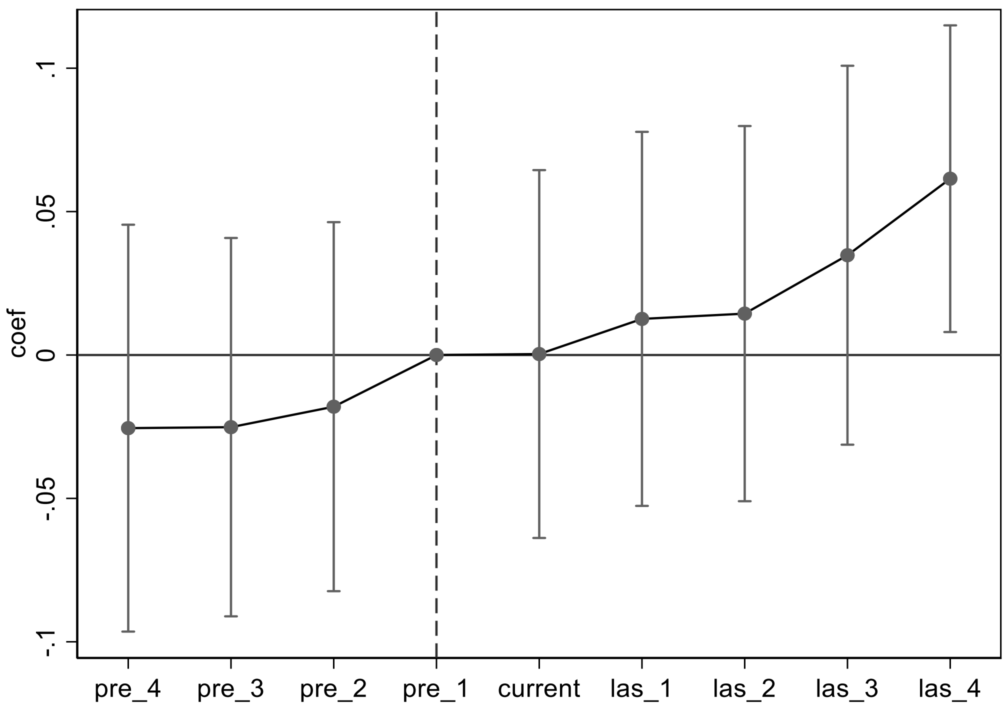

Figure 3: CE parallel trend test

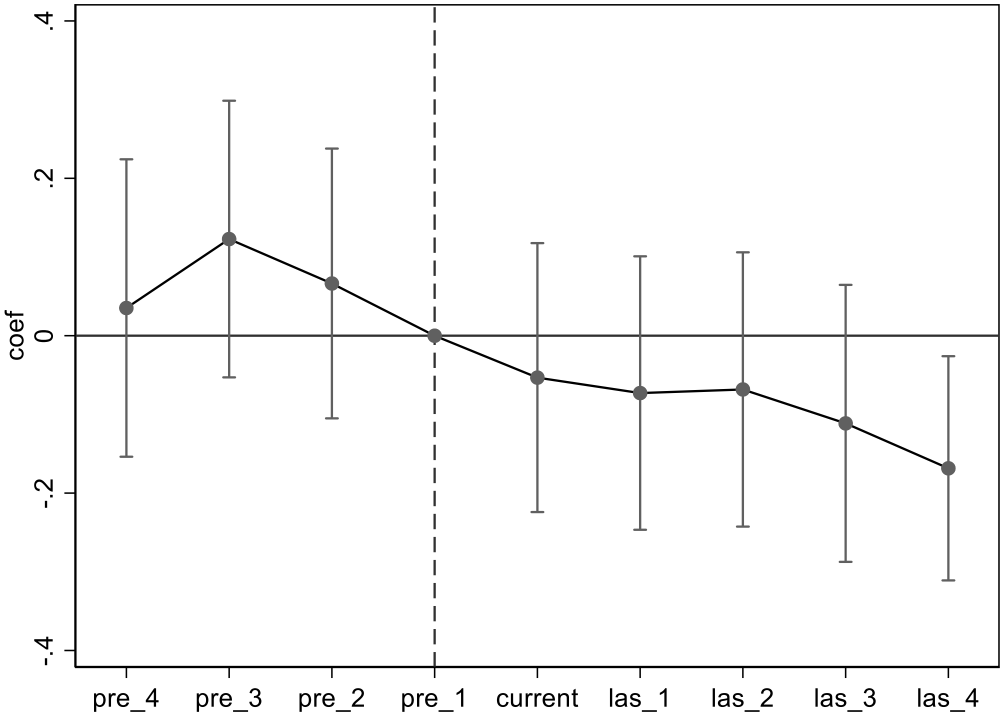

Figure 4: CO2 parallel trend test

4.4.2 Placebo Test

To further examine whether the estimated effect of the carbon emissions trading policy on pilot regions' carbon emissions is driven by random factors or confounding policies, this study conducts a placebo test by randomly assigning pseudo-treatment and control groups. The specific procedure involves: Randomly reassigning the treatment status across all 30 provinces to simulate counterfactual scenarios without actual policy intervention. Estimating regression equation (2) using these artificially constructed samples. Repeating steps 1-2 for 500 iterations to generate a distribution of 500 estimated DID coefficients. As shown in Figures 5 and 6, the estimated coefficients for the placebo policy variable are centered around zero, statistically insignificant at the 10% level in most iterations. This distribution confirms that the baseline regression results are robust and unlikely to be driven by unobservable confounding factors.

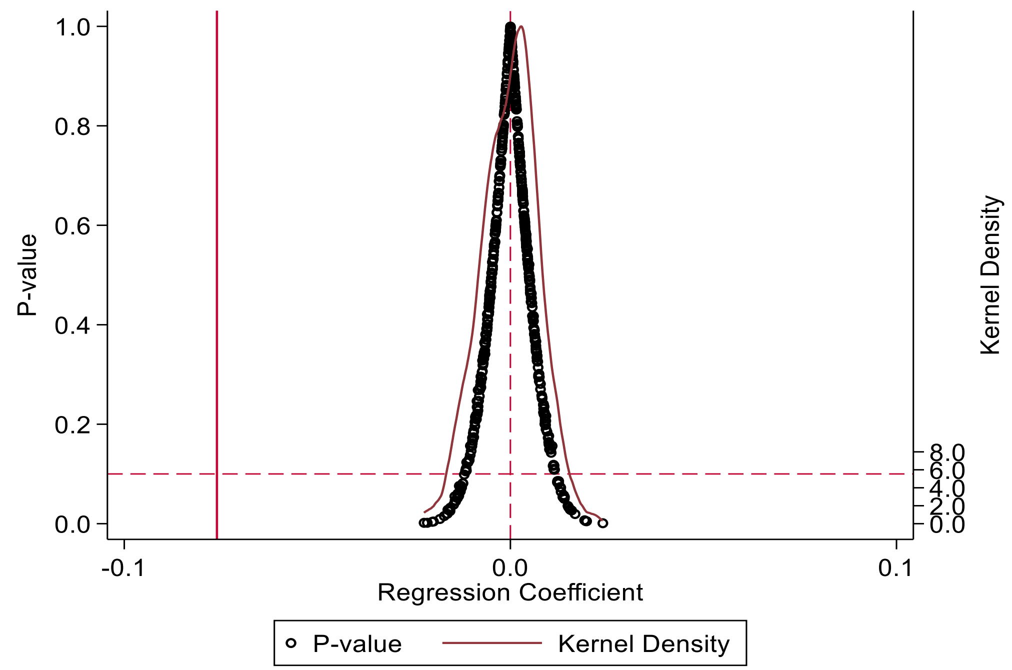

Figure 5: CE placebo test

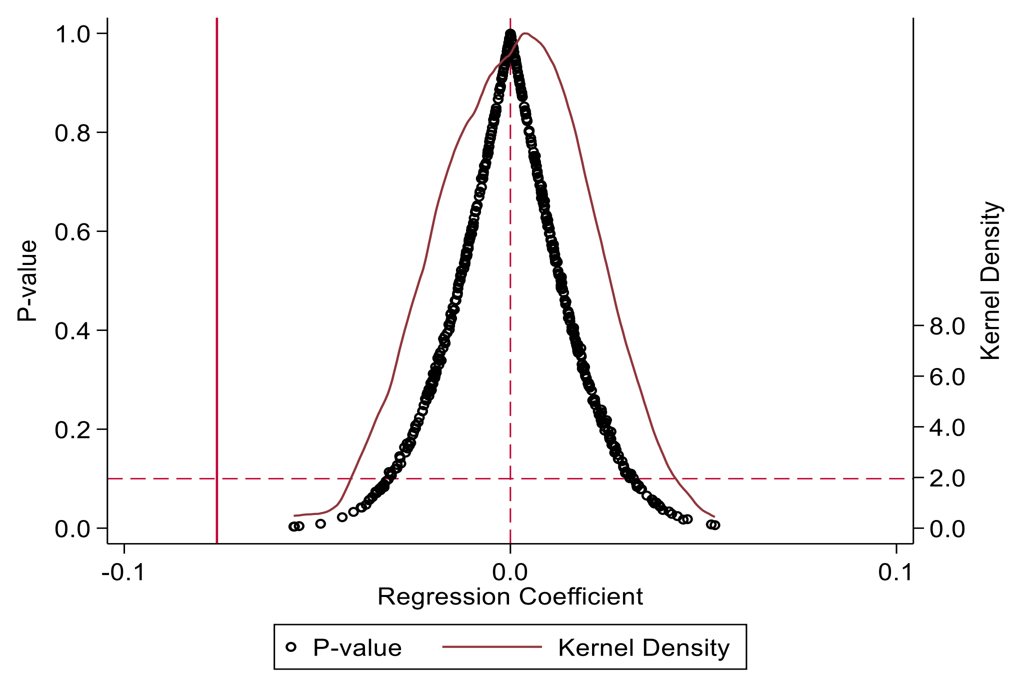

Figure 6: CO2 placebo test

4.4.3 Additional Robustness Tests

The potential self-selection effects induced by the carbon emissions trading policy may compromise the randomness of pilot sample assignment, necessitating mitigation of selection bias between treatment and control groups. Robustness tests employing the Propensity Score Matching-Difference-in-Differences (PSM-DID) methodology were thus implemented: Pilot regions were designated as the treatment group during the sample period; control variables served as covariates for propensity score estimation; kernel matching and radius matching techniques reconstructed comparable treatment groups; unmatched control units were pruned from the sample; and Model (2) was re-estimated using the refined sample. Results presented in Table 3 (Columns 1 & 3: kernel matching; Columns 2 & 4: radius matching) demonstrate statistically significant coefficients, confirming the robustness of baseline findings.

Concurrently, a temporal robustness check artificially lagging policy implementation timing by two years (Table 3, Columns 5-6) yields coefficients significant at the 1% level, evidencing pronounced policy effects with measurable temporal persistence.

Table 3: Other robustness test results

	(1)	(2)	(3)	(4)	(5)	(6)
VAR	**CE**	**CE**	**lnCO2**	**lnCO2**	**CE**	**lnCO2**
DID	0.031**	0.025*	-0.119***	-0.139***		
	(2.29)	(1.78)	(-3.66)	(-4.17)		
DID_las					0.054***	-0.150***
					(4.64)	(-4.78)
lnGDP	0.380**	0.367*	0.036	-0.004	0.317***	-0.052
	(2.00)	(1.95)	(0.08)	(-0.01)	(3.11)	(-0.19)
lnPGDP	-0.114	-0.127	0.246	0.218	-0.003	0.051
	(-0.62)	(-0.70)	(0.56)	(0.50)	(-0.03)	(0.18)
lnP	0.121	0.123	0.581	0.598	-0.285*	1.060***
	(0.49)	(0.50)	(0.97)	(1.01)	(-1.95)	(2.70)
ES	-0.444***	-0.453***	0.846***	0.818***	-0.340***	0.731***
	(-4.85)	(-4.97)	(3.82)	(3.73)	(-5.04)	(4.04)
EI	0.192***	0.183***	0.294**	0.269**	0.168***	0.259***
	(3.73)	(3.57)	(2.36)	(2.17)	(5.45)	(3.13)
Constant	-3.035	-2.767	-2.676	-2.085	-0.276	-3.576
	(-1.46)	(-1.34)	(-0.53)	(-0.42)	(-0.23)	(-1.10)
Observations	262	259	262	259	360	360
R-squared	0.926	0.926	0.987	0.987	0.915	0.979
Year FE	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES

4.4.4 Mediation Effect Analysis

Empirical results presented in Table 4 demonstrate statistically significant positive coefficients in Columns (1)-(3) and a significant negative coefficient in Column (4), indicating that the CETP effectively upgrades industrial structure, increases foreign direct investment, and enhances openness, while concurrently suppressing green innovation. These findings validate Hypotheses H2a, H2b, and H2c but lead to rejection of Hypothesis H2d.

Industrial structure optimization enhances carbon emission reduction efficiency and facilitates emission abatement, fundamentally because the secondary sector - predominantly comprising industry and manufacturing - typically exhibits high energy intensity and carbon emissions, while the tertiary sector (largely services) demonstrates comparatively lower energy and carbon footprints. When the ratio of secondary-to-tertiary sector value-added declines, signifying an increased share of tertiary activities, the overarching economic structure transitions toward lower energy consumption and reduced carbon intensity. This structural shift not only diminishes the proportion of high-emission industries but also stimulates service sector development, thereby elevating economy-wide carbon efficiency. Consequently, strategic optimization of industrial composition through reallocating resources from secondary to tertiary sectors constitutes an effective pathway toward achieving carbon mitigation targets.

Increased foreign direct investment elevates carbon emission reduction efficiency and contributes to emission abatement, primarily because foreign-invested enterprises introduce advanced technologies and managerial expertise—particularly in energy-efficient operations and environmental technologies. Subject to global competitive pressures, these firms demonstrate a heightened propensity to adopt low-carbon and green technologies compliant with international standards. Furthermore, foreign investment catalyzes technological upgrading and managerial improvements among domestic enterprises, thereby enhancing sector-wide carbon efficiency. Augmented FDI inflows amplify the diffusion effects of these innovations, significantly elevating economy-wide carbon productivity and ultimately achieving emission reduction targets.

Enhanced openness elevates carbon emission reduction efficiency and contributes to emission abatement through catalyzing international trade and investment flows, which introduce advanced technologies and managerial innovations—particularly in energy utilization and environmental protection. These innovations enable domestic enterprises to optimize production processes, improve energy efficiency, and reduce carbon emissions. Furthermore, heightened openness intensifies competitive pressures, accelerating the adoption of green manufacturing paradigms and low-carbon technologies. As openness expands, the systematic integration of these technological and managerial advancements generates knowledge spillovers that significantly boost economy-wide carbon productivity, thereby advancing progress toward emission reduction targets.

The Carbon Emissions Trading Policy (CETP) may suppress green innovation capacity by incentivizing firms to prioritize short-term cost containment over long-term innovation investments. First, compliance costs associated with purchasing emission allowances increase operational expenditures, potentially crowding out R&D funding for green technologies. Second, the policy's market-based mechanism encourages firms to meet emission requirements through allowance trading or incremental process optimization rather than committing substantial resources to transformative innovation. Furthermore, implementation uncertainties and regulatory complexities may reinforce corporate preference for low-risk technical adjustments over high-risk, capital-intensive innovation initiatives. Collectively, these dynamics likely constrain green innovation capabilities within regulated enterprises.

This analysis yields a critical conclusion: Whereas the CETP enhances carbon efficiency and facilitates emission reduction through industrial restructuring, foreign direct investment inflows, and openness expansion, its short-term compliance pressures inadvertently diminish corporate focus on green innovation technologies due to prevailing cost-control imperatives.

Table 4: Results of mechanism analysis

	(1)	(2)	(3)	(4)
VAR	**IS**	**FDI**	**OPEN**	**lnGI**
DID	0.082***	0.052***	5.216***	-0.166***
	(3.37)	(3.28)	(3.28)	(-3.18)
lnGDP	-0.285	-0.290**	-28.953**	-0.238
	(-1.46)	(-2.28)	(-2.28)	(-0.57)
lnPGDP	0.606***	0.064	6.375	1.026**
	(3.04)	(0.49)	(0.49)	(2.41)
lnP	1.323***	0.947***	94.666***	2.817***
	(4.71)	(5.18)	(5.18)	(4.69)
ES	0.394***	-0.120	-11.999	1.255***
	(3.04)	(-1.42)	(-1.42)	(4.53)
EI	-0.343***	0.086**	8.625**	-0.327***
	(-5.84)	(2.26)	(2.26)	(-2.61)
Constant	-13.600***	-5.515***	-551.459***	-24.716***
	(-5.87)	(-3.65)	(-3.65)	(-4.99)
Observations	360	360	360	360
R-squared	0.920	0.888	0.888	0.986
Year FE	YES	YES	YES	YES
Province FE	YES	YES	YES	YES

4.4.5 Heterogeneity Analysis

Geographical heterogeneity analysis was conducted to examine the differential impacts of the Carbon Emissions Trading Policy (CETP) on carbon emission reduction across regions with distinct urban characteristics. Results presented in Table 5 reveal significant spatial variations. Based on the National Bureau of Statistics' regional classification framework, the sample was partitioned into Eastern, Central, and Western China. Columns (1), (2), and (3) report estimates for these regions, respectively. Statistically significant positive coefficients for the DID term emerge in Central and Western regions, whereas the Eastern region exhibits statistically insignificant effects - empirically validating Hypothesis H3 regarding regional heterogeneity of policy impacts.

The differential impacts of the Carbon Emissions Trading Policy (CETP) on carbon emission reduction efficiency across regions stem primarily from disparities in economic development levels, industrial structures, and policy enforcement rigor. In Western China, the policy’s significantly positive effects likely arise from its relatively underdeveloped industrial composition and elevated carbon emission baselines, which amplify the marginal benefits of emission trading and enhance the visibility of abatement outcomes. Concurrently, this region exhibits greater reliance on policy incentives to catalyze green technology adoption and industrial upgrading. Central China demonstrates moderate positive impacts; however, its intermediate economic development tier and structurally complex industrial landscape attenuate policy effectiveness compared to Western regions. Conversely, Eastern China’s advanced industrial framework, heightened environmental awareness, and robust corporate autonomous abatement capacity diminish the incremental effect of CETP. Enterprises in this region predominantly leverage pre-existing environmental measures and technologies for emission reduction, reducing their marginal dependence on market-based policy instruments.

Table 5: Heterogeneity analysis

	(1)	(2)	(3)
VAR	**CE**	**CE**	**CE**
DID	0.012	0.043*	0.070**
	(0.63)	(1.97)	(2.62)
lnGDP	0.340	1.853**	0.387***
	(1.38)	(2.63)	(3.73)
lnPGDP	0.026	-1.499**	0.300**
	(0.11)	(-2.14)	(2.44)
lnP	-0.048	-1.649**	-0.942***
	(-0.14)	(-2.34)	(-3.80)
ES	-0.702***	-0.170**	-0.226**
	(-3.98)	(-2.40)	(-2.05)
EI	0.302**	0.041	0.188***
	(2.22)	(1.00)	(4.95)
Constant	-2.825	12.058*	0.994
	(-1.03)	(1.91)	(0.46)
Observations	132	120	108
R-squared	0.933	0.952	0.898
Year FE	YES	YES	YES
Province FE	YES	YES	YES

5. Conclusions and Policy Implications

5.1 Conclusions Utilizing

Carbon emission panel data from 30 Chinese provinces, this study employs the Super-Slacks-Based Measure (SBM) model to evaluate operational efficiency in seven pilot carbon markets and nationwide carbon emission reduction efficiency. The multi-period Difference-in-Differences (DID) approach examines whether carbon emissions trading policies enhance carbon efficiency and promote emission reduction, with robustness checks validating core findings. Key conclusions emerge: (1) Operational efficiency disparities exist among pilot carbon markets, with Beijing, Guangdong, and Shenzhen demonstrating superior performance, followed by Shanghai and Tianjin, while Hubei and Chongqing exhibit the lowest efficiency. Regarding carbon emission reduction efficiency, nationwide metrics demonstrate an upward trajectory. Among pilot regions, Beijing and Shenzhen achieve higher efficiency, whereas Hubei, Shanghai, Tianjin, and Chongqing underperform. Relative to the control group, the carbon emissions trading pilot policy significantly enhances carbon efficiency by 11.3% and reduces CO_2 emissions by 3% in the treatment group. Economic development correlates with declining carbon emissions and rising carbon efficiency, with no evidence of inverted U-shaped or N-shaped relationships observed.

(2) The CETP enhances carbon emission reduction efficiency and reduces carbon emissions through empirically validated pathways: industrial restructuring, foreign direct investment (FDI) expansion, and openness advancement. Specifically, an increased tertiary sector share transitions the economic structure toward lower energy intensity and carbon intensity. Augmented FDI inflows introduce advanced energy-efficient technologies and environmental management expertise, thereby strengthening green innovation capacity. Heightened openness intensifies competitive pressures that accelerate the adoption of green production paradigms and low-carbon technologies - collectively achieving significant emission abatement.

(3) Heterogeneity analysis reveals a pronounced regional gradient in CETP efficacy: the strongest and most statistically significant effects emerge in Western China, followed by moderate impacts in Central China, while Eastern China exhibits insignificant policy influence. This spatial divergence is ascribed to structural and developmental factors—Western regions' less developed industrial composition and elevated carbon baselines amplify policy effectiveness, driving their reliance on policy-driven green technology transitions; Central China's intermediate economic tier and complex industrial landscape attenuate outcomes; whereas Eastern enterprises leverage advanced autonomous abatement capacities rooted in economic maturity and heightened environmental consciousness, diminishing incremental policy dependence.

5.2 Policy Recommendations

Based on empirical findings, the following evidence-based proposals are advanced:

(1) Enhance CETP Enforcement Capability Local governments should formulate context-specific regulatory frameworks to strengthen compliance oversight and ensure policy implementation fidelity. Market vitality and trading volumes can be amplified by incentivizing corporate participation. Concurrently, upgrading carbon market infrastructure and operational protocols will optimize transactional efficiency. Professional competency development - through specialized training programs and strategic talent acquisition - is critical to elevate participant sophistication and ensure market efficacy.

(2) Strategic enhancement of industrial restructuring, foreign direct investment (FDI) attraction, and openness amplification will significantly elevate CETP efficacy to achieve carbon abatement targets. Industrial optimization constitutes the pivotal lever: Accelerating the transition of energy-intensive sectors while strategically supporting low-carbon industries enables source-level emission reduction. Concurrently, institutional safeguards through robust legal frameworks ensure the continuity and effectiveness of this structural shift. Targeted attraction of FDI from firms possessing advanced low-carbon technologies augments domestic enterprises' decarbonization capabilities and catalyzes cross-border technological collaboration, thereby optimizing emission reduction efficiency. Parallel expansion of openness - through proactive engagement in international carbon market cooperation and

adoption of global best practices - fosters market maturation and regulatory standardization. Empirical mediation analysis confirms these measures collectively accelerate carbon neutrality pathways, advance green low-carbon economic development, and demonstrate China's tangible contributions to global climate governance frameworks.

(3) Strengthen CETP implementation by strategically advancing green innovation and scaling technological investments. Empirical evidence indicates corporate prioritization of short-term cost containment constrains green innovation focus. To counteract this, governments should incentivize enterprises and research institutions to amplify R&D expenditures through targeted subsidies, dedicated innovation funds, and industry-academia-research consortia that accelerate low-carbon technology development and deployment. Concurrently, elevate corporate decarbonization capacity via technology assimilation, process optimization, and managerial upgrading to comprehensively enhance emission reduction capabilities. Establish open-access innovation platforms to facilitate cross-sectoral knowledge sharing and collaborative ventures, catalyzing the translation of technological breakthroughs into scalable applications. This integrated approach underpins green low-carbon transition, ensures sustainable development trajectories, and fortifies the achievement of carbon abatement targets.

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