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Original Research

The Impact and Mechanism of the Chinese Certified Emission Reduction Policy on Carbon Emission Intensity

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Abstract

Under the constraints of the "dual carbon" targets, relaunching the Chinese Certified Emission Reduction Policy (CCER) is essential to supplement and improve China's carbon market trading. This paper employs interrupted time series analysis and static panel models to assess the impact and mechanism of the CCER policy on carbon emission intensity from 30 provinces in China, comprehensively revealing the policy's role in promoting the synergy of regional emission reductions. The study finds that: (1) After the implementation of the CCER policy in 2015, carbon emission intensity significantly decreased, while the suspension of the policy in 2017 led to a short-term increase in carbon emission intensity. Despite this rise, the long-term emission reduction trend persisted, though with a diminished effect. Heterogeneity analysis indicates that the policy has a pronounced effect on suppressing carbon emission intensity in the eastern areas with higher technological innovation and non-industrial bases. (2) Higher CCER trading volume can raise carbon emission intensity, but stable carbon market transaction prices help reduce it. The CCER policy helps decrease carbon emission intensity by incentivizing green technological innovation and optimizing energy structure, while it has a negative impact through the scale effect. (3) A significant spatial positive correlation exists in carbon emission intensity's temporal and spatial distribution. The CCER policy also exerts a restraining influence on neighboring regions through its spatial spillover effect.

Keywords: CCER policy, carbon emission intensity, interrupted time series analysis, spatial spillover effects

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Introduction

With the rapid growth of China's economy, the traditional labor-intensive production model has led to substantial greenhouse gas emissions, becoming one of the key factors contributing to global warming, especially those caused by carbon emissions. From the 19th to the 20th century, global CO_2 emissions increased by 30%, with energy consumption being identified as the primary driver of this growth [1, 2]. Although energy is critical for economic growth, excessive consumption has become a key factor contributing to environmental degradation [3].

According to the Intergovernmental Panel on Climate Change (IPCC), energy-related CO_2 emissions are projected to increase by 41% to 109% by 2030 [4]. The 2023 United Nations Climate Change Conference (COP28) reaffirmed the importance and urgency of the temperature targets set by the Paris Agreement. As one of the world's largest carbon emitters, China has been actively promoting the goals of carbon peaking and carbon neutrality, which are vital for mitigating climate change and promoting sustainable development. China's carbon emission trading market plays an important role in achieving the dual carbon targets, mainly including two forms of Carbon Emission Allowance Trading (CEA) based on total control and the Chinese Certified Emission Reduction Policy (CCER) based on projects. Among them, CCER, as an integral supplement to China's carbon emissions trading market, can enhance the carbon market more effectively, optimally fulfill its supportive role, and actively advance the achievement of 'dual carbon' objectives through its robust market mechanisms. Since the CCER policy was first implemented in 2015, its trading volume accounted for 34.6% of China's carbon emission trading market. Due to problems with trading volume, management, and project standardization, the issuance of CCER projects was suspended in 2017, but the stock can still be traded on the carbon market.

In 2021, with the launch of China's carbon market, the trading volume of CCER grew to 49.5%, and the remaining volume on the market struggled to meet demand. Among them, there are large differences in the volume of transactions between provinces. Shanghai had the largest cumulative CCER trading volume, exceeding 110 million tons, accounting for 41% of the total CCER transactions. Guangdong ranked second, contributing 21% of the total. The cumulative trading volumes in Beijing, Tianjin, Shenzhen, Sichuan, and Fujian ranged between 12 and 26 million tons, representing 5%-9% of the total. In contrast, Hubei's market traded less than 8 million tons, while Chongqing recorded a cumulative volume of 490,000 tons. In order to address these challenges more effectively, the Chinese government officially relaunched the CCER voluntary emission reduction project and aided carbon market trading on the 22nd of January, 2024. It introduced a new management specification, "Administrative Measures on Greenhouse Gas Voluntary Emission Reduction Trading (Trial)", which aims to introduce a more standardized and efficient operation mechanism for the carbon market and encourage more enterprises and organizations to actively participate in carbon emission reduction actions. However, details of regional differences and trading scales still need to be clarified and optimized in specific practice. Therefore, an in-depth analysis of the impact mechanism of CCER policy on carbon emission intensity not only contributes to improving the trial management measures and formulating more targeted policy measures for different regions, including details such as trading volume and interprovincial trading restrictions, which can maximize the effect of carbon emission reduction, but also provides more valuable experience for other countries and regions in carbon emission reduction.

The voluntary emission reduction market is formed by participants who purchase carbon emission reductions based on voluntary motivation to reduce greenhouse gas emissions [5]. At present, the international voluntary carbon market mechanism consists of three main components: the international carbon emission reduction mechanism, the third-party independent voluntary emission reduction mechanism, and each country's domestic voluntary emission reduction mechanism [6]. International carbon emission reduction mechanisms include the Clean Development Mechanism (CDM), Joint Implementation (JI), and International Emissions Trading (IET), which promote cooperation and trading of carbon emission reduction on a global scale [7]. In addition to these international mechanisms, various voluntary emission reduction mechanisms led by independent third parties have also been developed, and there are currently more than 20 such mechanisms worldwide. Among these, the Verified Carbon Standard (VCS), the Gold Standard (GS), the American Carbon Registry (ACR), and the Climate Action Reserve (CAR) are the four independent mechanisms with the largest issuance volumes. In addition, several country-specific or region-specific carbon credit mechanisms are often subject to local laws and policies, for example, Japan's Domestic Offset Mechanism, Korea's Carbon Credit Mechanism, and Australia's Carbon Emission Reduction Fund [8]. These different standards and mechanisms reflect the international trend of the carbon market and demonstrate their respective features and advantages, contributing to the development of the global carbon emission reduction cause. Among them, the CCER policy is a domestic emission reduction project based on the international Clean Development Mechanism (CDM) [9], incorporating China's regional characteristics and industry differences [10]. The complexity of this policy, which involves multiple stakeholders and business entities, has attracted widespread attention [11].

China's carbon market is still in the development stage, and the CCER policy has become an important complementary mechanism to the carbon market [12]. The core of the policy is to allow enterprises or individuals to offset their carbon emission allowances by purchasing CCER projects, which effectively fills the supply gap in the carbon market and potentially contributes to improving the efficiency of the carbon market, promoting technological innovation, and realizing carbon emission reduction targets [13].

Regarding implementing international carbon reduction policy, most literature focuses on project implementation and carbon emissions accounting [14, 15]. As an early international mechanism, the Clean Development Mechanism (CDM) has been discussed in terms of its additionality and actual emissions reduction effects in various evaluations [16-18]. Both domestically and internationally, China's carbon emissions trading policy has been extensively discussed, including its role mechanism, environmental impact, and economic impact [19, 20]. However, most scholars have focused on carbon quota trading as the primary form, neglecting the significance of CCER policy in China's carbon emissions market [21]. Previous research has primarily examined the effects of CCER policy from theoretical and empirical perspectives. The theoretical level explores the operation of the CCER policy in China's carbon market. The study finds that the CCER trading policy plays a vital role in increasing market liquidity, improving the participation of non-emission-control entities, reducing the emission reduction costs of carbon emission control enterprises, and increasing the carbon trading revenues of renewable energy enterprises [22-24]. These roles are crucial for smoothly operating the entire carbon market and mitigating carbon price volatility [25]. However, the introduction of CCER trading and offsetting mechanisms also brings some problems and potential risks [26, 27], such as an imperfect policy framework, a lack of technical talent for adequate support, incomplete settings in the registration management system, non-transparent trading, and the trading price of CCER being lower than the market price for carbon quota trading, which has hindered progress [28-30], which may affect the effectiveness of CCERs and the stability of the market. Additionally, scholars at home and abroad have mainly tested the specific impacts of CCER trading policies on an empirical level. From a management perspective, the research not only confirmed the cost-saving effect of the CCER policy in China by using game theory [31] but also explored how to build a low-carbon trading market and achieve the evolutionary stability of the CCER policy [32, 33]. Optimization strategies were used to investigate the impacts of CCER policies on particular industries, such as forestry carbon sinks, battery energy storage systems, and thermoelectric hydrogen energy systems [34, 35]. Furthermore, scholars have analyzed the coupling effect of carbon emissions trading and CCER schemes and explored the cost-saving effect of dual-trading market scenarios through system dynamics [36], which pointed out that appropriately relaxing the CCER carbon offset ratio can promote renewable energy development [37]. From an economic perspective, scholars use the Computable General Equilibrium (CGE) Model and a difference-in-difference method to comprehensively analyze the economic and environmental impacts of CCER policy [21, 38]. Zhu discovered a positive correlation between CCER and technological innovation in Chinese steel companies through a fixed-effects model [39].

In general, the existing research still needs some improvement: (1) Most of the literature on carbon market research focuses on the impact of environmental regulation and technological innovation under the carbon quota trading policy. Several international mechanisms, such as the Clean Development Mechanism (CDM) and Verified Carbon Standard (VCS), have been evaluated for their effectiveness in reducing carbon emissions. However, there is a significant lack of studies assessing the Certified Emission Reduction Policy (CCER), which serves as a complementary mechanism to China's carbon market. Given the policy's suspension, research on the CCER's impact on carbon emission intensity remains limited. This paper fills that gap by employing the interrupted time series analysis to test the CCER policy's effectiveness.

(2) An in-depth analysis of the theoretical construction and mechanism of CCER trading policy on carbon emission reduction, as well as empirical tests, especially from the perspective of the market mechanism, which is relatively insufficient, needs to be conducted.

(3) Although pilot carbon markets have some geographic restrictions on using CCER offsets for local carbon credits, CCER projects are registered and issued by the whole country and can still be traded across provinces. So far, scholars have paid little attention to the spatial spillover effects generated by CCER policies, ignoring the impact of how the policies are transferred and diffused across different regions.

To thoroughly examine the impact of the CCER policy on carbon emissions and explore the effectiveness of the CCER policy in reducing carbon emission intensity, as well as the specific mechanisms driving this reduction, this study selects panel data from 30 Chinese provinces spanning 2000 to 2021. The paper applies interrupted time series analysis to test whether the implementation of the policy in 2015 and its suspension in 2017 had any significant effects on carbon emission intensity. Additionally, a static two-way fixed effects panel analysis is employed to evaluate the extent of the policy's impact on carbon emission intensity after its implementation in 2015. Moreover, the paper uses mediation effect analysis to assess how the policy influences carbon emission intensity through resource allocation optimization, scale effects, technological innovation, and structural adjustments. To further expand the research on the spatial spillover effects of the CCER policy, the study applies the Moran index and spatial Durbin model to better capture the actual effects of the policy in pilot regions and reflect regional heterogeneity. These findings provide important theoretical and practical insights for further reducing carbon emission intensity and improving market-based regulatory frameworks following the resumption of the CCER policy.

Analysis of Theoretical Mechanisms

The Chinese Certified Emission Reduction Policy (CCER), as a supplementary mechanism to the carbon trading market, adopts a logic similar to the Coase property rights path [40]. Under total volume control, this policy treats carbon emission credits as commodities and allows them to be traded in the market. It incorporates the negative externalities of environmental pollution generated by enterprises' production and business behaviors into the market pricing, which is directly included in enterprises' operating and investment opportunity costs of enterprises. Through the carbon trading market, the CCER policy effectively coordinates the transfer of carbon emission allowances between high-emission and low-emission enterprises, thereby optimizing resource allocation. When high-emission enterprises face insufficient initial free allowances or high carbon market prices, they can partially offset their emissions obligations by purchasing unused allowances from low-emission enterprises or developing their own CCER projects. This allows them to meet their emission reduction targets and avoid hefty fines. Meanwhile, low-emission enterprises can profit by selling their unused allowances. This mechanism not only provides flexibility for enterprises to reduce emissions but also incentivizes them to upgrade their technologies and adopt environmental improvements, thereby achieving energy conservation and emission reduction goals.

Since implementing the CCER policy in 2015, enterprises facing quota and cost pressures actively seek to reduce their carbon emissions through technological innovation. Particularly when carbon allowance prices are high, companies have greater motivation to accelerate the transition to green technologies, thereby reducing long-term costs. Low-emission enterprises further contribute to market vitality by selling their allowances, which enhances the overall emission reduction effects in the market. However, the suspension of the policy in 2017 led to increased uncertainty in the carbon market, and enterprises relaxed their efforts in emission reduction. In the short term, carbon emission intensity increases, and some companies may postpone their technological upgrades and environmental investments due to policy suspensions. Nevertheless, existing CCER credits continue to flow and trade in the market. From a long-term perspective, the overall trend of carbon emissions remains downward. Although the policy suspension weakens the short-term emission reduction effects, as market confidence is restored, enterprises continue to push forward technological innovation and energy structure adjustments to meet potential future emission reduction requirements.

This paper analyzes the influence mechanism of CCER policy from the perspectives of optimizing resource allocation, scale effect, technical effect, and structural effect, as shown in Fig. 1. From a market mechanism perspective, the CCER policy assigns an economic cost to carbon emissions, optimizes resource allocation through trading volume and market trading prices, and aims to achieve environmental protection and carbon emission reduction targets. Additionally, it encourages the market mechanism to reduce emissions more effectively. The trading volume of CCER is a crucial indicator of the carbon market's operation status. It reflects the level of activity in the carbon market. An increase in the active degree of the CCER market enhances trading efficiency and encourages enterprises to take more initiative in reducing emissions. It leads to the prosperity and activity of the entire carbon market and, to some extent, realizes the emission reduction effect in the region. The carbon market trading price is also crucial for the efficient operation of the carbon market, as it conveys information about the market supply and demand situation and the cost of reducing emissions through the price signal [41]. When carbon market trading is too expensive, enterprises can purchase a certain percentage of CCER to obtain additional carbon emission credits to meet compliance requirements. The price of CCER is usually lower than the carbon market trading price, which means

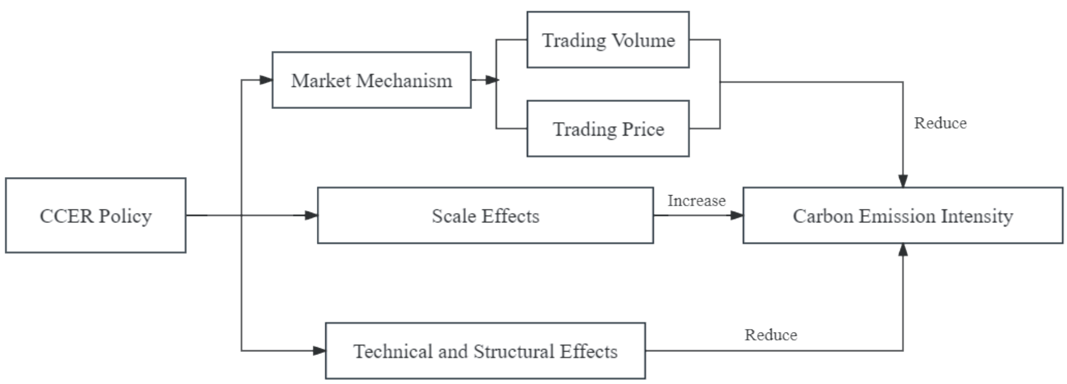

Fig. 1. The Mechanism of CCER Policy Affecting Carbon Emission Intensity.

enterprises can fulfill emission reduction obligations at a lower cost, achieving cost-effectiveness. However, this cost incentivizes enterprises to take measures to reduce carbon emissions and avoid additional cost expenditure through emission reduction. Therefore, the following hypotheses are proposed:

Hypothesis 1: Implementing the CCER policy can significantly reduce carbon emission intensity in various pilot regions.

Hypothesis 2: Market mechanisms can significantly enhance the emission reduction effect under the influence of the CCER policy.

The Chinese Certified Emission Reduction Policy (CCER) internalizes the externality of corporate carbon emissions through the above logic of property rights definition. It optimizes the allocation of resources through CCER trading volume and carbon market trading price, effectively solving the problem of mismatch between corporate emission reduction costs and benefits. Following this logic, this paper applies the environmental Kuznets curve to analyze the impact of CCER policy on regional carbon emissions, mainly embodied in three paths: scale effect, technology effect, and structural effect [42]. On the one hand, implementing CCER projects may generate scale effects, especially in energy-intensive industries such as iron, steel, and chemicals. These industries typically produce large amounts of carbon emissions in their production processes. Due to the relatively fixed nature of their industrial structure, they find it difficult to transition quickly in the short term. However, the incentives provided by the policy have led them to expand production by purchasing CCER projects to offset their carbon compliance requirements. This practice increases the value of the company's output in the short term but raises overall carbon emissions. Therefore, CCER projects may have the side effect of increasing carbon emissions and carbon intensity while promoting economic growth.

On the other hand, implementing the CCER policy may also reduce regional carbon emissions through technical and structural effects. Some renewable energy projects and emission reduction projects, such as wind power, hydropower, and forestry carbon sinks, have the potential to significantly reduce carbon emissions in the short term by adopting cleaner technologies, which can help to replace traditional high-carbon energy sources and thus reduce carbon emissions [43]. At the same time, influenced by market pressure, rising production costs, and insufficient carbon emission allowances, enterprises are forced to increase their research and development on green technology innovation to reduce the intensity of carbon emissions and achieve the emission reduction targets of each region through the optimization of green production technologies. In addition, the CCER policy may also push enterprises to adjust their production structure towards a more environmentally friendly and low-carbon direction, further reducing carbon emissions.

In China, energy consumption is one of the primary sources of carbon emissions, so the main measure to control carbon emissions is to control the consumption of fossil fuels. After implementing the CCER policy, the pressure on firms to reduce emissions costs in the short term has prompted them to actively adjust their energy structures, develop and utilize clean energy, and increase investment in non-fossil energy sectors, all in pursuit of optimizing carbon reduction costs. However, the suspension of the policy has introduced a degree of market uncertainty and led to a relaxation of emission reduction efforts. During the suspension, firms may delay technological upgrades and green investments due to the lack of policy constraints. Nevertheless, with the policy's resumption, firms are once again incentivized by the carbon market mechanisms to continue advancing technological innovation and adjusting energy structures to meet future emission reduction requirements. The CCER policy not only effectively facilitates corporate emission reduction behavior and promotes the adoption of green technologies in the short term through market mechanisms but also serves as a crucial driver for firms to achieve their long-term emission reduction goals and optimize carbon reduction costs through its sustained implementation. Therefore, the following hypotheses are proposed:

Hypothesis 3: Implementing the CCER policy increases carbon emission intensity through the scale effect.

Hypothesis 4: Implementing the CCER policy contributes to reducing carbon emission intensity through technical and structural effects.

Materials and Methods

Interrupted Time Series Analysis

This paper uses the interrupted time series analysis method to test whether the implementation of the CCER policy in 2015 and its suspension in 2017 had an impact on carbon emission intensity, as shown in the model:

$$\begin{aligned} CI_{it} = {} & \alpha_0 + \alpha_1 t_{before} + \alpha_2 Policy_{2015} + \alpha_3 t_{after1} Policy_{2015} \\ & + \alpha_4 Z + \alpha_5 Z t_{before} + \alpha_6 Z Policy_{2015} + \alpha_7 Z t_{after1} Policy_{2015} \\ & + \alpha_8 Policy_{2017} + \alpha_9 t_{after2} Policy_{2017} + \alpha_{10} Z Policy_{2017} \\ & + \alpha_{11} Z t_{after2} Policy_{2017} + \theta X_{it} + \lambda W \varepsilon_{it} + \varepsilon_{it} \end{aligned} \tag{1}$$

Where CI_{it} is the carbon emission intensity of province i in year t; Z is the experimental dummy variable, with Z = 1 for the experimental group and Z = 0 for the control group. $Policy_t$ represents the policy dummy variable (t = 2015, 2017), where $Policy_t = 0$ indicates that it has not been implemented and $Policy_t = 1$ indicates that it has been implemented. The variable t_{after2} has a similar meaning to t_{after1}, representing the time point after implementation.

The other variables are set similarly to those in Equation (1). X_{it} is the set of all control variables and ε_{it} is the random disturbance term.

Static Panel Models

This paper further uses the static panel models to evaluate the impact of the carbon trading policy on carbon emission intensity, as shown in the model:

$$CI_{it} = \alpha_0 + \alpha_1 Policy_{it} + \theta X_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (2)$$

Where $Policy_{it}$ is the carbon trading pilot policy variable; X_{it} is the set of all control variables; μ_i and η_t are the individual and time-fixed effects of the regions, respectively.

Furthermore, to assess the spatial spillover effect of the CCER policy, further construct the Spatial Error Model (SEM), Spatial Autoregressive Model (SAR), and Spatial Durbin Model (SDM), respectively, as follows:

$$CI_{it} = \alpha_0 + \alpha_1 Policy_{it} + \theta X_{it} + \lambda W \varepsilon_{it} + \mu_i + \eta_t + \mu \quad (3)$$

$$CI_{it} = \alpha_0 + \alpha_1 Policy_{it} + \theta X_{it} + \rho WCI_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (4)$$

$$CI_{it} = \alpha_0 + \alpha_1 Policy_{it} + \theta X_{it} + \phi W X_{it} + \rho WCI_{it} + \gamma_1 WDID_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (5)$$

Where W is the weight matrix describing the spatial adjacency relationship of the regions; μ represents the normal distribution; λ and ρ represent the intensity and coefficient of spatial correlation; the rest of the variables are defined consistently with Equation (1).

Mediation Effect Model

Based on the mechanism analysis above, this paper introduces a mediation effect model to identify the key factors affecting carbon emission intensity under the CCER policy and test the hypothesis of the transmission mechanism. According to the method by Baron and Kenny [44], the identification mechanism of the mediation effect is divided into three steps, as shown in the models:

$$CI_{it} = \alpha_0 + \alpha_1 Policy_{it} + \alpha_2 Control_{it} + \varepsilon_{it} \quad (6)$$

$$MV_{it} = \beta_0 + \beta_1 Policy_{it} + \beta_2 Control_{it} + \mu_{it} \quad (7)$$

$$CI_{it} = \alpha'_0 + \alpha'_1 Policy_{it} + \alpha'_2 MV_{it} + \alpha'_3 Control_{it} + \delta_{it} \quad (8)$$

Where MV_{it} is the mediating variable, $Control_{it}$ is the control variable, ε_{it}, μ_{it}, δ_{it} is the random disturbance term; the rest of the variables are defined consistently with Equation (5).

Variables

1. The dependent variable. In this study, Carbon Emission Intensity (*CI*) is selected as the dependent variable. Carbon dioxide emissions were calculated based on existing studies and the Intergovernmental Panel on Climate Change (IPCC) carbon accounting method, where carbon intensity is calculated by dividing carbon emissions by regional GDP [45].

2. Core independent variable. We construct an interaction dummy variable to identify policy effects $Policy = Z \times Time$ as the core independent variable. If a province enters the CCER trading system as a pilot province for carbon emissions trading after 2015, the interaction is defined as "1"; otherwise, it is defined as "0".

3. Control variables. We chose the economic development level, urbanization, population density, openness, depth of industrialization, energy intensity, market development level, and level of technological innovation as control variables referring to previous studies [46-48]. The economic development level (*AGDP*) is measured by per capita GDP. Urbanization (*UR*) is measured by the proportion of the urban

Table 1. Descriptive Statistics of Variables.

Variable	Mean	Std. Dev.	Min	Max
CI	3.398	2.676	0.319	19.106
DID	0.073	0.260	0	1
AGDP	11383.590	7674.203	2661.557	48075.030
UR	0.517	0.158	0.139	0.896
PD	439.957	633.124	7.151	3925.870
DO	0.024	0.021	0.0001	0.147
ID	1.064	0.588	0.494	5.297
EI	1.530	1.008	0.368	5.805
MG	7.083	2.111	2.243	12.390
TI	18730.13	35340.18	36	242551

population to the total population. Population density (*PD*) is measured by the ratio of the permanent population to the regional area. The degree of openness to the outside world (*DO*) is measured by the proportion of foreign direct investment to GDP. Depth of industrialization (*ID*) is represented by the ratio of the added value of the tertiary industry to the secondary industry. Energy intensity (*EI*) is measured by the proportion of total energy consumption to GDP. Market development (*MD*) is measured by the Fan Gang marketization index. Technological innovation (*TI*) is represented by the number of patent authorizations to indicate technological innovation.

Data Sources

This paper uses panel data from 30 Chinese provinces from 2000 to 2021 as the research sample (Tibet, Hong Kong, Macao, and Taiwan are not included due to data availability issues). The data sources include the China Statistical Yearbook and the China Energy Statistical Yearbook. Missing data were filled in using linear interpolation, and extreme values were reduced-tailed. All monetary indicators were deflated at the constant price in 2000 to eliminate the influence of price fluctuations. To facilitate the economic interpretation of coefficients and eliminate the influence of heteroskedasticity, variables other than the ratio were processed by taking the natural logarithm. The descriptive statistics of each variable are shown in Table 1.

Table 2. Regression Results of the Interrupted Time Series Analysis.

Variable		Coef.	Sd. Err.
Intercept_0		0.0010***	0.0086
$Policy_{2015}$	Intercept	-0.1511***	0.0546
	Slope	-0.0566**	0.0663
	Trend	-0.1898*	0.1032
$Policy_{2017}$	Intercept	0.1039*	0.0770
	Slope	-0.0126***	0.0648
	Trend	-0.1718**	0.1017
AGDP		1.0276***	0.1054
ID		-0.1584***	0.0679
PD		0.4477***	0.2057
DO		-0.0501***	0.0155
UR		-0.0445*	0.0586
EI		0.6692***	0.0670
MG		-0.1555***	0.0872
TI		-0.1001***	0.0264
Cons		10.8057***	1.5308
DW		2.54	
DW (Corrected)		2.13	

Note: ***, **, and * representing significant levels at 1%, 5%, and 10%, respectively.

Results and Discussion

Policy Effect Assessment

Interrupted Time Series Analysis

Overall, after adjusting the model using the Prais-Winsten AR(1) correction, the DW test values became closer to 2, indicating that the corrected model essentially does not have autocorrelation issues. Therefore, the regression results from the corrected model are accepted. As shown in Table 2, the regression results indicate that the implementation and suspension of the CCER policy had a significant phased impact on carbon emission intensity. Following the policy's implementation in 2015, carbon emission intensity decreased sharply in the short term. This can be attributed to the policy's incentives for enterprises to actively adopt measures to reduce emissions. At the same time, carbon emission intensity gradually declined over time, indicating that the policy effectively promoted long-term emission reductions. The policy negatively impacted the long-term trend in carbon emission intensity. However, after the policy was suspended in 2017, carbon emission intensity increased in the short term, likely due to decreased market activity or enterprises relaxing their emission reduction efforts during the suspension. Although the long-term trend of carbon emission intensity continued to decrease, the reduction was less pronounced than during the policy's implementation phase. Therefore, the overall results suggest that while the suspension of the policy weakened the emission reduction effect, the long-term implementation of the CCER policy has generally played a positive role in promoting carbon emission reductions.

Static Panel Model

Table 3 presents the static panel models, with the first column showing the fixed effects model, the second column showing the random effects model, and the third column showing the pooled panel model estimated using ordinary least squares (OLS).

The optimal static panel model is determined through F-tests and Hausman tests. The F-test rejects the null hypothesis, indicating that the fixed effects model is superior to the pooled panel model. The Hausman test accepts the null hypothesis, suggesting that the fixed effects model is also superior to the random effects model. Therefore, the fixed effects model is the most optimal among the three types of static panel models.

The regression results show that the core explanatory variable Policy coefficient is significantly negative. Under the two-way fixed effect, the CO_2 emission intensity of pilot provinces is reduced by 26.09% compared with non-pilot provinces, which indicates that the implementation of CCER policy can effectively reduce carbon emission intensity, and this result supports Hypothesis 1. Among the control variables, the degree of industrial deepening, openness to the outside world, urbanization, market development, and technological innovation dampen carbon emission intensity. In contrast, the level of economic development, population density, and energy intensity positively affect emissions. With the deepening of industrialization, the number of high-tech and innovative enterprises tends to increase. These enterprises are incentivized to adopt cleaner and low-carbon production technologies due to the CCER policy [49]. Furthermore, to comply with carbon market regulations, energy-intensive enterprises also reduce carbon emissions by purchasing CCER projects, such as clean energy and forest carbon sinks [50]. Additionally, regions with more open policies tend to have more advanced public transport systems, efficient resource-sharing mechanisms, mature and robust market environments, and more substantial technological innovation capabilities. These factors can effectively reduce resource waste and lower the carbon intensity of the region [51]. On the other hand, regions with high levels of economic development and population density are usually accompanied by more consumption and production activities, resulting in higher carbon emissions, which is in line with the theory of the environmental Kuznets curve. In the early stages of economic development, environmental degradation is typically low, but as per capita income rises, environmental degradation tends to increase from a low level. As the economy develops, environmental degradation becomes more severe [52]. In addition, the higher the consumption of traditional fossil fuels such as coal, the higher the carbon emissions from the region's economic production activities.

Robustness Test

(1) Excluding interference from other policies. During the period covered by this paper, carbon emission intensity may have been affected by similar policies, such as emissions trading pilots, low-carbon provincial and regional pilots, and carbon quota policy. To obtain the net effect of the Chinese Certified Emission Reduction Policy (CCER), this paper includes

Table 3. Regression Results of the Static Panel Models.

Variable	Static panel models		
	Fixed effects model	Random effects model	Pooled panel model
Policy	-0.2609^{**} (0.2308)	-0.1237^{***} (0.0436)	-0.2609^{**} (0.2308)
AGDP	0.5044^{***} (0.1798)	0.5251^{***} (0.0831)	0.5044^{***} (0.1798)
ID	-0.6238^{***} (0.2076)	-0.4340 (0.1604)	-0.6238^{***} (0.2076)
PD	5.0758^{***} (0.6773)	4.9741^{*} (1.8541)	5.0758^{***} (0.6773)
DO	-8.9823^{**} (4.1184)	-7.0239^{**} (4.0160)	-8.9823^{**} (4.1184)
UR	-2.1255^{***} (0.5832)	-2.6473 (1.2103)	-2.1255^{***} (0.5832)
EI	0.4125^{**} (0.0393)	0.6868^{***} (0.0634)	0.4125^{**} (0.0393)
MG	-0.1378^{*} (0.1097)	-0.1561^{*} (0.0865)	-0.1378^{*} (0.1097)
TI	-0.3635^{**} (0.1495)	-0.1561^{***} (0.0237)	-0.3635^{**} (0.1495)
Cons	7.8460^{*} (1.3200)	6.7996^{***} (1.1621)	7.8460^{*} (1.3200)
Province	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	660	660	660
R^2	0.8361	0.7982	0.7643

Note: Standard errors are included in parentheses, respectively.

these policies in the regression analysis, and the results are presented in Table 4. After excluding other similar policies, the net effect of the policies is consistent with the conclusion of the benchmark regression.

(2) Replacement of the dependent variable. In this paper, the dependent variable carbon emissions intensity is replaced by carbon emissions per capita in the original model, as shown in Table 4. The estimated coefficients of Policy remain unchanged regarding the sign and significance, further supporting the robustness of the conclusions.

Heterogeneity Test

(1) Heterogeneity analysis based on different geographical locations. Since the promotion and implementation of the policy are affected by the differences in geographical locations and thus have different effects on the impact of carbon emission intensity, this paper divides the research sample into eastern, central, and western regions for analysis, as shown in Table 5. The study indicates that the CCER policy significantly reduces the carbon emission intensity in the eastern, central, and western regions, and the eastern region>central region>western region. The carbon emission intensity base of the eastern region is higher than that of the central and western regions. Additionally, the eastern region is superior to the central and western regions in terms of economic development level, industrial structure upgrading, market development level, and technological innovation level, so the policy effect is also more significant. Meanwhile, due to the guidance of the national policy on inter-regional industrial gradient transfer, the western region tends to become a transfer site for highly polluting enterprises in the eastern and central regions [53], which seriously hampers its ability to reduce emissions. Therefore, its emission reduction effect is the weakest.

(2) Heterogeneity analysis based on the level of technological innovation. The sample is divided into high and low-innovation areas according to each province and city's median annual patent applications. Table 5 shows that high-innovation areas significantly impact carbon reduction more than low-innovation areas, indicating that technological innovation is crucial in promoting sustainable development and reducing carbon emissions. Through the research, development, and application of advanced clean energy technologies, high-level innovation regions seek renewable energy solutions to replace traditional fossil fuels, such as solar, wind, and hydro energy. Additionally, clean energy power generation projects have also been constructed and expanded, reducing reliance on high carbon emissions and thus effectively lowering carbon emissions. In particular, high innovation areas focus on promoting and deploying efficient energy-saving appliances, introducing advanced energy-saving technologies and equipment, including smart home systems, more energy-efficient vehicles, and industrial production lines [54], and minimizing energy waste and greenhouse gas emissions.

(3) Heterogeneity analysis is based on whether it is an Industrial Base. With the increasing demand for environmentally friendly and sustainable economic development, traditional industrial bases must be transformed and upgraded. This paper divides the sample according to whether it is one of the four major industrial bases, analyzing the heterogeneous impact of industrial structure in pilot areas on carbon emission intensity. As shown in Table 5, compared to non-industrial bases, the CCER policy has a positive trend on the carbon emission intensity of industrial bases, indicating that industrial bases still have room for improvement in carbon emissions and are more sensitive to environmental policies aimed at carbon reduction [55]. On the other hand, the industrial base has traditionally relied on high-carbon conventional energy sources and faces challenges regarding technology and plant upgrading. Although implementing the CCER policy provides an opportunity for transformation, transitioning from traditional to clean energy requires a gradual process.

Table 4. Regression Results of Robustness Tests.

Variable	Excluding interference from other policies	Replacement of the Dependent variable
Policy	-0.4869*** (0.1003)	-0.2450** (0.2832)
Controls	Yes	Yes
Cons	5.9667** (2.0795)	4.7210** (3.8361)
Province	Yes	Yes
Year	Yes	Yes
N	660	660
R^2	0.6247	0.7740

Spatial Spillover Effects

Temporal and Spatial Evolution Trend of Carbon Emission Intensity

The spatial and temporal evolution trend of carbon emission intensity was determined using ArcGIS software by averaging the carbon emission intensity before and after 2015, as illustrated in Fig. 2. The results show that the carbon emission intensity of the central and western regions is higher than that of the eastern region and that the carbon emission intensity of all regions in China has decreased after implementing the CCER policy, with the most significant impact on the eastern region. The central and western regions are rich in coal and other energy resources and rely more on traditional heavy and energy-intensive industries, which tend to

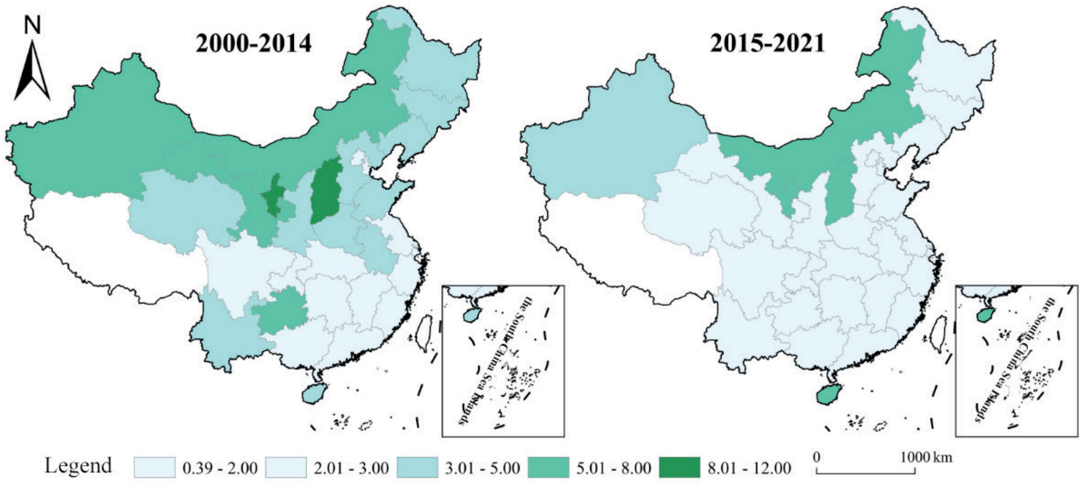

Fig. 2. Temporal and Spatial Evolution Trend of Carbon Emission Intensity.

have higher carbon emission intensities. Conversely, the eastern region has prioritized the development of service and light industries and has adopted cleaner and more efficient energy technologies. In addition, the eastern region, which has a certain specific economic structure and resource utilization, has received more focused policy attention, and most of the pilot provinces are also concentrated in this region. As a result, implementing the CCER policy leads to a more pronounced decrease in the carbon emission intensity of the eastern region, which is consistent with the heterogeneity analysis in the previous section.

Spatial Autocorrelation Test

This paper employs spatial econometrics to examine the spatial spillover effects of the CCER policy on regional carbon emission intensities. An aspatial autocorrelation test is necessary for the study object before analysis. Therefore, this paper calculates the Moran's I index of carbon dioxide emission intensity under the inverse distance matrix (W_1) and the economic-geographical distance matrix (W_2), shown in Table 6. The Moran's indices are all positive, with most being significantly positive at the 1% level. The results reveal that the spatial and temporal distribution of carbon emission intensity across 30 provinces and cities in China is not entirely random. There is a significant positive spatial correlation, and each province and city's carbon emission intensity trend is influenced by its neighboring provinces and cities.

SDID Model Test and Regression Results

Based on the Hausman, LM, LR, and Wald tests, the paper identifies the spatial-temporal double-fixed SDM-DID model as the optimal choice. Table 7 presents the regression results of the SDID model using the 0-1

Table 5. Regression Results of Heterogeneity Analysis.

Variable	Geographical location			Level of technological innovation		Industrial Base	
	Eastern regions	Central regions	Western regions	High	Low	Yes	No
Policy	-0.5385*** (0.3533)	-0.0807* (0.3228)	-0.0317** (0.0139)	-0.1774** (0.6103)	-0.1351*** (0.1184)	0.1001** (0.1921)	-0.2080** (0.4730)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cons	-5.4690** (15.7312)	24.4633** (13.8977)	24.3101* (25.4364)	13.8540** (8.4856)	7.1845** (4.7751)	9.4205** (6.3418)	21.9578* (21.0290)
Province	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	264	198	198	330	330	198	462
R^2	0.7937	0.8295	0.6514	0.6265	0.6434	0.7333	0.6220
P-value for coefficient gap test between groups	0.0173***			0.0473*		0.0346**	

Table 6. Spatial Autocorrelation Test.

Year	0-1 Adjacency Matrix (W_1)		Economic-geographical Distance Matrix (W_2)	
	Moran's I	Z-value	Moran's I	Z-value
2000	0.2361**	2.4976	0.0580***	2.5932
2001	0.2541***	2.5976	0.0611***	2.6320
2002	0.2273***	2.4157	0.0530**	2.4506
2003	0.2239***	2.2991	0.0515**	2.3465
2004	0.2857***	2.7592	0.0608**	2.5407
2005	0.3025***	2.8825	0.0642***	2.6159
2006	0.2837***	2.7261	0.0633***	2.5974
2007	0.2610***	2.4917	0.0603**	2.4857
2008	0.2933***	2.7245	0.0693***	2.6932
2009	0.2585***	2.4254	0.0640**	2.5486
2010	0.2321***	2.2025	0.0534**	2.2699
2011	0.1846***	1.8349	0.0400**	1.9440
2012	0.1801***	1.8004	0.0403**	1.9537
2013	0.1858***	1.848	0.0404**	1.9586
2014	0.1602***	1.6429	0.0308**	1.7138
2015	0.1338***	1.4281	0.0221**	1.4909
2016	0.1488***	1.5456	0.0234***	1.5187
2017	0.1833***	1.8318	0.0289*	1.6590
2018	0.1775***	1.7971	0.0251*	1.5707
2019	0.2146***	2.1049	0.0299*	1.6919
2020	0.3469***	3.3782	0.0660***	2.7344
2021	0.3410***	3.3581	0.0623***	2.6508

adjacency matrix (W_1) and the economic-geographical distance matrix (W_2) regression model. Additionally, the paper presents the estimation results of the SAR model under spatial-temporal double fixation to test the robustness of the estimation results. After controlling for control variables and bidirectional fixed effects, the autocorrelation coefficients ρ of the dependent variables are all positive at the 1% significance level. The direct effect of the CCER policy on carbon emission intensity is greater than the indirect effect under different matrices. Both effects are significantly adverse, suggesting that the policy has a two-way suppressive effect on carbon emission intensity in the pilot region and neighboring regions.

In order to meet China's international commitment to reduce carbon emissions, the governments of the pilot regions have strengthened the review and management of carbon emission intensity, which has demonstrated to neighboring regions the need to increase constraints on carbon emissions and consequently has a significant driving effect on the reduction of regional carbon emission intensity. After implementing the CCER policy, the pilot regions have created a technological spillover effect by promoting low-carbon technologies and using clean energy. These advanced technologies and experiences can be transferred to neighboring regions, encouraging them to adopt more environmentally friendly and efficient production methods, reducing carbon emission intensity. Furthermore, the availability of CCER projects on multiple exchanges encourages collaboration between pilot regions and neighboring areas, allowing for sharing resources and joint efforts toward achieving low-carbon project cooperation. Through these CCER projects, the carbon intensity of the entire region can be comprehensively reduced.

Analysis of Impact Mechanisms

Market Mechanism Perspective

The trading volume (*TV*) of CCERs and the carbon market trading price (*CP*) are used as proxy variables to determine the market size [56]. The mediating effect of CCER trading volume and the carbon market trading

Table 7. Spatial Spillover Effect Test.

Variable	W_1		W_2	
	SAR	SDM	SAR	SDM
ρ	0.4244*** (0.0395)	0.4038*** (0.0389)	0.3030*** (0.0496)	0.2926*** (0.0748)
Policy	-0.1747*** (0.0392)	-0.1605*** (0.0390)	-0.2855*** (0.0705)	-0.3052*** (0.0502)
$W_1 \times Policy$		-0.1522*** (0.1670)		
$W_2 \times Policy$				-0.2876*** (0.1038)
Controls	Yes	Yes	Yes	Yes
Direct Effect	-0.1641*** (0.0422)	-0.1664*** (0.0416)	-0.3049*** (0.0517)	-0.3030*** (0.0512)
Indirect Effect	-0.1200*** (0.0139)	-0.0996*** (0.0271)	-0.1008*** (0.1294)	-0.1266*** (0.0475)
Aggregate Effect	-0.2641*** (0.1240)	-0.2660*** (0.0661)	-0.4057*** (0.1444)	-0.4297*** (0.0836)
Province	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	660	660	660	660
R^2	0.2371	0.2778	0.5651	0.5666

Table 8. Mediating Effects of Market Mechanisms Test.

Variable	*TV*			*CP*		
	Step1	Step2	Step3	Step1	Step2	Step3
Policy	-0.261*** (0.231)	0.037*** (0.214)	-0.160*** (0.068)	-0.261*** (0.231)	-0.029*** (0.253)	-0.591*** (0.143)
TV			0.402*** (0.284)			
CP						-3.527*** (1.563)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	660	660	660	660	660	660
R^2	0.836	0.865	0.751	0.836	0.718	0.793

price is determined using the stepwise regression coefficient test based on Equations (9) to (11), and the results are presented in Table 8.

The empirical results demonstrate that the promotion of the CCER policy positively impacts the scale of trading. The main reason is that enterprises will actively participate in the project trading of CCERs to meet their emission reduction targets or compliance requirements, especially with the opening of China's carbon trading market in 2021; the trading volume of CCERs has warmed significantly [57]. However, the increase in trading volume will lead enterprises to overly rely on purchasing carbon emission reduction quotas to achieve their emission reduction targets, which may not achieve direct emission reduction in the short term. It will have a specific positive impact on carbon emission intensity. Therefore, in order to effectively manage and regulate the carbon market, the state has stipulated different CCER offset ratios for each region to maintain the stability and fairness of the market, which will more effectively promote the development of China's low-carbon economy in the future with

Table 9. Mediating Effects of Scale, Technology, and Structure Test.

Variable	*IV*			*GTI*			*ES*		
	Step1	Step2	Step3	Step1	Step2	Step3	Step1	Step2	Step3
Policy	-0.261*** (0.231)	0.033* (0.072)	-0.032* (0.321)	-0.261*** (0.231)	0.037*** (0.073)	-0.396** (0.322)	-0.261*** (0.231)	-0.008 *** (0.003)	-0.274*** (0.319)
IV			0.297*** (0.174)						
GTI						-0.116** (0.174)			
ES									-1.186* (0.505)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	660	660	660	660	660	660	660	660	660
R^2	0.836	0.913	0.838	0.836	0.954	0.843	0.836	0.652	0.656

the further improvement and implementation of the CCER policy. When assessing the intermediary role of carbon market trading prices, it is essential to point out that the operation of the carbon trading market is significantly driven by the CCER policy, especially when the carbon market trading price shows a negative impact. During the initial phase of policy implementation, CCER prices rose rapidly. With the complete opening of China's carbon market, high-emission enterprises may hoard carbon credits to meet compliance requirements. The enterprises' acquisition of CCERs drives up prices and surpasses traditional carbon market trading prices [58]. The policy's influence on the smooth development of carbon market trading prices imposes additional costs for enterprises, incentivizing them to focus on energy-saving, emission reduction, and technological innovation, ultimately reducing carbon emission intensity.

Scale, Technological, and Structural Effect

Based on the theoretical analyses above, implementing the CCER policy may increase carbon emission intensity through the scale effect while reducing it through the technological and structural effects. To test the scale effect, this paper uses the industrial gross output value of above-scale enterprises (*IV*) as the mediating variable [59], and the results are shown in Table 9. The implementation of the CCER policy leads to a significant increase in the gross industrial production value, which means that the policy promotes the expansion of the production scale and leads to a corresponding increase in the carbon emission intensity, indicating the existence of a scale effect and the establishment of hypothesis 3. In addition, two mediating variables are chosen for the technological and structural effects: the number of green patents granted (*GTI*) and the share of coal consumption in energy consumption (*ES*) [60, 61].

The empirical results show that the level of green technology innovation increases significantly after the implementation of the CCER policy, suggesting that the implementation of the CCER policy encourages enterprises to adopt cleaner and low-carbon production technologies, including investment in green energy and improvement of the production process, etc., and that the introduction of these technologies can partially offset the negative impact of the scale effect on the intensity of carbon emissions [52]. Simultaneously, the decrease in coal consumption suggests that the policy encourages industrial restructuring. Enterprises are more likely to integrate cleaner energy into their production processes, reducing their reliance on high-carbon energy and subsequently decreasing carbon emissions. Thus, Hypothesis 4 is confirmed.

Conclusions

Based on panel data from 30 provinces in China from 2000 to 2021, this paper uses an interrupted time series and a static panel data model to evaluate the impact and mechanism of the CCER policy on carbon emission intensity, providing a comprehensive assessment of the policy's effects. The study's conclusions are as follows: (1) The interrupted time series test shows that carbon emission intensity significantly decreased after implementing the CCER policy in 2015. However, following the suspension of the policy in 2017, while there was a short-term rebound in carbon emission intensity, the long-term emission reduction trend persisted, albeit with weakened effects. Using a two-way fixed effects model, the analysis demonstrates that overall, after implementing the CCER policy in 2015, carbon emission intensity decreased by 26.09%. The robustness tests further confirm that implementing the CCER policy significantly reduced carbon emission intensity in the pilot regions. Related studies can also confirm this conclusion [18, 37]. The heterogeneity analysis shows that the policy has a more significant effect on suppressing carbon emission intensity in the eastern region, the region with a higher level of technological innovation and the non-industrial base.

(2) An increase in the volume of CCER transactions under the policy increases carbon emission intensity, while maintaining a stable carbon market transaction price helps reduce it. Additionally, the CCER policy helps decrease carbon emission intensity by incentivizing enterprises' green technological innovation and optimizing energy structure, negatively impacting the scale effect.

(3) Carbon emission intensity's spatial and temporal distribution shows a significant positive correlation. The CCER policy aims to suppress carbon emission intensity in the region, but it also has a spatial spillover effect that affects neighboring regions.

Based on these conclusions, this paper proposes specific recommendations in three aspects, namely further strengthening the carbon market mechanism, formulating carbon emission reduction policies according to local conditions, and strengthening cross-regional cooperation to provide helpful guidance for future carbon market-oriented reforms, make the policies more precise and effective in promoting China's carbon emission reduction work, and contribute to the achievement of sustainable development goals. The specific suggestions are as follows:

(1) Strengthen the carbon market mechanism and improve the transparency and stability of the carbon market. Improving the CCER registration system and information platform to publicize carbon market information ensures that all market participants can obtain timely and accurate information about CCER prices and transaction sizes so enterprises can effectively respond to market changes and avoid risks. Furthermore, it is essential to scientifically establish the offsetting strategy and trading scale cap of CCERs to suit the unique needs and conditions of various industries and regions. In particular, high-emission industries should implement a stricter offset ratio to prevent excessive trading and market fluctuations. It is also crucial to adjust the offsetting strategy promptly in response to market changes to ensure the stability of the entire carbon market trading.

(2) Formulate carbon emission reduction policies according to local conditions. The government should set different carbon emission reduction targets based on each region's industrial structure and carbon emission status to achieve the dual benefits of economic growth and environmental protection. The eastern region's economic, technological, and human resources agglomeration advantages should be utilized to promote the development of green industries. Furthermore, the government ought to allocate resources towards the industrial development of the central and western regions, promoting economic agglomeration. More stringent carbon reduction targets could be introduced as an incentive for regions with high levels of green technology innovation to lead the low-carbon transition. Additionally, local governments can set progressive emission reduction targets and provide more policy support and time for transforming traditional industrial bases to prevent rapid industrial structure adjustment from leading to employment and social instability.

(3) Strengthening cross-regional cooperation. Taking into account the differences in carbon market management practices across regions, the government could introduce appropriate trading restrictions and establish a cross-regional cooperation framework for carbon markets. This strategy aims to balance regional carbon reduction objectives and resource allocation, enhancing the overall efficiency of emission reductions. Furthermore, it is recommended that experience sharing and cooperative research be enhanced, a cross-regional platform for sharing successful carbon emission reduction experiences and technologies be established, and regions be encouraged to share their achievements in reducing carbon emissions. Joint research should also be conducted to address common problems in carbon emission reduction to achieve synergistic effects and provide robust support for China to tackle climate change challenges better and achieve sustainable economic development and carbon neutrality.

Due to the short duration of the CCER implementation policy, the transaction price needs to be more transparent, making it challenging to comprehend its long-term effects and dynamic changes fully. With the relaunch of the CCER policy in 2024, the interaction between the supplementary role of the CCER policy and other environmental policies will be further considered in the future, and the CCER price will be added as an influencing factor to analyze the comprehensive effect of multiple policy tools; the optimal solution for the CCER offset ratio will be thoroughly explored to improve the economic efficiency of the policy while ensuring that the environmental objectives are achieved. Through an in-depth study of these aspects, we aim to provide accurate and effective policy recommendations for future carbon market reform in China and worldwide.

Abbreviations

IPCC	Intergovernmental Panel on Climate Change
COP28	2023 United Nations Climate Change Conference
CEA	Carbon Emission Allowance Trading
CCER	Chinese Certified Emission Reduction Policy
CDM	Clean Development Mechanism
JI	Joint Implementation

→

IET	International Emissions Trading
VCS	Verified Carbon Standard
GS	Gold Standard
ACR	American Carbon Registry
CAR	Climate Action Reserve
CGE	Computable General Equilibrium
SEM	Spatial Error Model
SAR	Spatial Autoregressive Model
SDM	Spatial Durbin Model

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Conflict of Interest

The authors declare no conflict of interest.

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