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Electricity Market-oriented Reform Empowers the "Dual Carbon" Strategy: Carbon Emission Reduction Paths and Heterogeneity Tests of Spot Market Pilot Policies

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Abstract
Under the dual pressure of increasing energy demand and reducing carbon emissions to protect the environment, the carbon reduction effect and dynamic transmission mechanism of the pilot policy of electricity spot market need to be systematically evaluated. Based on the panel data of 30 provincial-level regions in China from 2017 to 2021, this paper empirically tests the impact of policy on carbon emission intensity and its regional heterogeneity by using the panel fixed effect model, mediating effect analysis and moderating effect analysis. The findings are as follows: (1) In the short term, the imperfect market mechanism increases the dependence on thermal power, leading to a significant rise in carbon emissions. However, in the long run, the synergistic effect of industrial structure upgrading, low-carbon technology innovation and increased environmental awareness effectively reduces the emission intensity. (2) Prominent regional heterogeneity: high financial development regions inhibit emissions through technology diffusion and service industry transformation, while low financial development regions face carbon lock-in due to thermal power dependence. High sustainability regions accelerate emission reduction through innovation network externalities, while low sustainability regions require technological

Keywords
Electricity Spot Market; Carbon Emission Intensity; Mediation Effect; Moderation Effect; Regional Heterogeneity

1 Introduction

Against the urgent backdrop of global efforts to address climate change, the low-carbon transition of energy systems has become a core issue in advancing sustainable development. As one of the main sources of carbon emissions, the power industry's market-oriented reform is not only related to the improvement of energy resource allocation efficiency but also has a profound impact on achieving carbon emission reduction goals. In recent years, with the gradual advancement of the pilot policy for the electricity spot market, its role in optimizing power dispatching and promoting the integration of clean energy has gradually become apparent. However, the actual impact paths and mechanisms on carbon emissions still need systematic verification.

Existing literature mostly discusses the driving factors of carbon emission reduction from the macro policy level, such as industrial structure adjustment, technological innovation, and foreign direct investment. There are also many studies on the operation mechanism of the power market, new energy integration, and market design. Nevertheless, in-depth empirical analysis is lacking regarding the carbon emission reduction effect of the specific policy experiment of electricity spot market construction, especially its heterogeneous performance under different regional conditions. Most studies focus on the design and operation efficiency of the market mechanism itself, ignoring its dynamic connection with environmental goals and the underlying economic transmission mechanisms.

The electricity spot market guides power generation behavior through price signals, which in theory should help improve energy efficiency and the proportion of clean energy. However, problems such as market imperfections in the early stage of policy implementation and the locked-in path of dependence on thermal power may lead to a short-term increase rather than a decrease in carbon emissions. In the long run, the maturity of the market mechanism and the optimization of supporting structures are expected to reverse this trend and achieve emission reduction effects. This dynamic process of "short-term intensification and long-term mitigation" and its regional differences constitute the core concern of this study.

Based on China's provincial panel data from 2017 to 2021, this paper uses fixed-effects models, mediating effect, and moderating effect analysis methods to systematically examine the impact mechanism of the electricity spot market pilot policy on carbon emission intensity. It further explores the regional heterogeneous performance of the policy from the two dimensions of financial development level and sustainable development capacity. The study aims to reveal the transmission paths and effects of the policy under different regional conditions, providing theoretical and empirical basis for the coordinated promotion of electricity market-oriented reform and carbon emission reduction goals.

The contributions of this paper are as follows: First, it identifies the "double-edged sword" effect of the electricity spot market policy on carbon emissions and clarifies its short-term and long-term directions of action. Second, through the test of mediating effect, it reveals the key role of industrial structure optimization in policy transmission. Third, it conducts heterogeneity analysis from the two dimensions of finance and sustainable development to provide support for differentiated policy design. The research conclusions have important theoretical value and practical significance for improving the electricity market mechanism and optimizing regional emission reduction strategies.

2 Literature Review

The issue of carbon emissions has long attracted considerable attention from scholars, who have conducted extensive discussions on how to effectively save energy and reduce emissions. Wang et al. (2024) found that low-carbon transformation is conducive to achieving "carbon neutrality" and coordinated regional development[3] . Fang et al. (2024) pointed out that the carbon market promoted carbon emission reduction in the thermal power industry, but its impact had a lag effect, and there was a robust "inverted U-shaped" relationship between carbon price and carbon emission reduction in the thermal power industry [4] . He Fengzhi (2024) adopted the DID method and concluded that the adoption of TPS pilot carbon emission trading policy and the improvement of carbon market in China's power generation industry significantly reduced the carbon emissions and intensity of the power generation industry [5]. The research conclusions of Wang (2024) [6] and Ji (2025) [7] verified the above views, and further proposed that the pilot policy of carbon trading could reduce the level of carbon emissions by improving the level of digital industry and green technology innovation, technological innovation, government intervention and other ways.

As a key component of the current electricity market system, the research on electricity spot market has been increasing in recent years. At present, domestic scholars' research on the electricity spot market mainly focuses on basic issues of market construction, such as congestion management mechanisms [8] and construction mode strategies [9] . With the development of the electricity spot market, research has gradually expanded to multiple fields.

In terms of market operation optimization, some studies focus on balancing the absorption of new energy and the economic benefits of other units, such as considering the time-sharing bidding game of new energy-thermal power bilateral peak-shaving

transactions to optimize market operation [10], and designing transaction mechanisms that take into account the absorption of high-proportion new energy and peak-shaving compensation for thermal power units [11]. Regarding market transaction decisions, aiming at the transaction decisions of wind and solar power generators participating in the electricity spot-green certificate market, a two-layer coupled transaction model considering the bilateral deviation penalty price mechanism is proposed [12], and the bidding strategies and business development strategies of thermal power enterprises in the electricity spot market environment are analyzed [13] . In terms of market data processing and scheduling, some studies have proposed an adaptive scheduling method for multi-party transaction data in the electricity spot market to cope with the data scheduling challenges brought by the expansion of transaction scale [14] . In terms of market settlement and price mechanisms, discussions are made on the evaluation and optimization of market operation status under the new energy settlement mechanism [15], the analysis of the value of medium and long-term contracts and pricing suggestions [16], and the study of expanding the linear relaxation pricing method of node prices to improve market fairness and operational efficiency [17] . In addition, some studies focus on the participation of specific subjects in the market. For example, analyzing the risks faced by pumped storage in participating in the spot market and constructing a report quantity decision model [18], and studying the problems and countermeasures of hydropower stations participating in the electricity spot market [19] . At the same time, there are also studies discussing the structural design theory and methods of a unified electricity spot market system from a macro perspective [20], thinking about the development of virtual power plants in the electricity spot market environment [21], and studies on improving the quality and efficiency of meter reading, verification and collection work under the electricity spot market [22] . In addition, there are studies on the electricity spot market model considering carbon emission rights trading, proposing a two-stage electricity spot market clearing model in which load subjects participate in carbon emission rights trading [23] . Compared with the traditional electricity planning system, the electricity spot market innovatively proposes solutions to key issues such as interest balance, risk control, and market connection in the electricity spot market, and is a electricity spot market transaction rule in line with China's national conditions and with Chinese characteristics [24] .

To sum up, the issue of carbon emissions has always been a core topic in academic circles. Existing studies have focused on the influencing factors of carbon emissions. Domestic research on the externalities of the electricity spot market is relatively scarce, and there is a lack of research on evaluating the implementation effect of the electricity spot market construction pilot policy. Currently, the pilot work of the electricity spot market is still being carried out in depth. However, what is the carbon emission reduction effect of China's electricity spot market construction pilot policy? How does this pilot policy affect carbon emission reduction? Are there differences in the effect of the pilot policy in different regions? These issues need further analysis.

2 Research Design

2.1 Model Construction

This paper uses fixed effects to analyze the carbon emission reduction effect of the pilot policy, and constructs the model as follows:

$$\begin{aligned}\ln CE_{it} = {} & \beta_0 + \beta_1 Policy_{it} + \beta_2 Ur_{it} + \beta_3 \ln GDP_{it} + \beta_4 \ln Population_{it} + \beta_5 FP_{it} + \beta_6 IS_{it} \\ & + \beta_7 SD_{it} + \beta_8 IV_{it} + \gamma_1 (SD_{it} \times Policy_{it}) + \gamma_2 (IS_{it} \times Policy_{it}) \\ & + \gamma_3 (IV_{it} \times Policy_{it}) + \mu_i + \lambda_t + \varepsilon_{it}\end{aligned}$$

2.2 Data Sources

The quasi-natural experiment in this study is defined as the first official implementation of the electricity spot market construction pilot policy in 2017. Eight provincial administrative units including Guangdong, Inner Mongolia, Zhejiang, Shanxi, Shandong, Fujian, Sichuan, and Gansu are selected as the experimental group, and the remaining 22 provinces and autonomous regions as the control group. Panel data of 30 provincial administrative regions (provinces, municipalities directly under the Central Government, and autonomous regions) from 2005 to 2021 are used (originally 34 provincial administrative regions, excluding Hong Kong, Macao, Taiwan, and Tibet due to missing data). The data are obtained from the China Statistical Yearbook, China Energy Statistical Yearbook, and the official website of the National Bureau of Statistics. In addition, to avoid the impact of outliers, all continuous variables are subjected to logarithmic processing. The descriptive statistics of each variable are shown in Table 1.

2.3 Variable Description

2.3.1 Dependent variable: Carbon emission intensity(CE). Its reduction can not only directly reduce carbon dioxide emissions but also promote the transformation of the economy towards green and low-carbon development. It is expressed by the carbon dioxide emissions of each region.

2.3.2 Core explanatory variable: Electricity spot market construction pilot policy (Policy). Among them, Policy is the product of treat and period. Treat is an individual dummy variable, which equals 1 if the region is a pilot policy implementation area, otherwise 0; Period is a time dummy variable, which equals 1 if the time is before the implementation of the pilot policy, otherwise 0.

2.3.3 Mediating variable: Industrial structure optimization. Different industries have different degrees of resource consumption, and changes in industrial structure will affect the generation of carbon emissions. It is expressed by the ratio of the total output value of the tertiary industry to that of the secondary industry.

2.3.4 Control variables: The control variables are selected as follows: (1) Urbanization rate, measured by the proportion of urban population in the total population; (2) Per capita GDP after price adjustment, using per capita GDP with logarithm taken; (3) Population density. Human activities are the main cause of carbon emissions, and population density affects regional carbon emissions, measured by the ratio of the total population at the end of the year to the regional area; (4) Fuel commodity price index, based on statistical yearbook data; (5) Thermal power proportion, the proportion of thermal power generation in total power generation within a certain period and scope. All variables are taken as natural logarithms.

3 Empirical Analysis

3.1 Benchmark Regression

As shown in Table 2, both before and after the inclusion of control variables, the electricity spot market construction pilot policy has a significant positive impact on the amount of carbon emissions, but the degree of impact varies slightly.

Column (1) only shows the regression results of core explanatory variables and dependent variables. The coefficient of the pilot policy of electricity spot market construction on carbon emissions is significantly positive. Column (2) shows the regression results after adding control variables such as urbanization rate, GDP, population and fuel commodity prices. The coefficient of the pilot power spot market construction policy on carbon emissions is still significantly positive, indicating that the implementation of the policy leads to a significant increase in carbon emissions on average. This effect may stem from the immaturity of the market mechanism in the early stage of policy implementation. For example, the pilot policy of electricity spot market construction has stimulated the trading activities of high-emission energy sources (such as thermal power) in the short term (in the short term), while factors such as lagging substitution of clean energy have led to a temporary increase in carbon emissions. Compared with the regression results in Column (1), the positive promoting effect of the policy pilot on carbon emissions is significantly weakened, and part of the policy effect is absorbed by the urbanization rate, GDP and other variables, but it is still positive. This may be due to the insufficient role of the current electricity spot market trading mechanism in promoting the optimal allocation of electricity resources, or the low proportion of new energy electricity in the transaction, which makes the implementation of electricity trading policy increase carbon emissions to a certain extent.

Table 2 Benchmark Regression Results

	(1) ln(CE)	(2) ln(CE)
Policy	0.86*** -8.98	0.41*** -4.96
Urbanization		-0.93** (-2.71)
ln(GDP)		0.38** -2.6
ln(Population)		0.27* (2. 10)
Fuel Price		-0. 11 (-0.43)
_cons	5.45*** -62.53	0.67 -0.5
N	510	510

3.2Mediating Effect

As shown in Table 3, Column (1) conducts the benchmark regression, and the influence coefficient of the pilot policy of electricity spot market construction on carbon emissions is significantly positive at the significance level of 1%. This indicates that the implementation of the pilot policy led to a significant increase in the average level of carbon emissions. Column (2) is the regression of mediating variables, and the estimated coefficient of the industrial structure pilot policy is significantly positive at the significance level of 10%. This shows that the implementation of the pilot policy will lead to a significant average growth of the industrial structure, which means that the policy has a certain positive role in promoting the upgrading of the industrial structure. The mechanism may be that policies guide capital to flow to clean and renewable energy, high-end manufacturing or high value-added industries through market-oriented means such as pricing mechanisms, thus promoting the optimization of industrial structure. It is worth noting that the estimated coefficient of the proportion of thermal power is significantly negative, indicating that the expansion of thermal power scale significantly inhibits the optimization and upgrading of industrial structure, further indicating the conflict between high energy consumption and industrial structure.

Column (3) shows the joint regression, where after incorporating both the pilot policy and industrial structure into the model, the coefficient of the pilot policy drops to 0.116 ($p<0.01$), a decrease of approximately 72% compared to the benchmark regression. This indicates that industrial structure plays a partial mediating effect (72%). The coefficient of industrial structure is -0.241 ($p<0.01$), revealing a close negative correlation between industrial structure and carbon emissions, with carbon emissions decreasing by 0.241%. This result is consistent with the Environmental Kuznets Curve (EKC) theory, i.e., industrial upgrading can inhibit carbon emissions through technical effects and structural effects.

In summary, the electricity trading pilot policy has a dual effect of "direct promotion and indirect inhibition" on carbon emissions. On one hand, the electricity spot market construction pilot policy directly stimulates and increases carbon emissions in pilot areas; on the other hand, industrial structure upgrading can significantly inhibit carbon emissions, and the inhibitory effect is considerable as indicated by the estimated coefficient, reflecting a complex mechanism. This means that in the early stage of the electricity spot market pilot, although the policy itself may directly stimulate transactions of high-carbon energy such as thermal power in the short term, leading to a rise in carbon emissions, promoting industrial structure upgrading can partially offset this impact, thereby gradually achieving carbon reduction.

Table 3 Results of Mediating Effect Test Based on Industrial Structure

	(1)ln(CE)	(2)Industrial Structure	(3)ln(CE)
Policy	0.41***	0.07*	0. 12**
	-4.96	-1.97	(3. 13)
Industrial Structure			-0.24***
			(-5.55)
lnPt*h*		-1. 10***	0.19
		(-4.09)	(1. 16)
Control	YES	YES	YES
N	510	510	510

3.3Moderating Effect

In Table 4, columns (1)-(3) respectively test the regression results of the electricity spot market construction pilot policy with the awareness of sustainable development, industrial structure, and comprehensive innovation index. In all columns, the electricity spot market construction pilot policy shows a significant positive impact on carbon emissions, indicating that the current electricity spot pilot policy may indirectly promote the increase of carbon emission levels by expanding electricity market transactions, which leads to a rise in power generation.

In column (1), the interaction term coefficient between the electricity spot market construction pilot policy and the awareness of sustainable development is significantly negative, indicating that the electricity spot market construction pilot policy has a significant moderating effect on environmental protection awareness. Under the implementation of the electricity spot market construction pilot policy, for every 1% increase in environmental protection awareness, the amount of carbon emissions decreases by an average of 2.721%. The interaction between the electricity spot market construction pilot policy and environmental protection awareness shows that public participation is a key social capital for achieving carbon emission reduction in the market-oriented reform of electricity spot, and social capital can strengthen its carbon emission reduction leverage effect through information disclosure and green certification.

In column (2), the interaction term between the electricity spot market construction pilot policy and industrial structure is significantly negative, indicating that the electricity spot market construction pilot policy has a significant moderating effect on industrial structure. Under the implementation of the electricity spot market construction pilot policy, for every 1% improvement in industrial structure, the amount of carbon emissions decreases by an average of 0.907%. The electricity spot market construction pilot policy guides the dynamic adjustment of industrial structure through price signals, and can achieve long-term emission reduction dividends of market-oriented reform by supporting industrial access standards and energy efficiency subsidies.

In column (3), the interaction term between the electricity spot market construction pilot policy and the comprehensive innovation index is significantly negative, indicating that the electricity spot market construction pilot policy has a significant moderating effect on the comprehensive innovation index. Under the implementation of the electricity spot market construction pilot policy, for every 1% increase in the comprehensive innovation index, the amount of carbon emissions decreases by an average of 1.281%. The electricity spot market construction pilot policy has built a market-oriented incentive mechanism for technological innovation. The government expands the emission reduction multiplier effect of enterprise technological innovation by strengthening intellectual property protection and green financial support.

To sum up, the electricity spot market construction pilot policy presents a "double-edged sword" effect of "directly aggravating and indirectly alleviating" on carbon emissions. The implementation of the electricity spot market policy needs to rely on the synergistic mechanism of industrial structure optimization, technological innovation incentives, and the improvement of public environmental protection awareness to reverse the short-term carbon lock-in risk, and finally realize the compatibility between the electricity market-oriented reform and the carbon neutrality goal.

Table 4 Moderating Effect Test Based on Sustainable Development Level, Industrial Structure and Innovation Level

	(1) ln(CE)	(2) ln(CE)	(3) ln(CE)
Policy	10.40***	1.17***	2.14***
	(7.73)	(3.00)	(6.54)
Industrial Structure	-0.40***	-0.41***	-0.38***
	(-18.39)	(-25.98)	(-20.50)
$\ln P_{th}$	1.29***	1.34***	1.36***
	(19.84)	(16.24)	(18.25)
Sustainable Development×Policy	-2.40***		
	(-7.34)		
Industrial Structure×Policy		-0.50*	
		(-1.76)	
Innovation Value×Policy			-0.51***
			(-4.58)
Sustainable Development	-0.32**		
	(-2.46)		
Control	YES	YES	YES
N	510	510	510

4 Heterogeneity Analysis

4.1 Analysis Based on the Heterogeneity of Financial Development Level

The research samples are divided into two categories, namely regions with a high level of financial development and regions with a low level of financial development, based on the average value of the financial development level of 30 provinces and cities. This is to investigate the implementation effect of the electricity trading pilot policy in regions with different sustainable development levels.

It can be seen from the financial benchmark regression in Table 5 that whether in regions with a high level of financial development or regions with a low level of financial development, the implementation of the electricity spot market construction pilot policy has a significant promoting effect on carbon emissions. That is, compared with non-pilot regions, the carbon emissions in pilot policy regions increase by an average of 0.328%. At the same time, after adding control variables such as the urbanization rate, the increase in carbon emissions becomes insignificant. This may be because, whether in economically developed or underdeveloped regions, the power dispatching departments and the current development level of power grid infrastructure are limited. After the implementation of the electricity spot market trading policy, the trading policy cannot be effectively used to trade electricity generated by clean energy that is difficult to dispatch quickly, so thermal power, which is convenient and quick to generate, is used for trading, thus significantly increasing carbon emissions.

Table 5 Benchmark Regression Based on Heterogeneity in Financial Development Level

Policy	Regions with a high level of financial development		Regions with a low level of financial development	
	ln(CE)	ln(CE)	ln(CE)	ln(CE)
	0.33***	0.06	0.36***	0.03
	(4.54)	(1.18)	(4.34)	(0.39)
Urbanization		-4.32***		1.39
		(-6.64)		(1.49)
ln(GDP)		0.33***		0.29
		(5.42)		(1.72)
ln(Population)		0.52***		0.37**
		(3.57)		(2.42)
Fuel Price		0.09		0.04
		(0.51)		(0.14)
_cons	5.78***	-0.29	5.42***	-0.97
	(129.50)	(-0.26)	(53.16)	(-0.73)
N	102	102	408	408

As shown in Table 6, the mediating effects of the pilot policy, thermal power proportion, and carbon emissions are elaborated as follows: The pilot policy has a significant inhibitory effect on the proportion of thermal power in both regions with above-average financial development and those with below-average financial development. Meanwhile, the proportion of thermal power in regions with below-average financial development has a significantly positive promoting effect on carbon emissions, whereas in regions with above-average financial development, the promoting effect of thermal power proportion on carbon emissions is only slightly significant. This may be because the environmental constraint mechanism for thermal power proportion has weakened in regions with above-average financial development. Carbon emissions in such regions are composed of multiple industries, and thermal power only accounts for a small part. Therefore, the impact of thermal power proportion on the increase in carbon emissions is slightly significant. In contrast, in regions with below-average financial development, carbon emissions from thermal power account for a major part of total carbon emissions, so the proportion of thermal power can significantly increase carbon emissions.

The mediating effects of the pilot policy, industrial structure, and carbon emissions are elaborated as follows: It can be seen from Figure 2 that in regions with above-average financial development, the pilot policy has a significant promoting effect on the industrial structure, and the industrial structure also has a slightly significant inhibitory effect on carbon emissions. However, in regions with below-average financial development, neither the pilot policy on the industrial structure nor the industrial structure on carbon emissions has a significant impact. This indicates that there is an obvious mediating effect among the three in regions with above-average financial development, while such a mediating effect is not obvious in regions with below-average financial development. This may be due to the dual regulatory role of financial development level on policy transmission efficiency and industrial transformation capacity, as well as the mechanism blockage in financially underdeveloped regions: In financially underdeveloped regions, zombie enterprises occupy a large amount of credit resources, policy funds are locked in inefficiently, and there may even be a phenomenon of pseudo-upgrading. The statistically increased "proportion of the tertiary industry" is essentially the expansion of low-end service industries, whose carbon emissions per unit of added value are even higher than those of some manufacturing industries.

Table 6 Test of Heterogeneous Mediating Effects Based on Financial Development Level

	Regions with a high level of financial development				Regions with a low level of financial development			
	Industrial Structure	$\ln P_{th}$	ln(CE)	ln(CE)	Industrial Structure	$\ln P_{th}$	ln(CE)	ln(CE)
Policy	0.07***	-0.04***	0.10**	0.09**	0.03	-0.08***	0.17**	0.18**
	(4.06)	(-5.76)	(2.62)	(2.42)	(0.76)	(-6.03)	(2.70)	(2.76)
Industrial Structure			-0.67*				-0.13	
			(-1.91)				(-1.19)	
$\ln P_{th}$				1.76*				0.82***
				(1.94)				(4.99)
Control	YES	YES	YES	YES	YES	YES	YES	YES
N	102	102	102	102	408	408	408	408

As shown in Table 7, in regions with a high level of financial development, the coefficient of "pilot policy * industrial structure" is 4.440 with a positive significance, indicating that in such regions, the industrial structure plays a significant moderating role in the relationship between the pilot policy and carbon emissions. That is, the higher the level of industrial structure optimization, the more the impact of the pilot policy on carbon emissions will change. The coefficient of "comprehensive innovation index * pilot policy" is significantly positive, suggesting that the comprehensive innovation index also has a significant moderating effect on the relationship between the pilot policy and carbon emissions. The effect of the pilot policy on carbon emissions varies under different levels of the comprehensive innovation index.

In regions with a low level of financial development: the coefficient of "pilot policy * industrial structure" is 1.625, which passes the test at the 5% confidence level, meaning that in regions with low financial development, the industrial structure has a significant moderating effect on the relationship between the pilot policy and carbon emissions. The coefficient of "comprehensive innovation index * pilot policy" is significantly negative, indicating that the comprehensive innovation index has a significant moderating effect on the relationship between the pilot policy and carbon emissions, but the direction of moderation is opposite to that in regions with a high level of financial development.

To sum up, both the industrial structure and the comprehensive innovation index have significant moderating effects on the relationship between the pilot policy and carbon emissions in both high and low financial development regions, but there are differences in the magnitude and direction of the moderating effects. The specific directional differences and their explanations are as follows:

Positive moderation mechanism in high financial development regions: The positive moderation of the industrial structure coefficient (+4.440) indicates that when a region has a modern financial service system, the service-oriented transformation of the industrial structure (increased proportion of the tertiary industry) and the agglomeration of high-value-added industries can significantly amplify the emission reduction effect of the electricity spot market policy. The underlying mechanism is that a developed financial market effectively guides capital to low-energy-consuming industries through green credit, carbon financial instruments, etc., while supporting the clean transformation of traditional industries. The positive moderation of the innovation index (+3.448) stems from the synergistic effect of innovation factors brought by financial deepening. Regions with high financial development are often characterized by active venture capital and mature technology trading markets, enabling technological innovations (such as smart grids and energy storage technologies) to achieve commercial application faster and strengthening the technological emission reduction path of the policy.

Differentiated moderation in low financial development regions: The industrial structure coefficient (+1.625) remains positive but with a weakened effect, reflecting that industrial transformation in underdeveloped regions mainly relies on mandatory policy-driven rather than spontaneous market regulation. Due to the lack of green financial support, the emission reduction effect of industrial upgrading is limited by the constraints of enterprise technological transformation funds. The negative moderation of the innovation index (-1. 177) reveals the "innovation paradox": when the regional financial foundation is weak, enterprise R&D investment may squeeze productive funds, resulting in the inability of short-term energy efficiency improvements to offset the emission increase caused by capacity expansion. A deeper reason is that low-end innovations (such as partial improvement of coal-fired equipment) may produce a technology lock-in effect, which is instead unfavorable to systematic emission reduction.

Table 7 Test of Heterogeneous Moderating Effects Based on Financial Development Level

	Regions with a high level of financial development			Regions with a low level of financial development		
	ln(CE)	ln(CE)	ln(CE)	ln(CE)	ln(CE)	ln(CE)
Policy	46.84***	-3.40***	-12.63***	4.45	-1.11**	3.80***
	(4.13)	(-4.06)	(-6.83)	(1.38)	(-2.63)	(5.38)
Sustainable Development ×Policy	-11.09***			-1.02		
	(-4.11)			(-1.34)		
Sustainable Development	0.10	0.11	-0.01	-0.47**	-0.49**	-0.36**
	(0.81)	(0.88)	(-0.02)	(-2.77)	(-2.60)	(-2.32)
Industrial Structure ×Policy		4.44***			1.63***	
		(4.31)			(3.17)	
Industrial tructure	-0.86***	-0.86***	-0.77***	-0.89***	-0.93***	-1.20***
	(-12.15)	(-12.04)	(-10.22)	(-4.89)	(-5.28)	(-6.75)
Innovation Value×Policy			3.45***			-1.18***
			(6.82)			(-5.33)
Innovation Value			-1.07***			-1.19***
			(-5.55)			(-5.79)
_cons	-3.68*	-3.91*	-1.47	4.91***	4.93***	6.81***
	(-1.96)	(-2.01)	(-1.17)	(3.37)	(3.41)	(4.45)
N	102	102	102	408	408	408

4.2Heterogeneity in Sustainable Development Level

Based on the average value of the sustainable development level of 30 provinces and cities, the research samples are divided into two categories: regions with a high level of sustainable development and regions with a low level of sustainable development, so as to investigate the implementation effect of the electricity trading pilot policy in regions with different sustainable development levels.

Table 8 shows the benchmark regression results of the two types of regions. It can be seen that the electricity trading pilot policy has a significant effect on the carbon emission volume in both types of regions. The electricity trading pilot policy has a stronger effect on the carbon emission volume in regions with a low level of sustainable development, but the pilot policy has a positive effect on the carbon emission volume in both types of regions, and both have passed the significance test. After adding control variables, the electricity trading pilot policy failed the significance test in regions with a high level of sustainable development.

Table 9 shows the mediating effect results of the two types of regions. The results show that the coefficient of the impact of the pilot electricity trading policy on carbon emissions is significantly positive in regions with low levels of sustainable development. After the intermediary variable of industrial structure is added, the influence coefficient of the pilot power trading policy on carbon emissions increases and is still significant. There may be other factors that work together with industrial structure to promote carbon reduction. At this time, the industrial structure plays a partial intermediary role in carbon emission reduction in the region.

Table 10 shows the moderating effect results of the two types of regions. In regions with a high level of sustainable development, although the pilot policy has a significant positive impact on carbon emissions, the impact intensity is significantly lower than that in high-level regions. After adding environmental protection awareness, the interaction coefficient is -1.443. The first column shows that under the implementation of the electricity spot market construction pilot policy, for every 1% increase in environmental protection awareness, the carbon emission volume decreases by an average of 1. 132%. The second column shows that under the implementation of the electricity spot market construction pilot policy, for every 1% optimization of the industrial structure, the carbon emission volume decreases by an average of 0.916%. The third column shows that under the implementation of the electricity spot market construction pilot policy, for every 1% increase in the comprehensive innovation index, the carbon emission volume decreases by an average of 1.84%.

In regions with a high level of sustainable development, although the pilot policy has a significant positive impact on carbon emissions, the impact intensity is significantly lower than that in high-level regions. The third column shows that under the implementation of the electricity spot market construction pilot policy, for every 1% increase in the comprehensive innovation index, the carbon emission volume decreases by an average of 0.991%.

To sum up, in regions with a high level of sustainable development, it is necessary to promote the simultaneous implementation of three measures: "improving environmental protection awareness, optimizing and upgrading the industrial structure, and increasing the comprehensive innovation index". In regions with a low level of sustainable development, the focus should be on increasing the comprehensive innovation index.

Table 8 Benchmark Regression Based on Heterogeneity in Sustainable Development Level

	Regions with a high level of sustainable development		Regions with a low level of sustainable development	
	ln(Carbon Emis sion) (1)	ln(Carbon Emis sion) (2)	ln(Carbon Emis sion) (3)	ln(Carbon Emis sion) (4)
Policy	0.35***	0.06	0. 10***	0.40***
	-4.23	(1. 18)	-8.78	-4.27
Urbanization		0.49**		0.73
		-2.3		-0.79
ln(GDP)		0.11		0.34*
		-1.46		-1.89
ln(Populatio		0.68***		0.23
		-16.46		-1.3
Fuel Price		-0.37		-0.12
		(-1.41)		(-0.46)
cons	5. 15***	0.14	5.81***	1.08
	-67.94	(0. 12)	(56. 15)	-0.85
N	272	272	238	238

t statistics in parentheses* p < 0. 10, ** p < 0.05, *** p < 0.01

Table 9 Test of Heterogeneous Mediating Effects Based on Sustainable Development Level

	Regions with a high level of sustainable development				Regions with a low level of sustainable development			
	Industrial Structure	$\ln P_{th}$	ln(Carbon Emission)	ln(Carbon Emission)	Industrial Structure	$\ln P_{th}$	ln(Carbon Emission)	ln(Carbon Emission)
Policy	-0.02	-0.04*	0.04	0.04	0.08*	-0.01	0.12**	0.14***
	(-0.18)	(-1.79)	(1.13)	(0.68)	(1.82)	(-0.69)	(2.30)	(3.05)
Urbanization	0.01	1.47***	0.11	0.42	-0.16	0.38***	-2.91**	-2.27**
	(0.05)	(4.92)	(0.13)	(0.41)	(-1.32)	(3.32)	(-2.42)	(-2.63)
ln(GDP)	0.19***	-0.15***	0.39***	0.32**	0.09**	-0.05*	0.81***	0.80***
	(5.51)	(-5.68)	(3.85)	(2.60)	(2.53)	(-1.76)	(9.09)	(10.94)
ln(Population)	-0.39***	0.09**	-0.16	-0.23	-0.14***	0.12***	-1.00***	-1.10***
	(-6.64)	(2.60)	(-1.00)	(-0.81)	(-4.66)	(3.99)	(-3.53)	(-6.72)
Fuel Price	0.04	-0.04	-0.14	-0.13	-0.25**	0.11*	-0.23*	-0.22**
	(0.37)	(-0.70)	(-0.99)	(-0.67)	(-2.90)	(2.03)	(-2.05)	(-2.49)
Industrial Structure			-0.49***				-0.11	
			(-3.20)				(-0.39)	
$\ln P_{th}$				0.42				1.53***
				(1.55)				(5.68)
_cons	1.91***	0.77**	3.81**	4.25*	2.24***	-0.61**	8.82***	8.39***
	(3.05)	(2.28)	(2.91)	(2.09)	(5.50)	(-2.83)	(5.40)	(8.43)
N	272	272	272	272	238	238	238	238

t statistics in parentheses* p < 0.10, ** p < 0.05, *** p < 0.01

Table 10 Test of Heterogeneous Moderating Effects Based on Sustainable Development Level

	Regions with a high level of sustainable development	Regions with a low level of sustainable development

	ln(Carbon Emission) (1)	ln(Carbon Emission) (2)	ln(Carbon Emission) (3)	ln(Carbon Emission) (4)	ln(Carbon Emission) (5)	ln(Carbon Emission) (6)
Policy	6.31***	-1.27***	4.26***	0.26***	0.25**	0.22***
	(5.95)	(-8.87)	(4.43)	(3.45)	(2.92)	(5.02)
Sustainable Development ×Policy	-1.44***			0.07***		
	(-5.81)			(5.83)		
Sustainable Development	0.31**	0.30**	0.35***	0.16	0.18	-0.02
	(2.56)	(2.59)	(3.40)	(0.89)	(0.97)	(-0.26)
Industrial Structure ×Policy		1.70***			0.37***	
		(11.12)			(4.22)	
Industrial Structure	-0.77***	-0.79***	-0.63***	0.63	0.45	-0.70**
	(-17.02)	(-15.53)	(-17.55)	(1.46)	(1.08)	(-2.28)
Innovation Value×Policy			-1.28***			0.08***
			(-4.25)			(7.51)
Innovation Value			-0.56***			-1.07***
			(-4.87)			(-12.88)
_cons	-1.39	-1.46	-1.82	1.80	1.87	4.67***
	(-1.21)	(-1.28)	(-1.29)	(1.38)	(1.41)	(5.81)
N	272	272	272	238	238	238

t statistics in parentheses* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$ (Due to space constraints, the control variables are not included in the table. They can be obtained from the author upon request.)

5 Conclusions and Policy Recommendations

Through multi-dimensional empirical analysis, this study reveals that the impact of the electricity spot market construction pilot policy on carbon emissions exhibits significant dynamic effects and regional heterogeneity characteristics: (1) Dynamic effect mechanism: In the early stage of the policy, the strengthening of dependence on thermal power caused by imperfect market mechanisms led to a significant increase in carbon emissions; however, within the 3-5 year policy cycle, through the synergistic effect of industrial structure upgrading, low-carbon technological innovation, and the strengthening of environmental regulations, the carbon emission intensity finally decreased. This finding confirms the phased characteristics of the Environmental Kuznets Curve. (2) Laws of regional heterogeneity: In terms of financial development level: high financial agglomeration areas significantly inhibit carbon emissions through the service-oriented industrial structure and technology diffusion effects, while areas with low financial levels show negative policy spillover due to the thermal power lock-in effect; in terms of sustainable development capacity: regions with leading sustainable development levels accelerate the emission reduction process relying on the internalization of environmental protection awareness and the externality of innovation networks; at the same time, underdeveloped areas need to break through path dependence through technology catch-up strategies. (3) Core transmission path: Industrial structure optimization constitutes a key mediating variable. Each 1% increase in its cleanliness can reduce carbon emissions by 0.241%, but each 1% increase in the proportion of thermal power will offset the effect of industrial upgrading and lead to an increase in carbon emissions by 1.358%. This indicates that the lag in energy structure transformation may form a systemic resistance to emission reduction.

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