Study On the Impact of Carbon Emission Trading Policy on Enterprise'S Green and Low-Carbon Transformation——Evidence based on natural experiments

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Abstract. Carbon emission trading policies serve as a crucial market-oriented instrument for achieving China's "dual carbon" goals and form a strategic pillar in global climate governance alongside national economic transformation. Using data from A-share listed companies in China between 2010 and 2023, this study employs a multi-period difference model to examine the impact of carbon emission trading policies on corporate green and low-carbon transitions. The findings reveal that implementing such policies effectively promotes corporate green transition with robust results. Enterprises exhibiting regional diversity, varying scales, or ownership structures demonstrate heterogeneous responses to these policies. Mechanism analysis indicates that enhanced green technological innovation amplifies the policy's positive effects on corporate green transition, while digital transformation levels mitigate its inhibitory effects.

Keywords: carbon emission trading policy; multi-time point difference model; green and low-carbon transition; green technology innovation level; digital transformation level.

1. Foreword

Under the guidance of the national strategic goal of "dual carbon", China is accelerating a broad and profound systemic transformation in its economy and society. The "dual carbon" commitment not only represents China's responsibility to address the global climate crisis but also serves as an inevitable choice to promote high-quality development and achieve modernization characterized by harmonious coexistence between humanity and nature. As the core policy tool for implementing the "dual carbon" goals, the carbon emission trading market is advancing rapidly: Since 2013, China has successively launched carbon trading pilots in seven provinces and municipalities—Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, and Shenzhen—effectively driving emission reductions among enterprises in pilot regions while accumulating institutional experience and talent foundations for national market development; Following Fujian Province's accession to the pilot system in 2016, the national carbon emission trading market officially launched its online trading in July 2021, marking the entry of China's carbon pricing mechanism into a new phase of nationwide operation.

Enterprises are pivotal players in carbon emission trading. Under the "dual carbon" goals, corporate green transition has become a crucial pathway to resolve resource and environmental bottlenecks while enhancing industrial competitiveness. This transformation fundamentally shifts production models from high-carbon dependency to low-carbon efficiency through technological innovation and management optimization, ultimately decoupling corporate long-term development from carbon emissions. The implementation of carbon trading pilot policies converts emission costs into decision-making variables, driving enterprises to proactively reduce carbon intensity via energy structure optimization, energy efficiency improvements, and technological upgrades. As a key engine for green transformation, this shift not only directly cuts compliance costs but also creates new profit growth points through carbon asset surpluses, potentially reshaping industrial chain competition dynamics. Therefore, clarifying the relationship between carbon trading policies and corporate green transition holds significant implications for adjusting national carbon market mechanisms and activating enterprises' internal growth drivers.

While existing academic research has explored the impact of carbon emission trading policies on corporate green transition, no consensus has been reached. Moreover, the moderating mechanisms between green technological innovation and digital transformation require further analysis. This study employs a multi-period difference model with dual-differential analysis, using A-share listed companies from 2010 to 2023 as samples. It investigates whether carbon emission trading policies facilitate corporate green transition while examining the moderating effects of technological innovation levels and digital transformation capabilities.

The potential contributions are as follows: (1) By employing a multi-time-point DID model based on corporate annual report data, this study empirically examines whether carbon emission trading policies can drive enterprises' green and low-carbon transition, thereby enriching research in related fields. (2) The research explores the impact mechanisms of carbon emission trading policies on corporate green transition from two perspectives: green technology innovation levels and digital transformation capabilities. The findings contribute to promoting the sustainable development of China's national carbon emission trading market. (3) This study investigates the heterogeneous effects of carbon emission trading policies across different corporate characteristics including geographical location, scale, and ownership structure, providing a theoretical foundation for differentiated policy formulation.

2. Literature review

First, the factors influencing enterprises' green and low-carbon transition can be summarized into multiple dimensions. At the external environment level, Yuren Qian et al. pointed out that China's "waste-free city" pilot policies and other local environmental regulations have significantly accelerated the green and low-carbon transformation process of enterprises by promoting green technology innovation, strengthening government supervision, and enhancing investors' environmental awareness [1]. From the perspective of market transmission mechanisms, Hexuan Wang's research demonstrates that supply chain mechanisms also play a crucial role, where the influence of downstream enterprises can effectively incentivize upstream suppliers to adopt more sustainable practices, thereby proactively implementing green transformation [2]. Regarding corporate strategies, Xianghan Zhang and Zhengwei Li argue that an enterprise's ESG (Environmental, Social, and Governance) strategy is vital for transformation. Its integration provides systematic guidance for green transition, converting environmental costs into innovation opportunities that enhance financial returns and brand reputation [3]. In terms of internal organizational factors, Saratian Eko Tama Putra employed a systematic literature review (SLR) method to find that organizational culture, as a catalytic factor, significantly promotes structural adjustment processes in sustainable green transformation through improved leadership efficacy and employee engagement [4].

Secondly, academic research has conducted multi-perspective studies on the effects of carbon emission trading policies. Most scholars have confirmed the policy's significant effectiveness in emission reduction through comparative analyses between pilot and non-pilot regions [5-6], with Kebei Shi et al.'s research indicating a 78.6% reduction in carbon emissions within specific regions [7]. Regarding innovation, Jingbo Cui et al. support the "Porter Effect", arguing that policies incentivize corporate technological innovation through carbon pricing mechanisms [8]. However, some scholars have identified an "innovation paradox", where high compliance costs may hinder green technology development in sectors like energy, particularly impacting non-pollution-intensive industries more significantly [9]. Simultaneously, these policies drive energy efficiency improvements and structural transformations, enhancing urban single-factor and total factor energy efficiency through technological innovation and resource reallocation [10]. On employment, Mengmeng Qiang et al. suggest carbon emission trading policies could boost job creation by 16.3%, achieving "dual dividends" for both environmental protection and employment growth, while revealing an inverted U-shaped relationship between carbon prices and employment [11].

Finally, there remains academic debate regarding the impact of carbon emission trading policies on enterprises' green and low-carbon transition. Some scholars argue that carbon emission trading serves as a crucial driving force for corporate transformation [12-13]. Zheng Zhou et al. contend that higher carbon prices and more active markets will amplify the positive effects of carbon emission trading policies on green total factor productivity, thereby accelerating the green and low-carbon transition process of Chinese manufacturing enterprises [14]. Sheng Xu et al. demonstrated that carbon emission trading policies significantly enhance the green development efficiency of heavily polluting enterprises, promoting their transition to low-carbon operations [15]. However, some studies have revealed the negative effects and complexities of such policies [16]. Xiaohuan Lyu et al. tested the mechanism through a difference-in-differences model examining the impact of carbon emission trading policies on low-carbon technological innovation, finding that these policies may suppress innovation development in the short term and hinder corporate green transformation [17]. Additionally, Yuxuan Wang and Chan Lyu's research indicates that some enterprises might engage in opportunistic behaviors like "carbon laundering" to reduce compliance costs, which not only impedes their green transition but also increases production costs and financial risks [18].

In summary, the academic community has identified multiple factors influencing corporate green and low-carbon transition, yet there remain divergent views regarding the effectiveness of carbon emission trading policies. Meanwhile, substantial discussion space persists regarding the specific mechanisms through which these policies operate. Current research predominantly suggests that advancements in green technology innovation drive green and low-carbon transitions in manufacturing and logistics sectors [19-20], while digital transformation significantly accelerates this process [21-22]. However, the regulatory mechanisms through which these technological drivers interact with carbon emission trading policies to influence corporate transition pathways require further validation.

3. Research design

3.1. Sample selection and data sources

Since the carbon emission trading markets in pilot provinces and cities were gradually launched after 2013, this study selects A -share listed companies from 2010 to 2023 as initial research samples. As the pilot regions only involved specific industries within these provinces, eight key sectors—petrochemicals, chemicals, building materials, steel, non-ferrous metals, papermaking, power, and aviation—are selected for analysis. The indices for corporate green transition and digital transformation are derived from annual reports and social responsibility disclosures of listed companies, while green patent applications are sourced from the China National Intellectual Property Administration (CNIPA) database. Other data are obtained from CSMAR Database and Wind Data. The raw data undergoes three processing steps: (1) removing ST, ST*, and PT companies; (2) eliminating companies with significant data gaps; (3) applying 1% truncation to reduce outliers. This yields 7,778 valid observations from 594 listed companies.

3.2. Variable descriptions

3.2.1 The explained variable

The dependent variable is corporate green and low-carbon transition (GLC). Drawing on Loughran et al. 's research, this study measures corporate green and low-carbon transition through textual information disclosed in annual reports. We selected 113 key terms related to green and low-carbon transition from five dimensions: advocacy, strategic concepts, technological innovation, pollution control, and monitoring management. By counting the frequency of each keyword in listed companies' annual reports, we generated a word frequency index for green and low-carbon transition, which was then transformed into a natural logarithm using 1+ frequency value [23]. Compared with content analysis methods, text analysis employs computer-based natural language processing technology, enabling precise recognition of large-scale unstructured texts while significantly reducing error rates and improving consistency in judgment. This study selects annual reports of listed companies as textual samples based on two key considerations: (1) Information significance and carrier compatibility. Green and low-carbon transition serves as critical strategic information for listed companies, typically disclosed in publicly accessible annual reports that align with their summarizing and guiding nature; (2) Data standardization advantages. As mandatory disclosure documents, annual reports of listed companies adhere to strict formatting and wording requirements, effectively enhancing keyword matching efficiency. Therefore, measuring corporate green and low-carbon transition through word frequency analysis of relevant terms in annual reports demonstrates high feasibility.

3.2.2 Interpretive variables

The core explanatory variable is the policy dummy variable (DID) for carbon emission trading pilot programs. This study uses the interaction term between the pilot region dummy variable (treat) and the policy implementation time dummy variable (time) to represent the policy effects of carbon emission trading systems (DID). If a company's registered province is a key pilot province for carbon emission trading policies, treat takes a value of 1; otherwise, it is 0. Beijing, Tianjin, Shanghai, Hubei, Chongqing, Guangdong, Shenzhen, and Fujian form the experimental group in this study, with Guangdong and Shenzhen combined into one group, while other provinces/cities constitute the control group. The implementation start time for pilot policies in Beijing, Tianjin, Shanghai, Hubei, Chongqing, Guangdong, and Shenzhen is set to 2014. For years after 2014, time takes a value of 1; otherwise, it is 0. Fujian's implementation start time for pilot policies is set to 2017. For years after 2017, time takes a value of 1; otherwise, it is 0.

3.2.3 Moderating variables

The moderating variables in this study are Green Technology Innovation (GTI) and Digital Transformation (DX). Following the methodology of Xu Jia and Cui Jingbo, we employ the number of green patent applications from listed companies as a measurement indicator for GTI [24]. This approach is chosen because compared to green patent authorization data, green patent applications provide more timely evidence of carbon emission trading policy impacts. Drawing on Zhao Chenyu et al. 's research, we analyze the "operational analysis" sections of listed companies' annual reports. Through manual screening and segmentation of benchmark samples, we identify keywords across four dimensions: digital technology application, internet-based business models, intelligent manufacturing, and modern information systems. After refining the lexicon, we conduct full-sample term frequency analysis and use the entropy method to synthesize the Digital Transformation Index [25]. This methodology enables objective, multi-dimensional quantification of corporate digital transformation levels, accurately capturing changes in digital transformation capabilities before and after policy interventions.

3.2.4 Control variables

According to existing research, this paper selects enterprise size (SIZE), equity multiplier (EM), return on equity (ROE), total asset turnover/agency cost (ATO), and financing constraint (SA) as control variables, while controlling for year and individual effects. The variable setting and explanation are listed in Table 1.

Table 1. Variable symbols and definitions

variable	variable symbol	Variable description
Green and low-carbon transformation of enterprises	GLC	Green transition disclosure keyword frequency logarithmic
scale	SIZE	Natural logarithm of total assets for the year
equity multiplier	EM	Total assets at the end of the year/total owners' equity at the end of the year
Return on equity	ROE	Net profit/owner's equity
Total asset turnover ratio/agency costs	ATO	Operating income/total average assets
Financing constraints	SA	SA index (the smaller the value, the greater the financing constraints faced by enterprises)
Green technology innovation level	GTI	Number of green patent applications
Level of digital transformation	DX	Digital transformation discloses entropy weighting

3.3. Model-building

The difference-in-differences (DID) method can identify the net policy effect by identifying the differences between the experimental group and the control group before and after the implementation of policies. In order to test the impact of carbon emission trading system on the green and low-carbon transformation of enterprises, this paper adopts the following multi-period DID model:

$$\mathrm{GLC}_{i,t}=\alpha_0+\alpha_1\mathrm{DID}_{i,t}+\alpha_2\mathrm{Control}_{i,t}+\delta_i+\mu_t+\varepsilon_{i,t} \quad (1)$$

Among them, $\mathrm{GLC}_{i,t}$ is the dependent variable, namely the green and low-carbon transformation of enterprises; i represents the enterprise, t represents time; $\mathrm{DID}_{i,t}$ is the core explanatory variable, namely the multi-point double difference variable, $\mathrm{DID}_{i,t}$=treat* time; $\mathrm{Control}_{i,t}$ is the control variable; δ_i is the individual fixed effect; μ_t is the time fixed effect; $\varepsilon_{i,t}$ is the random error term.

4. Empirical results and analysis

4.1. descriptive statistics

The descriptive statistics of key variables in this study are presented in Table 2. The GLC (Green Low-Carbon Transition Index) ranges from 0 to 3.970, indicating significant variations in corporate green transition progress across samples with non-uniform distribution patterns. The DID (Difference-in-Differences) mean of 0.176 suggests limited sample exposure to carbon trading policies. The DX (Digital Transformation Index) average of 0.007 reflects generally low digital transformation levels, though notable inter-firm disparities exist. The right-skewed GTI distribution demonstrates that green technology innovation activities are predominantly driven by a minority of enterprises. Control variables show standardized deviation sizes: SIZE (Standardized Deviation) measures 1.289, reflecting diverse enterprise scales within the sample. Demographic indicators including EM (Environmental Management), ROE (Return on Equity), ATO (Asset Turnover), and SA (Sales Activity) all fall within statistically valid ranges as per prior research.

Table 2. Descriptive statistics of variables

VARIABLES	N	mean	sd	min	max
GLC	7,778	2.127	0.811	0.000	3.970
DID	7,778	0.176	0.381	0.000	1.000
SIZE	7,778	22.494	1.289	19.653	26.452
EM	7,778	2.110	1.170	1.022	10.789
ROE	7,778	0.055	0.139	-2.175	0.418
ATO	7,778	0.657	0.398	0.048	2.645
SA	7,778	-3.840	0.249	-4.641	-3.020
GTI	7,557	6.407	25.187	0.000	832.000
DX	7,682	0.007	0.010	0.000	0.134

4.2. Correlation test

The results of correlation test are shown in Table 3. According to the correlation analysis between the main variables, the correlation coefficient between the variables is less than 0.6, indicating that the empirical research will not have the problem of multicollinearity.

Table 3. Variable correlation test

	GLC	DID	SIZE	EM	ROE	ATO	SA
GLC	1.0000						
DID	0.2106	1.0000					
SIZE	0.4077	0.1214	1.0000				
EM	0.1040	-0.0367	0.3745	1.0000			
ROE	-0.0206	0.0004	0.0707	-0.3876	1.0000		
ATO	0.0196	-0.0564	0.0338	0.0455	0.1167	1.0000	
SA	-0.2414	-0.1457	-0.0978	-0.0362	0.0595	-0.0159	1.0000

4.3. ADF unit root test

The results of ADF unit root test are shown in Table 4. According to the test results, there is no unit root for each variable and it is stationary.

Table 4. Variable ADF unit root test

VARIABLES	ADF Fisher	Conclusion
GLC	3188.302***	Steady
DID	1350.862***	Steady
SIZE	1413.193***	Steady
EM	1940.973***	Steady
ROE	2190.216***	Steady
ATO	2512.472***	Steady
SA	1521.195***	Steady
GTI	1316.610***	Steady
DX	1282.553**	Steady

4.4. Benchmarking

The benchmark regression results are presented in Table 5. Column (1) shows the regression results without control variables, while column (2) presents those with control variables. The analysis reveals that the DID regression coefficients remain significantly positive regardless of whether control variables are included, demonstrating that the implementation of carbon emission trading policies can positively influence corporate green and low-carbon transition. In other words, carbon emission trading policies can significantly accelerate the green and low-carbon transformation of enterprises.

Table 5. Benchmark regression results

	(1)	(2)
VARIABLES	GLC	GLC
DID	0.134***	0.111***
	(0.0408)	(0.0400)
SIZE		0.165***
		(0.0265)
EM		-0.0248*
		(0.0126)
ROE		-0.0435
		(0.0589)
ATO		0.103**
		(0.0440)
SA		0.389**
		(0.189)
Firm FE	YES	YES
Year FE	YES	YES
Constant	1.553***	-0.662
	(0.0284)	(0.893)
Observations	7,778	7,778
R-squared	0.406	0.416

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

4.5. Robustness test

4.5.1 Parallel trend test

The validity of the multiple time points double difference model is predicated on the parallel trend assumption. Given that carbon emission trading pilot policies were implemented at varying dates across regions, we selected relative implementation time points to assess whether there was a common trend before and after policy implementation. The test results are illustrated in Figure 1. The x-axis indicates policy implementation time (0 represents the year of policy implementation; negative values to the left of 0 denote pre-policy years, while positive values to the right indicate post-policy years), and the y-axis represents policy effects.

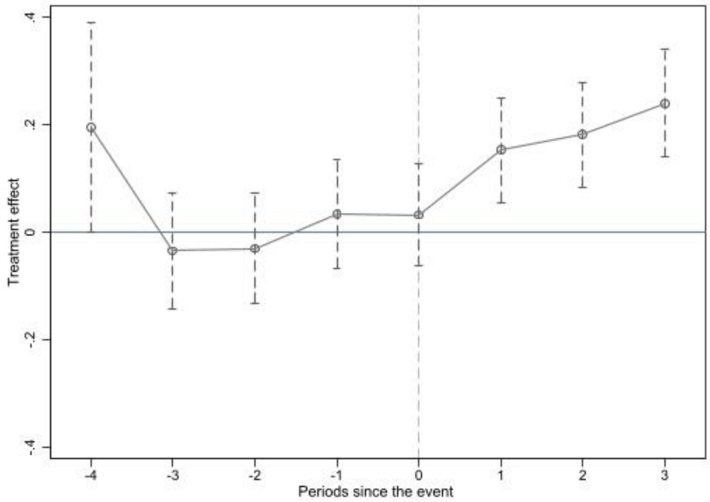

Figure 1. Parallel trend test

The parallel test results indicate that prior to policy implementation, the policy effect fluctuated near zero with no significant impact (the 95% confidence interval includes zero), demonstrating that enterprises in pilot cities and non-pilot cities generally followed similar trends in green and low-carbon transition, thus passing the parallel trend hypothesis test. After policy implementation, the green and low-carbon transition effect became significantly positive starting from the first post-policy period, showing an overall upward trend with continuity. This further validates the robustness of the regression results presented in this study.

4.5.2 Placebo tests

To prevent regression results from being influenced by unobservable factors and rule out the possibility of accidental events in the research conclusions, this study conducted placebo tests by randomly generating experimental groups. The experimental group and control group were randomly assigned, with samples selected at random to form new experimental groups and the remaining samples used as control groups for Model (1) testing. This process was repeated 500 times, with the results shown in Figure 2. The analysis revealed that the randomly estimated coefficients clustered near zero, the regression results exhibited a close approach to normal distribution, and the true regression coefficients showed significant outliers. These findings demonstrate that the research outcomes are not attributable to accidental factors, confirming the robustness of the conclusions.

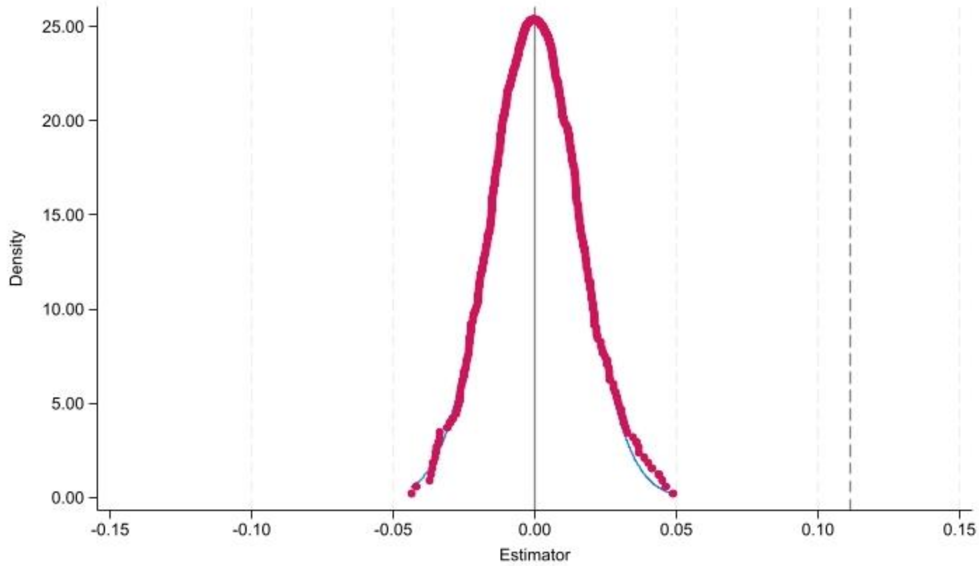

Figure 2. Placebo test

5. Heterogeneity analysis

5.1. Regional heterogeneity of enterprises

Given significant regional disparities in economic development levels, market mechanism sophistication, and resource endowments across enterprises, the impact of carbon emission trading policies on corporate green transition may exhibit heterogeneity. This study conducts group regression analysis between eastern and central & western regions (see Table 6), revealing that carbon emission policies demonstrate a significant positive effect on green transition in eastern enterprises, while showing no notable impact in central and western regions. This divergence likely stems from: Eastern regions typically possess more sophisticated market mechanisms, stricter environmental enforcement, and more dynamic carbon trading markets, enabling effective policy signal transmission to incentivize green technology investments and management innovation. Additionally, eastern enterprises generally possess stronger financial capacity and technological reserves, allowing them to efficiently respond to policy requirements and bear transition costs. In contrast, central and western enterprises face constraints in resource accessibility, technology absorption capacity, and market maturity, which may weaken the short-term effectiveness of policies.

Table 6. Regional heterogeneity test of enterprises

	(1)	(2)
VARIABLES	GLC Eastern Regions	GLC Central and Western Regions
DID	0.133***	0.101
	(0.0486)	(0.102)
SIZE	0.219***	0.113***
	(0.0387)	(0.0378)
EM	-0.0235	-0.0168
	(0.0202)	(0.0155)
ROE	-0.0706	-0.0141
	(0.0821)	(0.0820)
ATO	0.131**	0.0792
	(0.0588)	(0.0660)
SA	0.632**	0.0960
	(0.261)	(0.265)
Constant	-0.995	-0.570
	(1.206)	(1.334)
Firm FE	YES	YES
Year FE	YES	YES
Observations	4,555	3,223
R-squared	0.399	0.445

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

5.2. Enterprise size heterogeneity

Due to systematic differences in resource endowment, technological adaptability, and management structure across enterprise scales, the impact of carbon emission trading policies on corporate green and low-carbon transition may exhibit scale heterogeneity. Drawing on Guo Jun He et al.'s research, this study measures enterprise scale using total assets [26], dividing the sample into high and low groups using industry median as the threshold. As shown in Table 7, the regression results reveal that carbon emission trading policies have a significant positive effect on green and low-carbon transition for large-scale enterprises, while showing no significant impact on small-scale enterprises. This difference can be attributed to: Large-scale enterprises typically possess stronger financial capabilities and economies of scale, enabling them to afford high-cost investments in cutting-edge low-carbon technologies and efficiently implement emission reduction measures through professional management teams. Additionally, their well-established supply chain systems and strong market bargaining power help absorb cost impacts during the transition. In contrast, small-scale enterprises, despite their flexibility advantages, face higher compliance costs and technological upgrade barriers due to financing constraints and insufficient technical reserves, thereby reducing the short-term incentive effects of policies.

Table 7. Enterprise size heterogeneity test

	(1)	(2)
VARIABLES	GLC Large-scale	GLC Small-scale
DID	0.154***	0.102
	(0.0536)	(0.0683)
SIZE	0.129***	0.179***
	(0.0482)	(0.0609)
EM	-0.0237*	-0.0219
	(0.0138)	(0.0226)
ROE	-0.00946	-0.0743
	(0.0754)	(0.0867)
ATO	0.115*	0.0461
	(0.0587)	(0.0789)
SA	0.241	0.0541
	(0.316)	(0.496)
Constant	-0.399	-2.115
	(1.884)	(1.558)
Firm FE	YES	YES
Year FE	YES	YES
Observations	4,902	2,876
R-squared	0.425	0.300

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

5.3. Heterogeneity of enterprise ownership nature

Differences in corporate ownership structures may lead to variations in resource allocation, decision-making mechanisms, and management efficiency among enterprises, resulting in heterogeneous impacts of carbon emission trading policies on their green and low-carbon transitions. This study categorizes sample enterprises into state-owned and non-state-owned entities, with subgroup regression results presented in Table 8. The findings indicate that carbon emission trading policies significantly promote green and low-carbon transitions in non-state-owned enterprises, while showing no significant effect on state-owned enterprises. This disparity may stem from two factors: non-state-owned enterprises typically face stronger market competition pressures and tighter budget constraints, making them more sensitive to policy incentives. Their flexible operational decision-making mechanisms enable rapid resource reallocation adjustments to respond to carbon trading policies. Additionally, these enterprises demonstrate stronger endogenous motivation in technological innovation investments and emission reduction efficiency optimization, effectively converting policy pressure into transformational competitiveness. Conversely, although state-owned enterprises possess resource advantages, overlapping policy objectives such as stabilizing employment and maintaining economic growth may dilute the prioritization of environmental regulations, thereby weakening the immediate effectiveness of policies.

Table 8. Test of ownership heterogeneity of enterprises

VARIABLES	(1) GLC State-owned	(2) GLC Non State-owned
DID	0.0480	0.179***
	(0.0615)	(0.0536)
SIZE	0.153***	0.190***
	(0.0357)	(0.0381)
EM	-0.0130	-0.0389
	(0.0137)	(0.0237)
ROE	-0.0431	-0.0985
	(0.0794)	(0.0844)
ATO	0.124*	0.0794
	(0.0665)	(0.0596)
SA	0.194	0.700**
	(0.299)	(0.277)
Constant	-1.058	-0.152
	(1.395)	(1.275)
Firm FE	YES	YES
Year FE	YES	YES
Observations	3,472	4,306
R-squared	0.425	0.400

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6. Mechanism analysis

6.1. The moderating effect of green technology innovation level

In order to analyze the moderating effect of green technology innovation level between carbon emission trading policy and enterprise green low-carbon transformation, the following model is further established:

$$GLC_{i,t}=\tau_0+\tau_1 DID_{i,t}+\tau_2 GTI_{i,t}+\tau_3 DID_{i,t}*GTI_{i,t}+\tau_4 Control_{i,t}+\delta_i+\mu_t+\varepsilon_{i,t} \quad (2)$$

Among them, $GTI_{i,t}$ represents the level of green technology innovation of enterprises. The regression results are shown in Table 9 column (1).

Regression results demonstrate that the level of green technology innovation significantly moderates the relationship between carbon emission trading policies and corporate green transition. The interaction term DID*GTI coefficient is statistically significant at the 5% level, indicating that existing green technological capabilities effectively amplify the policy's catalytic effect on sustainable transformation. This mechanism operates through dual pathways: First, enhanced technological reserves reduce marginal costs for low-carbon transitions, enabling companies to swiftly convert policy incentives into equipment upgrades and process innovations. Second, mature knowledge bases improve technical adaptability, accelerating the adoption of emission-reduction technologies in production operations.

6.2. The moderating effect of digital transformation level

In order to verify the moderating effect of digital transformation level between carbon emission trading policy and enterprise green and low-carbon transformation, the following model is established:

$$GLC_{i,t}=\tau_0+\tau_1 DID_{i,t}+\tau_2 DX_{i,t}+\tau_3 DID_{i,t}*DX_{i,t}+\tau_4 Control_{i,t}+\delta_i+\mu_t+\varepsilon_{i,t} \quad (3)$$

Among them, $DX_{i,t}$ represents the level of enterprise digital transformation, and the regression results are shown in column (2) of Table 9.

Regression results indicate that while digital transformation significantly drives corporate green and low-carbon transitions, its interaction with policy implementation exhibits a significant negative moderating effect. This suggests that enterprises with advanced digitalization levels face weakened transition efficacy during policy implementation phases. The underlying causes may stem from resource competition and technological conflicts: Firstly, digital transformation requires sustained investment in capital and technical resources. When carbon emission trading policies are implemented concurrently, companies face dual resource pressures from compliance costs (e.g., upgrading carbon monitoring systems) and digital infrastructure development, leading to reduced short-term resource allocation efficiency. Secondly, large-scale digital infrastructure constitutes energy-intensive projects. If enterprises fail to synchronize energy structure greening (e.g., continued reliance on fossil fuel-powered data centers), the energy rebound effect from digitalization could increase operational carbon emissions, partially offsetting policy-driven emission reductions. Thirdly, deeply digitized enterprises' complex production systems may incur compatibility costs (e.g., conflicts between carbon accounting modules and existing ERP systems) when undergoing policy-mandated structural adjustments, further diverting resources from technological innovation.

Table 9. Mechanism test

	(1)	(2)
VARIABLES	GLC	GLC
DID	0.109***	0.154***
	(0.0408)	(0.0451)
GTI	-0.000301	
	(0.000410)	
DX		7.711***
		(1.883)
DID*GTI	0.00105**	
	(0.000476)	
DID*DX		-5.124**
		(2.007)
SIZE	0.170***	0.150***
	(0.0261)	(0.0272)
EM	-0.0223*	-0.0236*
	(0.0126)	(0.0131)
ROE	-0.0281	-0.0333
	(0.0590)	(0.0587)
ATO	0.0987**	0.103**
	(0.0428)	(0.0440)
SA	0.318	0.351*
	(0.197)	(0.195)
Constant	-1.033	-0.499
	(0.906)	(0.915)
Firm FE	YES	YES
Year FE	YES	YES
Observations	7,557	7,682
R-squared	0.440	0.414

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

7. Conclusion and suggestion

Under the dual-carbon goals framework, this study utilizes microdata from A-share listed companies between 2010 and 2023, focusing on eight key industries (petroleum & chemical, construction materials, steel, non-ferrous metals, papermaking, power, and aviation). Through a multi-period, difference-in-differences model, we examine how carbon emission trading pilot policies influence corporate green transition while analyzing policy heterogeneity and underlying mechanisms. Key findings include: 1) Carbon trading policies significantly accelerate corporate green transition with robust results; 2) Heterogeneity analysis reveals distinct regional impacts: Eastern regions, large-scale enterprises, and non-state-owned firms show stronger green transition effects, whereas central and western regions, small-scale and state-owned enterprises demonstrate negligible effects; 3) Moderation analysis demonstrates positive regulation from green technology innovation levels and negative moderation from digital transformation levels in carbon trading's impact on corporate green transition.

Based on the above conclusions, this paper proposes three targeted recommendations: First, further expand the scope of carbon emission trading across industries and regions. Governments should gradually extend carbon trading policy pilots to more sectors and areas, encouraging enterprises to actively participate in carbon trading. This will drive corporate green and low-carbon transitions, fostering sustainable market development. Second, fully consider enterprise heterogeneity by formulating customized carbon trading strategies based on specific corporate characteristics. For enterprises in central and western regions, governments should strengthen foundational capacity building through technical assistance and quota support to address resource constraints. For small-scale enterprises, focus on lowering transition thresholds by establishing streamlined compliance systems and financing channels to alleviate cost pressures. State-owned enterprises should deepen target management reforms by incorporating green transition efficiency into core performance evaluations to activate internal motivation. Third, actively enhance corporate green technology innovation capabilities, and promote coordinated development of digital transformation and green transition. For one thing, strengthening corporate green technology reserves can significantly amplify the transformative effects of carbon trading policies, reducing initial transition costs through technology subsidies and knowledge-sharing mechanisms. For another, green digital infrastructure subsidies can alleviate resource diversion, while renewable energy solutions for digital projects help avoid energy rebound effects. Establishing standardized carbon accounting system interfaces also reduces compatibility costs, thereby unlocking long-term synergies between digitalization and carbon policies.

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