energies

MDPI

Article

From High Energy Use to Sustainability: Mechanisms of Carbon Emissions Trading System in Driving Green Transformation of Energy-Intensive Firms

Ruofei Lan [1], Hsing Hung Chen [1], Hui Xie [2], Zhengyang Luan [1] and Guangxian Li [3,*]

[1] School of Business, Macau University of Science and Technology, Taipa, Macau 999078, China; 3250005701@student.must.edu.mo (R.L.); hhchen@must.edu.mo (H.H.C.); luanzy2022@outlook.com (Z.L.)
[2] Department of Finance, Nankai University Binhai College, Tianjin 300270, China; hui.xie@hud.ac.uk
[3] School of Mechanical Engineering, Guangxi University, Nanning 530004, China
* Correspondence: liguangxian@gxu.edu.cn

Abstract

Energy-intensive firms are key participants in China's carbon emissions trading system (CETS). However, evidence on whether CETS promotes the green transformation (GT) of these firms remains limited. In this study, a multi-period difference-in-differences (DID) model is applied to investigate the impacts of CETS on the GT of 529 listed firms from six energy-intensive industries over the period 2007–2024. Results show that CETS significantly promotes GT, and the findings remain robust after parallel trend, placebo, propensity score matching (PSM)-DID, Goodman-Bacon decomposition, and alternative variable tests. Further analysis reveals that internal control and green technological innovation (Ginn) positively moderate the effects of CETS on the GT of energy-intensive firms. Heterogeneity analysis reveals that the promoting effect is more pronounced in highly competitive industries and among firms with stronger green reputations. These findings provide empirical evidence on the effectiveness of CETS in facilitating the GT of energy-intensive firms.

Keywords: carbon emissions trading system; energy-intensive firms; green transformation; sustainability

1. Introduction

Due to rapid industrialization, China has become the world's largest carbon emitter, posing dual challenges of severe pollution and high energy consumption. To achieve decarbonization efficiently, the Chinese government has introduced a series of mitigation policies. Among these policies, the carbon emissions trading system (CETS) treats carbon emission rights as tradable commodities, allowing firms to buy and sell allowances within a prescribed regulatory cap [1]. This pricing mechanism encourages enterprises to internalize the external costs of their carbon emissions, ultimately fostering low-carbon competitiveness [2]. Following the successive rollout of regional pilot markets in 2013, the unified national carbon market was officially launched in 2021, establishing CETS as a core pillar of China's mandatory emission reduction framework [3].

Specifically, during the regional pilot phase, eight provinces and municipalities—Shenzhen, Shanghai, Beijing, Guangdong, Tianjin, Hubei, Chongqing, and Fujian—established independent carbon markets to explore quota allocation and trading rules tailored to local industrial characteristics. Building upon the extensive legislative and operational experience garnered from these pilots, the unified national carbon market initially targeted

Academic Editor: Jay Zarnikau

Received: 14 May 2026
Revised: 18 June 2026
Accepted: 24 June 2026
Published: 27 June 2026

the power generation sector as a breakthrough point. According to official statistics from the Ministry of Ecology and Environment of China, upon its launch, the national market covered over 2100 key emission entities and regulated approximately 4.5 billion tons of CO_2 emissions annually, making it the world's largest carbon market by volume. Under this framework, the government sets stringent industrial emission caps and allocates tradable quotas primarily based on historical emission intensity and industry benchmarks.

Given that energy-intensive firms account for a substantial share of China's total emissions, their mitigation behaviors are critical to the success of CETS. Under CETS, these firms face three compliance scenarios [4]: (1) purchasing additional allowances to offset excess emissions; (2) accepting financial penalties for non-compliance; and (3) selling surplus quotas for profit if their mitigation efforts are highly effective. Options (1) and (2) impose severe cost pressures on heavy emitters, while option (3) offers a lucrative financial incentive. This stringent environmental regulation theoretically compels firms to pursue green transformation (GT), thereby enabling them to achieve emission reductions, secure excess market returns, and ultimately realize long-term sustainable development.

Studies investigating the "green effect" of environmental regulations have predominantly been conducted from macro-regional or meso-industrial perspectives, focusing on how these policies affect industrial upgrading and overall mitigation efficiency [5,6]. However, empirical evidence at the micro-firm level remains scarce, particularly concerning the actual driving effect of CETS on energy-intensive enterprises. Moreover, the internal mechanisms facilitating this transition lack systematic explanations. To bridge the gaps, this study addresses the following core research questions: How exactly does CETS drive the GT of energy-intensive firms in China? What moderating roles do internal control and green technological innovation (Ginn) play in this process? Does the policy's driving effect vary significantly under different industry competition intensities and corporate green image (GI) profiles?

This study adopts the 2012 industry classification of the China Securities Regulatory Commission. The energy-intensive sectors analyzed are: (1) petroleum processing, coking, and nuclear fuel processing; (2) chemical raw materials and chemical products manufacturing; (3) non-metallic mineral products manufacturing; (4) ferrous metal smelting and rolling processing; (5) non-ferrous metal smelting and rolling processing; and (6) electricity and heat production and supply. These are the key sectors targeted by CETS, which contribute to a large proportion of the country's carbon emissions and consume most of the energy. These firms confront the most urgent demand for GT and suffer huge compliance cost pressure. The effectiveness of GT directly affects the effectiveness of the market mechanism [7]. However, critical research gaps remain in interpreting this transmission path. First, existing studies frequently consider carbon trading merely as a financial burden, largely ignoring the internal "governance precision–technical guarantee" mechanisms that firms use to absorb and convert carbon price signals. Specifically, it remains unclear how internal control optimizes carbon asset management by mitigating agency conflicts and how Ginn enhances a firm's responsiveness to market incentives. Furthermore, previous studies overlooked boundary conditions of policy effectiveness, particularly, the contextual constraints imposed by market competition pressure and the strategic value of a corporate GI as reputation capital.

To fill the aforementioned research gaps, this study uses 529 listed enterprises from six energy-intensive industries in China's A-share market from 2007 to 2024 as the sample and employs a multi-period difference-in-differences (DID) model to thoroughly analyze the net effect and underlying mechanisms of CETS on the GT of energy-intensive firms. This study contributes to the literature in the following aspects: (1) This study expands the research scope from a macro- to micro-enterprise level. Existing studies related to

CETS primarily focus on regional emission reductions or industry-level quota efficiency, while less attention has been paid to the proactive responses of enterprises as policy implementers [8]. Therefore, this study develops an analytical framework of "external policy shock–internal resource allocation–strategic transformation" to explore how policy pressure affects the decision-making of energy-intensive enterprises, thereby enriching micro-empirical research on CETS. (2) This study opens the "black box" of the internal transmission mechanism within enterprises. Existing studies treat carbon trading as a financial constraint, overlooking the specific process by which enterprises internally absorb carbon price signals. In this paper, two key factors, internal control and Ginn, are introduced, and the moderating roles of these factors in policy transmission are investigated. This not only confirms the value of internal control in mitigating agency problems but also illustrates how technological innovation helps enterprises transform external pressure into an internal driving force for transformation. (3) This study explores the boundary conditions of policy effects. Previous research often assumes that enterprises face a homogeneous market environment. In contrast, this study investigates the heterogeneity of policy effects by incorporating industry competition intensity and corporate GI. This not only reveals the differential impacts of CETS under varying market ecologies and resource endowments [9] but also provides empirical evidence for energy-intensive enterprises to formulate customized green strategies under mandatory emission reduction constraints [10].

The remainder of this paper is organized as follows: Section 2 introduces studies on the CETS and firms' GT, developing the foundation of theoretical framework, and the research hypotheses are proposed; Section 3 describes the research design, including sample selection, variable definitions, and model specification; Section 4 presents and discusses the empirical results of the benchmark regression, moderating effects, and heterogeneity analyses; Section 5 conducts a series of robustness checks, including parallel trend tests, propensity score matching (PSM)-DID estimation, placebo tests, Goodman-Bacon decomposition analysis, and alternative dependent variable specifications; Section 6 discusses the main findings, concludes the study, and provides managerial implications and policy recommendations. Figure 1 presents the overall research process.

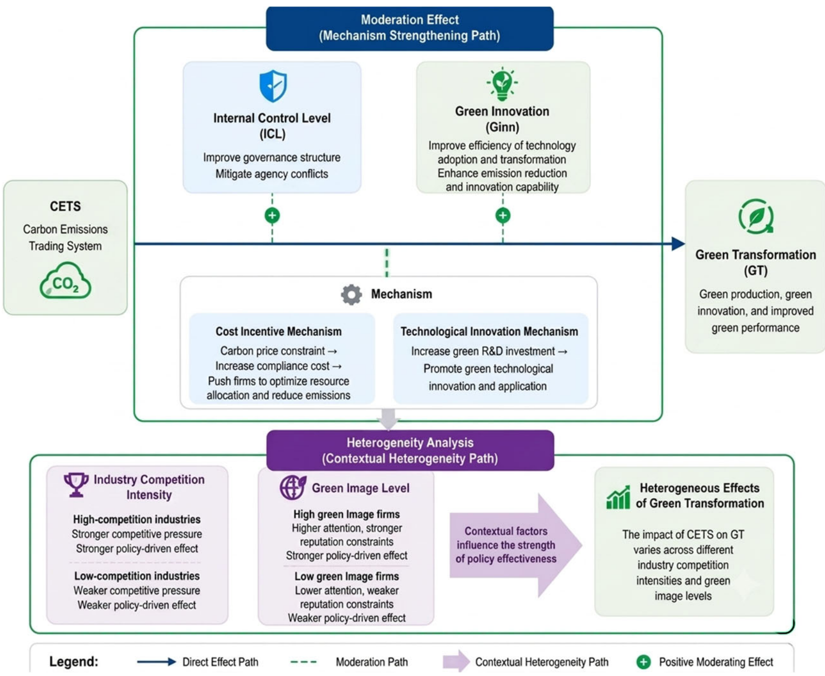

Figure 1. Overview of the research process.

2. Literature Review and Hypotheses

2.1. CETS and GT

As a typical environmental regulation tool, CETS grants carbon emission rights the legal attribute of an asset, converting the originally external social burden of carbon emissions into an internal environmental constraint for enterprises. Within CETS, the six energy-intensive industries represented by electricity and petroleum are the sectors most severely impacted by policy. According to statistics, these high-energy-consuming industries not only account for over 60% of the total carbon emissions, but also their transformation efficiency directly determines the long-term viability and core competitiveness of enterprises under low-carbon constraints [11].

Furthermore, during the implementation of GT and the improvement of emission reduction efficiency, technical monitoring serves as an indispensable foundation for accurately assessing energy consumption. Recent studies have emphasized the critical role of low-cost intelligent monitoring systems in supporting decarbonization strategies. For instance, Mobaraki et al. [12] developed an IoT-based low-cost thermal monitoring system (IoT HEAT) to evaluate the real-time thermal transmittance of building envelopes, providing a cost-effective basis for identifying energy losses and supporting energy-efficient retrofits. Similarly, regarding the monitoring of structural parameters in industrial production, Porras et al. [13] successfully applied low-cost wireless sensor systems to monitor the temperature and humidity of early-age concrete. By dynamically tracking thermal gradients, this system significantly improves material and energy efficiency in industrial manufacturing environments. These micro-level innovations in low-cost sensing technology provide crucial technical safeguards and real-time data support for energy-intensive sectors to implement substantive carbon reduction actions and accurately evaluate the effectiveness of GT.

Based on the incentive effect of the "Porter Hypothesis", when carbon emission quotas become a regulatory factor, excessive emissions will directly lead to high punitive expenditures, while the surplus quotas generated by technological advantages can be converted into additional profits through market transactions [14,15]. The coexistence of cost pressure and profit opportunities constitutes the innovation compensation mechanism of enterprises, prompting them to shift from innovating green technologies to optimizing production processes, achieving a leap from passive compliance to a comprehensive GT [16]. From the perspective of the signaling theory, CETS not only brings cost constraints but also serves as an effective channel for enterprises to convey their sustainable development capabilities to external stakeholders. In the case of environmental information asymmetry, carbon trading performance and transformation willingness have become important signals for outsiders to measure an enterprise's risk response ability and social responsibility [17]. For energy-intensive enterprises, responding positively to policies and implementing GT can release positive signals of long-term competitiveness and governance norms to the capital market, thereby helping to alleviate financing constraints and attract green capital support [18]. This signal dividend triggered by policies can effectively compensate for initial compliance costs and enhance the internal driving force of enterprises to achieve comprehensive transformation.

Existing studies have widely explored the positive role of CETS in promoting corporate Ginn and improving external financing environments, which provides an important theoretical foundation for this study to investigate deeper transformation. Driven jointly by the Porter Hypothesis and signaling theory, CETS not only imposes substantive cost constraints on energy-intensive firms but also compels them to fully integrate environmental performance into their core governance structures. Consequently, the technological advantages and financing support accumulated by firms responding to carbon regulations will be transformed into a driving force for systematic strategic adjustments, propelling the firms from passive compliance to comprehensive GT. Based on the above analysis, the following hypothesis can be proposed:

H1. *CETS significantly promotes the GT of energy-intensive enterprises.*

2.2. The Moderating Effect of Internal Control Level (ICL) and Ginn

In the process through which CETS drives enterprises to adopt GT, the efficiency of policy signal transmission is often constrained by the internal governance level and technical support capacity of the enterprises. From the perspective of enterprise governance, the ICL directly determines the accuracy of policy constraints being transformed into management decisions. According to the principal-agent theory, there is an inconsistency of interests between the management and the shareholders. The management often tends to pursue short-term business performance while avoiding risky and long-term green investments [19]. High-quality internal control systems can effectively suppress the short-sighted behavior of the management under agency problems by strengthening internal supervision and information disclosure mechanisms [20]. When enterprises face quota constraints and cost pressures generated by CETS, a well-established internal control system helps the management to more accurately identify policy risks and embed environmental goals into long-term business plans. This governance mechanism ensures that the limited funds of the enterprises can be prioritized for GT projects, thereby alleviating the financial risks caused by increased compliance costs and ensuring that the external pressure of CETS can be transformed into systematic strategic adjustments [21].

From the perspective of technical support, the level of Ginn is the core support for enterprises to make the leap from "passive compliance" to "active transformation". Based on the absorptive capacity theory, firms' responsiveness to external policy signals depends on their existing knowledge reserves and technical foundation. Higher levels of Ginn mean that enterprises have stronger abilities to identify and internalize external environmental technologies, and can quickly convert the price incentives of the carbon emission market into actual production process innovations [22]. Combined with the dynamic capability theory, Ginn is not only a direct means to reduce carbon emission intensity but also a key link for enterprises to perceive market changes and restructure production factors under carbon emission regulations [23]. When enterprises have substantial green patent outputs, the technical achievements can be more effectively transformed into production efficiency, significantly reducing emission reduction costs, and enhancing the dynamic matching ability of enterprises in the GT process.

Although the above studies confirm the direct driving effect of environmental regulations on corporate behavior, the moderating mechanisms that influence policy transmission efficiency within enterprises are often overlooked. Based on the preceding analysis, this study argues that the promoting effect of CETS on the GT of energy-intensive firms is not static; rather, it can be significantly amplified by improvements in firms' governance and technological capabilities. Specifically, internal control and Ginn, as two distinct moderating pathways, optimize the absorption of policy signals from the perspectives of "governance willingness" and "technological foundation", respectively. When confronting the compliance pressure of CETS, a higher level of internal control effectively reduces agency costs, ensuring that management smoothly translates policy pressure into long-term green investment decisions. Concurrently, a higher level of Ginn endows firms with stronger absorptive capacity, enabling them to convert carbon price signals into actual production process upgrades at a lower cost. Functioning as "accelerators" in policy transmission, these two internal capabilities independently strengthen firms' responsiveness to environmental regulations, thereby positively moderating the driving effect of CETS on GT. Therefore, the following hypotheses can be proposed:

H2a. *The level of enterprise internal control exerts a significant positive moderating effect on the impact of CETS on the GT of energy-intensive firms.*

H2b. *Ginn exerts a significant positive moderating effect on the impact of CETS on the GT of energy-intensive firms.*

2.3. Heterogeneous Effects of CETS on GT in Energy-Intensive Enterprises

The driving effect of CETS on energy-intensive enterprises' GT is not uniformly distributed in all situations. The policy effect is often constrained by the external market competition environment and the internal resource endowment of the enterprises.

First, the intensity of industry competition is the key external constraint determining the policy transmission effect. From the perspective of market structure, the differences in the competitive environment significantly change the strategies that enterprises adopt when responding to environmental regulations. In industries with a high degree of competition, due to the severe homogeneity of products and limited profit margins, enterprises lack the ability to transfer the carbon trading costs to downstream consumers, which makes the survival pressure caused by compliance costs particularly intense. Under the pressure of CETS, enterprises are more motivated to pursue technological gains and differentiated competitive advantages through active GT, which in turn enhances their responsiveness to policy incentives [24]. Conversely, in industries with a high degree of monopoly, enterprises with stronger market power can often transfer the carbon emission costs to the outside through price adjustments, resulting in a lack of urgency for internal optimization of production processes and reconfiguration of governance systems, thereby weakening the policy's driving force for GT [25,26].

Second, the GI of enterprises, as a heterogeneous resource, determines the resource endowment capacity of enterprises under policy shocks. From the capital base perspective, an outstanding GI constitutes a kind of intangible capital for enterprises, which can significantly enhance their trust links with external stakeholders. In CETS, enterprises with a high level of green reputation often have stronger financing absorption capacity and can attract green credit and social capital at a lower premium to solve the potential risks of funding breaks during the transformation process [27–29]. Moreover, this reputation capital can also promote enterprises to integrate into the ecological innovation network, attract high-quality suppliers, consumers, and non-profit institutions to conduct collaborative research and development, and transform scattered environmental investments into systematic green technology solutions [30]. This logic of transforming reputation accumulation into transformation motivation essentially represents the strategic leap of enterprises to convert resources into technology through environmental governance, ultimately driving energy-intensive enterprises to complete a deep transformation under carbon constraints [31].

From the above studies, it can be generalized that the implementation effects of environmental regulation policies are not uniformly distributed but are constrained by the external market ecology and internal resource endowments of enterprises. This study argues that the driving effect of CETS on the GT of energy-intensive firms exhibits significant heterogeneity among groups with different characteristics. Specifically, industry competition intensity and corporate GI constitute the external constraints and internal support influencing policy transmission efficiency. On the one hand, in highly competitive industries, firms cannot easily pass on the added carbon trading costs to consumers; this severe external survival pressure forces firms to actively undertake GT to rebuild differentiated competitive advantages. On the other hand, a good GI acts as intangible reputation capital. This effectively alleviates financing constraints and attracts external innovation resources during GT, which provides solid internal resource support for firms to respond to carbon reduction policies. Therefore, firms in highly competitive industries or with a strong green reputation reserve possess stronger motivation and capability to translate the policy pressure of CETS into substantive transformation actions. Accordingly, this study proposes two additional hypotheses:

H3a. *The promoting effect of CETS on the GT of energy-intensive firms is more significant in industries with higher competition intensity.*

H3b. *The promoting effect of CETS on the GT of energy-intensive firms is more significant for firms with a positive GI.*

3. Research Design

3.1. Sample Selection and Data Sources

This research uses a sample of 529 firms from six energy-intensive industries listed on China's A-share market during 2007–2024. These medium-to-large listed firms represent industry leaders and major carbon emitters within these critical sectors. As the primary targets of CETS, their transition effectiveness largely determines the overall success of the national carbon market. Therefore, these listed firms are highly representative of the broader trajectory of Chinese corporate GT under mandatory carbon reduction constraints. Furthermore, A-share listed firms are subject to stringent financial auditing and environmental disclosure standards, providing a reliable foundation for empirical analysis.

Firms with abnormal financial conditions, including ST or *ST designations, as well as those that were suspended from trading, were excluded to ensure data reliability. Enterprises with severely missing data and those with extreme outliers were also excluded. Winsorization was applied at the first and 99th percentiles for the variables. Finally, a total of 6063 observation samples were determined.

The annual reports of listed companies were obtained from the Juchao Information Network (https://www.cninfo.com.cn). The frequency of 113 GT keywords in the annual reports of enterprises was calculated using Python 3.13.3. Enterprise-level data were collected from CSMAR. The internal control index was obtained from the DIB database (https://www.dibdata.cn/).

3.2. Variable Definition

3.2.1. Dependent Variable

The enterprise GT is regarded as the dependent variable in this study. Based on policy documents such as "Technical Guidelines for Assessing Enterprise Environmental Behaviors", "White Paper on Green Manufacturing", and "Made in China 2025", 113 keywords related to the enterprise GT were selected from five categories including technological innovation (TI), strategic concepts (SC), publicity initiatives (PI), pollution control (PC), and monitoring management (MM), as shown in Figure 2. The frequency of these keywords appearing in the annual reports of listed companies was counted to quantify the level of the enterprise's GT. Finally, the logarithm of the frequency count plus 1 was used to represent the GT indicators of the company [32].

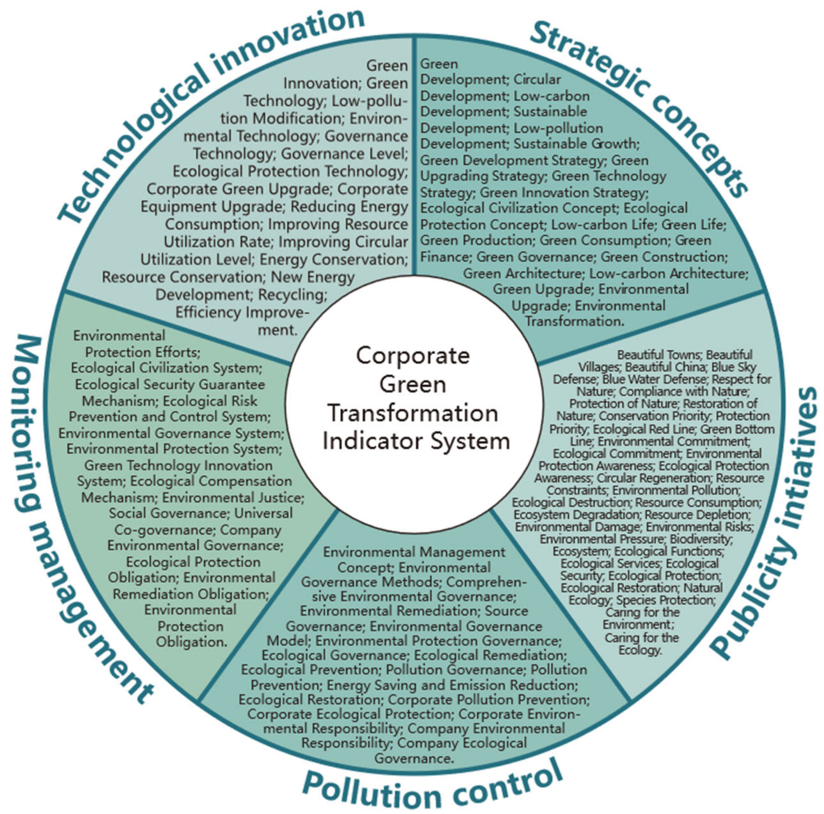

Figure 2. Word frequency-based hierarchical structure of the five-dimensional GT indicator system.

3.2.2. Core Explanatory Variable

In this research, the core explanatory variable is a multi-period difference-in-differences (DID) indicator that captures the policy shock of CETS on firms' GT. Considering that CETS was implemented gradually across different regions and years in China, firms are not assigned to the treatment and control groups solely according to whether they are located in carbon-trading pilot regions. Instead, the treatment status is identified based on the first year in which a firm was actually included among the key emission entities covered by CETS. Specifically, if firm i is first included in CETS in year t, the DID variable equals 1 for year t and all subsequent years and equals 0 for all years before its first inclusion. Firms that are never included in CETS during the sample period are assigned a DID value of 0 throughout the sample period and constitute the control group. This setting captures the staggered implementation of CETS across regions and years and helps avoid potential misclassification that can arise from defining treatment status only by firms' registered locations in pilot regions.

3.2.3. Moderating Variables

Enterprise ICL: Measured by the natural logarithm of the internal control index score plus 1, reflecting the ability of managers to enhance policy implementation accuracy by suppressing opportunistic behavior and to reduce green transition risks through standardized management [33].

Ginn: Natural logarithm of the number of green patents applied for by the enterprise plus 1 as an indicator of the level of Ginn, which indicates the ability of enterprises to internalize green technological achievements in their production efficiency and the dynamic matching of the allocation of resources with GT [34].

3.2.4. Control Variables

To isolate the net effect of CETS on the GT of energy-intensive firms, this study controls for firm-level characteristics across three dimensions. Regarding firm fundamentals, size and age of the firms are included because larger and longer-established firms tend to possess greater resource endowment and organizational experience to respond to regulatory pressure [35]. For financial characteristics, return on assets, current ratio, and intangible asset ratio are controlled, as profitability, liquidity, and knowledge capital endowment of a firm jointly shape the capacity to undertake green investment and absorb compliance costs [36]. Finally, Tobin Q and the largest shareholder ownership ratio are incorporated to account for the variation in market valuation and the ownership concentration, both of which influence managerial incentives and the allocation of resources toward long-term sustainability objectives [37]. Detailed descriptions of the variables are provided in Table 1.

Table 1. Definition and measurement of main variables.

Variable Type	Variable Name	Symbol	Variable Definition
Dependent Variable	Green Transformation	GT	ln (green transformation keywords frequency + 1)
Explanatory Variable	Multi-period DID Policy Shock	Treat × Post	Equals 1 for firm i in year t and all subsequent years after first entering the carbon emissions trading market; equals 0 for firms that have not entered the market or for years prior to entry.
Moderating Variable	Internal Control Level	ICL	ln (DIB Internal Control Index score + 1)
	Green Technology Innovation	Ginn	ln (green patents + 1)
Control Variables	Firm Size	Size	ln (total assets)
	Firm Age	Age	ln (number of years since companies established + 1)
	Profitability	ROA	Net income/total assets
	Current Ratio	CR	Current assets/current liabilities
	Intangible Asset Ratio	Intangible	Net intangible assets/total assets
	Firm Market Value	Tobin Q	Market capitalization/total assets
	Ownership Concentration	Top1	Shareholding ratio of the largest shareholder

3.3. Model

3.3.1. Benchmark Regression Model

The benchmark model is specified to identify the net effect of CETS on the GT of energy-intensive enterprises:

$$GT_{(i,t)} = \alpha_0 + \alpha_1 DID_{(i,t)} + \sum \beta_k Control_{(i,t)} + \mu_i + \lambda_t + \epsilon_{(i,t)} \quad (1)$$

where $GT_{(i,t)}$ is the dependent variable which represents the level of GT of enterprise *i* at the *t*-th year; $DID_{(i,t)}$ is the independent variable, reflecting the shock of CETS on the enterprise; μ_i and λ_t correspond to the firm fixed effect and the year fixed effect; and $\epsilon_{(i,t)}$ is the random error term.

3.3.2. Moderating Effect Model

To examine the moderating effect of internal capabilities and external environmental factors on the policy transmission process, this study extends the benchmark model (1) by introducing an interaction term between DID and the moderating variables. This moderating effect model enables an examination of how internal capabilities and green technology moderate the effect of CETS on enterprises' GT adoption.

$$GT_{(i,t)} = \alpha_0 + \alpha_1 DID_{(i,t)} + \alpha_2 DID_{(i,t)} \times ICL_{(i,t)} + \alpha_3 ICL_{(i,t)} + \sum \beta_k Control_{(i,t)} + \mu_i + \lambda_t + \epsilon_{(i,t)} \quad (2)$$

$$GT_{(i,t)} = \alpha_0 + \alpha_1 DID_{(i,t)} + \alpha_2 DID_{(i,t)} \times Ginn_{(i,t)} + \alpha_3 Ginn_{(i,t)} + \sum \beta_k Control_{(i,t)} + \mu_i + \lambda_t + \epsilon_{(i,t)} \quad (3)$$

Equation (2) investigates the moderation provided by internal control (ICL), and Equation (3) focuses on the moderation from green innovation capability (Ginn). The key coefficients of interest are the interaction terms, DID × ICL and DID × Ginn; a positive and significant estimate would signal that the corresponding internal factor strengthens the positive influence of CETS on enterprise GT. Both models continue to apply the same control variables and dual fixed effects as in the benchmark regression.

3.3.3. Heterogeneity Analysis Model

Considering that the differences in the external competitive ecosystems faced by different firms may lead to asymmetric policy implementation effects, this paper conducts a group test on the entire sample using the Herfindahl–Hirschman Index (HHI) from the perspective of industry competition intensity. Based on the median HHI of the industries to which the sample enterprises belong, the full sample is partitioned into high-competition and low-competition groups, and the benchmark regression model (1) is run separately for each group.

The enterprise GI is a variable used to measure the "resource endowment" level of energy-intensive enterprises during the transformation process. In this study, the GI is defined as:

$$GI_{it} = 100 \times \frac{\text{Environmental Investment}_{it}}{\text{Operating Revenue}_{it}} \quad (4)$$

This indicator reflects that the enterprise accumulates symbolic capital through resource allocation to alleviate financing constraints in the GT process [10] (Ma et al., 2025 [10]). Considering that the environmental information disclosure of Chinese listed companies is still in the initial and standardized stage, the disclosure of environmental protection investment amounts has many non-systematic deficiencies. To ensure the universality and robustness of the research conclusions, this paper focuses on examining the heterogeneity impact of policies on enterprises with different disclosure decisions and distinguishes between the disclosure group and the non-disclosure group. This not only captures the sensitivity of enterprises to regulatory pressure but also reflects their strategic motives for obtaining organizational legitimacy under CETS regulation.

4. Empirical Analysis

4.1. Statistical Description

Table 2 summarizes the descriptive statistics for the primary variables included in the analysis. The mean (2.6842) and median (2.8129) of the dependent variable are close, suggesting a relatively balanced distribution across enterprises. The considerable difference between the minimum value of 0.0000 and the maximum of 4.5768 demonstrates clear disparities in GT performance across the sampled enterprises. The core explanatory variable, DID, shows a small mean (0.1114) and median (0.0000), reflecting that only a limited proportion of enterprises are treated under the policy. Green innovation (Ginn) and internal control (ICL) display right-skewed distributions, with most firms exhibiting low values in Ginn, while ICL shows limited dispersion with a small standard deviation (0.6219), indicating relatively consistent ICL across firms.

Table 2. Descriptive statistics of main variables.

Variable	N	Mean	Std. Dev.	Median	Min	Max
GT	6063	2.6842	0.9383	2.8129	0.0000	4.5768
DID	6063	0.1114	0.3372	0.0000	0.0000	1.0000
ICL	6063	7.2992	0.6219	7.3678	0.0000	7.6914
Ginn	6063	0.3650	0.7819	0.0000	0.0000	3.6882
Intangible	6063	0.0484	0.0361	0.0401	0.0000	0.2327
Size	6063	25.4780	1.6145	25.2084	22.5893	29.8386
CR	6063	2.4556	2.5542	1.6312	0.2335	15.7021
ROA	6063	0.0474	0.0583	0.0436	−0.2298	0.2256
Age	6063	3.3734	2.5484	3.3331	0.7846	4.0246
Tobin Q	6063	1.9319	1.1049	1.5982	0.7032	14.6947
Top1 (%)	6063	40.5370	17.8588	38.0239	3.8375	93.2835

Furthermore, regarding the industry distribution of 529 sampled enterprises, the chemical raw materials and chemical products manufacturing sector accounts for the largest proportion of 52.36%, followed by the non-metallic mineral products manufacturing sector of 17.01%. The electricity and heat production and supply sector accounts for 11.72%, as does the non-ferrous metal smelting and rolling processing sector. The rest of the firms belong to the ferrous metal smelting and rolling processing sector (4.91%) and the petroleum processing, coking, and nuclear fuel processing sector (2.27%). This distribution reflects the realistic composition of key energy-intensive sectors regulated by China's CETS, confirming the representativeness of the sample.

To further assess potential multicollinearity among the explanatory variables, Table 3 reports the correlation matrix. The results show that the pairwise correlation coefficients among the variables are generally low. In addition, this study conducts variance inflation factor (VIF) tests, with VIF values ranging from 1.03 to 1.78 and a mean VIF of approximately 1.22. These results indicate that multicollinearity is not a serious concern in this study and is unlikely to bias the regression estimates.

Table 3. Correlation matrix.

Variable	GT	DID	Ginn	ICL	Intangible	Size	CR	ROA	Age	Tobin Q	Top1
GT	1										
DID	0.130 ***	1									
Ginn	0.175 ***	0.120 ***	1								
ICL	0.005	0.021	0.016	1							
Intangible	0.030 **	0.017	−0.005	−0.008	1						
Size	0.317 ***	0.091 ***	0.262 ***	0.027 *	−0.073 ***	1					
CR	−0.135 ***	−0.031 **	−0.095 ***	0.034 **	−0.095 ***	−0.457 ***	1				
ROA	0.019	0.039 ***	0.021	0.118 ***	−0.033 **	−0.100 ***	0.288 ***	1			
Age	−0.039 ***	0.052 ***	0.055 ***	−0.004	−0.036 **	0.203 ***	−0.357 ***	−0.187 ***	1		
Tobin Q	−0.164 ***	−0.060 ***	−0.079 ***	0.004	0.049 ***	−0.413 ***	0.227 ***	0.221 ***	−0.202 ***	1	
Top1 (%)	0.064 ***	0.032 **	0.112 ***	0.059 ***	−0.104 ***	0.272 ***	−0.059 ***	0.012	0.106 ***	−0.165 ***	1

Note: *** significance at 1% level. ** significance at 5% level. * significance at 10% level.

4.2. Benchmark Regression Results

Table 4, column (1), presents the benchmark regression estimates of the effect of CETS on the GT performance of energy-intensive firms. Enterprise fixed effects, year fixed effects, and control variables were included. The DID coefficient was 0.1504, which was significant at the 5% significance level. This indicates that under the CETS, the GT level of energy-intensive enterprises was significantly higher than that of the control group enterprises, thereby verifying Hypothesis H1.

Table 4. CETS and GT: benchmark regression and moderating effects.

Variables	(1) Benchmark Regression	(2) Internal Governance: ICL	(3) Technical Support: Ginn
DID	0.1504 ** (0.0599)	0.1468 * (0.0778)	0.1485 * (0.0846)
DID × ICL		0.1055 ** (0.0501)	
DID × Ginn			0.1152 ** (0.0523)
ICL		0.0727 (0.0478)	
Ginn			0.0855 *** (0.0321)
CR	−0.0156 ** (0.0076)	−0.0114 * (0.0066)	−0.0114 * (0.0067)
ROA	0.4023 (0.3170)	0.3719 (0.3340)	0.3807 (0.3327)
Age	−0.0026 (0.0034)	−0.0029 (0.0034)	−0.0032 (0.0034)
Tobin Q	−0.0409 ** (0.0181)	−0.0413 ** (0.0186)	−0.0428 ** (0.0185)
Intangible	1.0668 * (0.5515)	1.1786 ** (0.5725)	1.1460 ** (0.5633)
Size	0.1763 *** (0.0217)	0.1854 *** (0.0214)	0.1753 *** (0.0228)
Top1	0.0171 * (0.0128)	0.0247 * (0.0146)	0.0218 * (0.0121)
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	6063	6063	6063
R-squared	0.3928	0.4172	0.4159

Note: Standard errors are given in parentheses: *** significance at 1% level, ** significance at 5% level, * significance at 10% level.

4.3. Results of Moderation Effects

Table 4, columns (2) and (3), respectively, examine the moderating effects of the ICL and Ginn on the relationship between CETS and enterprises' GT.

Column (2) shows the moderating effect of the ICL. The estimated coefficient of the interaction term DID × ICL is 0.1055. The coefficient is positive and statistically significant at the significance level of 5%. This indicates that the higher the ICL of enterprises, the stronger the positive promoting effect of CETS on enterprises' GT. This result strongly supports Hypothesis H2a. This finding suggests that a well-established internal control system can effectively strengthen the transmission mechanism of CETS: On the one hand, a sound internal control system helps enterprises precisely control their carbon emissions within the carbon emission quota, reducing the cost of participating in the carbon market; on the other hand, internal control can effectively transform external policy pressure into internal green investment decisions, thereby amplifying the incentive effect of carbon market policies.

Column (3) reported that the estimated coefficient of DID × Ginn was 0.1152, which was also significantly positive at the 5% significance level, indicating that the stronger the green innovation capability of enterprises, the greater the promoting effect of carbon emission rights trading policies on enterprises' GT. This result strongly supports Hypothesis H2b. This finding indicates that green innovation capability constitutes an important prerequisite for the effectiveness of carbon market policies: Enterprises with strong green technology accumulation can respond to carbon market incentives at a lower cost, transform policy pressure into technological advantages, and thereby achieve higher-quality GT under carbon market constraints, further verifying the positive moderating effect of technological capabilities in the policy transmission process.

4.4. Heterogeneity Analysis Results

Table 5 groups the samples based on two dimensions: market competition intensity and corporate GI to test the heterogeneity characteristics of policy effects.

Table 5. Cross-sectional heterogeneity.

Variables	**Market Competition Heterogeneity**		**GI Disclosure Heterogeneity**	
	(1)	**(2)**	**(3)**	**(4)**
	GT Competition Low	**GT Competition High**	**GT Undisclosed**	**GT Disclosed**
DID	0.0848	0.1847 ***	0.0636	0.0895 ***
	(0.1007)	(0.0672)	(0.0429)	(0.0324)
Controls	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	3031	3032	4873	1190
R-squared	0.4108	0.4166	0.3831	0.3751

Note: Standard errors are given in parentheses: *** significance at 1% level.

Regarding market competition heterogeneity, this paper divides the samples into a low competition group (column (1)) and a high competition group (column (2)) based on the median of the Herfindahl–Hirschman Index (HHI). The results show that the coefficient of the DID term is 0.1847 in the high competition group, and it is statistically significant at the 1% level; while in the low competition group, the coefficient is 0.0848, and it fails to pass the significance test. This indicates that the promotion effect of CETS on corporate GT is more significant in industries with higher competition intensity. The possible mechanism is that intense competition puts enterprises under greater survival pressure, and policy shocks are more likely to force enterprises to enhance GT as a substantive response to external environmental pressure in order to maintain competitive advantages.

Regarding GI heterogeneity, this paper groups the samples based on the disclosure of green investment information in the enterprise annual reports. Since GI is measured by the ratio of green investment amount 100 to operating income, and the country has not yet mandated enterprises to disclose green investment information, enterprises that have not disclosed green investment usually indicate a very low or even zero green investment scale, and thus their GI level is also correspondingly lower, while enterprises that actively disclose in the annual reports usually have certain green investment accumulation and a relatively higher GI. Based on this, column (3) and column (4) correspond to the low GI group (no disclosure) and the high GI group (disclosure). For enterprises with a high

GI, the estimated coefficient of DID is 0.0895, significant at the 1% level. By comparison, in the low GI group, the coefficient decreases to 0.0636 and is not statistically significant, highlighting the moderating role of GI in shaping the impact of CETS on GT. This result indicates that enterprises with a certain GI foundation respond more positively to green policies, and the policy incentive effect is more fully released in the group of enterprises with a higher GI, while enterprises with a weak GI, due to insufficient green investment accumulation, find it difficult to obtain significant productivity improvement from the policy in the short term.

5. Robustness Test

To verify the robustness of the empirical findings regarding the effect of CETS on GT in energy-intensive firms and to mitigate potential biases from sample selection, model choice, or variable measurement, this study extends the benchmark DID regression and incorporates moderating and heterogeneity analyses. Robustness is assessed through multiple approaches. These include the parallel trend test, a PSM-DID model, a placebo test, and the use of alternative dependent variables. All tests are based on the unbalanced panel data after annual trimming from 1% to 99%, control for firm-specific fixed effects and year-specific fixed effects, and perform enterprise-level clustering adjustment on standard errors.

5.1. Parallel Trend Test

The parallel trend test is a prerequisite for the DID model, meaning that the green transition trends of the treatment group and the control group should remain consistent before the implementation of the policy. The model is constructed as follows:

$$\mathrm{GT_{it}} = \alpha_0 + \alpha_1 \sum_{t=-6}^{11} \mathrm{DID_{i,t}} + \gamma \mathrm{X_{it}} + \mu_i + \lambda_t + \varepsilon_{it} \tag{5}$$

Figure 3 reports the DID coefficient estimates, which are employed to examine the parallel trend assumption. In the pre-CETS period, the coefficients hovered around zero without reaching significance, implying that the experimental and control groups exhibited consistent trends. Once CETS was implemented, the coefficients showed a pronounced departure from zero, confirming that the parallel trend condition holds for this sample.

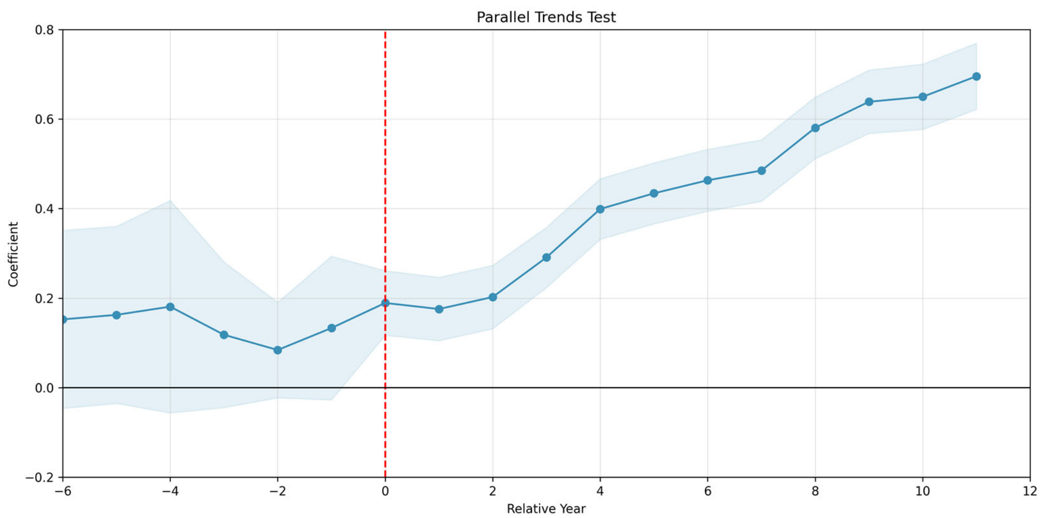

Figure 3. Parallel trend test and dynamic marginal effects. The vertical red dotted line indicates the implementation year of the CETS (Relative Year = 0).

5.2. Placebo Test

To rule out potential interference from unobserved random factors affecting the GT process, a placebo test is employed to verify the robustness of the benchmark regression results. In this procedure, enterprises equal in number to the actual treatment group are randomly assigned to form a pseudo-treatment group, while the remaining firms constitute a pseudo-control group. These groups are then analyzed using the baseline DID model. The random assignment is repeated 500 times, and the corresponding regression coefficients and *p*-values for the pseudo-policy shocks are recorded.

The test results show that the coefficient values of 500 random regressions fluctuate around zero (Figure 4). The kernel density distribution exhibits typical characteristics of a normal distribution, and most of the coefficients are not significant. However, the benchmark regression coefficient of 0.1504 is substantially larger than those obtained from the placebo regressions and lies in the extreme right tail of the simulated distribution. This pattern is reasonable because the placebo test randomly assigns treatment status to firms, which breaks the actual link between CETS exposure and firms' GT responses. In this case, the pseudo-policy shocks should not generate a systematic effect, so their estimated coefficients are expected to fluctuate around zero. By contrast, the benchmark coefficient is estimated based on firms' actual exposure to CETS. It is much larger magnitude therefore suggests that the observed effect is unlikely to result from random shocks or model specification bias, but instead reflects the actual impact of CETS on firms' GT. Overall, the placebo test provides further evidence that the benchmark findings are not driven by chance and supports the robustness of the main conclusions.

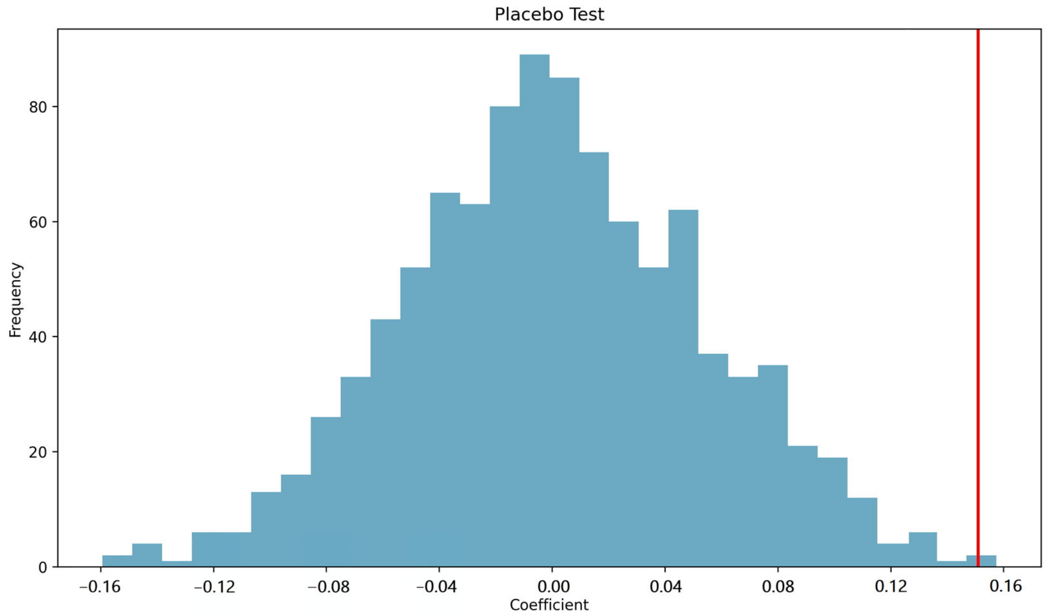

Figure 4. Distribution of coefficients and *p*-values from the placebo test. The vertical red line indicates the baseline regression coefficient (0.1504).

5.3. PSM-DID Model

To address the potential biases caused by a non-random sample selection and grouping, this study uses the PSM-DID approach for robustness testing. To improve the comparability between treated and control firms, a Logit model is employed to calculate propensity scores, which are then used in a kernel matching procedure to generate comparable control samples for the experimental group. Once the balance assumption is satisfied, the matched samples are incorporated into model (1) for re-estimation.

https://doi.org/10.3390/en19133037

To verify the validity of the matching procedure, a covariate balance test was conducted before and after matching. Results indicate that the standardized mean differences in all matching variables are substantially reduced after matching. In particular, the absolute standardized biases of all covariates are smaller than 5%, and the corresponding *t*-tests become statistically insignificant. These results suggest that the matching procedure effectively improves the comparability between treated and control firms and satisfies the balance requirement for subsequent PSM-DID estimation. Detailed balance diagnostics are listed in Appendix A (Table A1).

The PSM-DID estimation yields a DID coefficient of 0.1391, which remains positive and statistically significant at 10%. Compared with the benchmark estimate of 0.1504, the magnitude of the coefficient decreases slightly but remains economically meaningful. This finding suggests that the positive effect of CETS on the GT of energy-intensive firms persists even after controlling for potential sample selection bias. Therefore, the benchmark conclusion is robust and is unlikely to be driven by systematic differences between treated and control firms.

5.4. Goodman-Bacon Decomposition Analysis

Given that this study adopts a staggered DID design in which firms enter CETS in different years, the conventional two-way fixed effects (TWFE) estimator may be affected by heterogeneous treatment effects. To address this concern, this study further applies the Goodman-Bacon decomposition method to decompose the TWFE estimator in the benchmark regression and examine whether the estimated effect is mainly driven by potentially problematic comparisons [38]. The Goodman-Bacon decomposition results are shown in Figure 5.

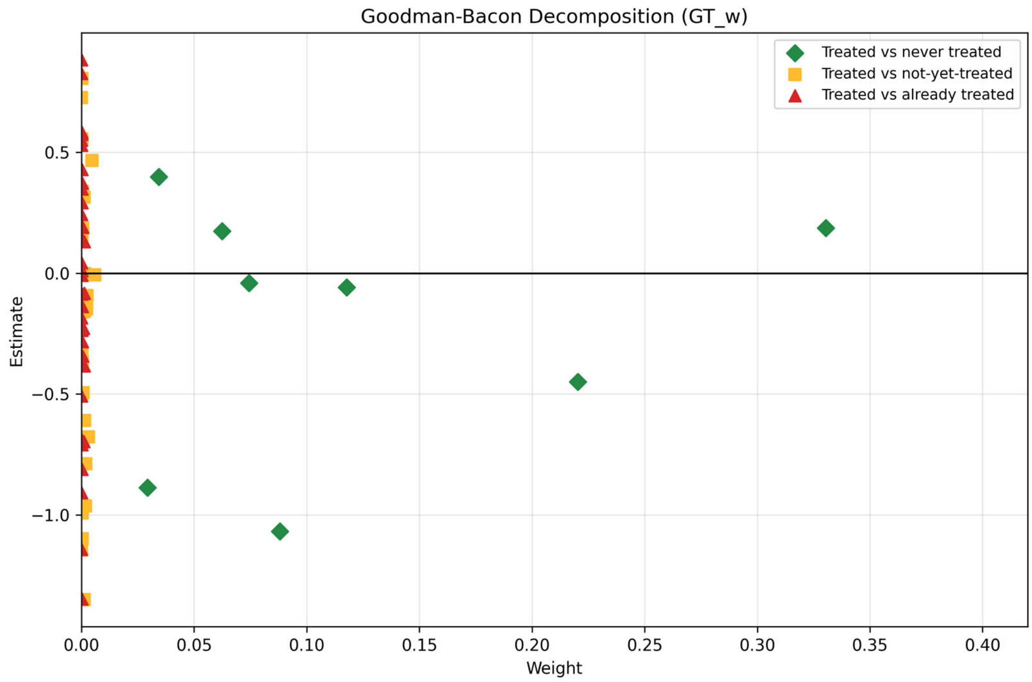

Figure 5. Goodman-Bacon decomposition of the TWFE estimator.

Green diamonds represent comparisons between treated and never-treated firms, yellow squares represent comparisons between treated and not-yet-treated firms, and red triangles represent comparisons between treated and already-treated firms. Horizontal axis is the weight assigned to each 2 × 2 DID comparison in the overall TWFE estimate, while the vertical axis is the corresponding 2 × 2 DID estimate.

Results show that comparisons between treated and never-treated firms receive relatively larger weights and constitute the main source of identification for the TWFE estimate. In contrast, comparisons between treated and already-treated firms generally receive weights close to zero, indicating that these potentially problematic comparisons contribute marginally to the overall estimation. This suggests that the benchmark regression results are not mainly driven by comparisons using already-treated firms as controls, and that the risk of severe bias caused by heterogeneous treatment effects under the staggered DID design is limited. Therefore, the Goodman-Bacon decomposition provides additional support for the robustness of the main findings.

5.5. Replacement of the Dependent Variable

To further validate the robustness of the findings, the study substitutes the original dependent variable with alternative measures. The benchmark regression uses a keyword frequency approach to construct a comprehensive index of firms' GT. While this index effectively captures strategic and managerial transformation trends, potential measurement errors arising from deliberate "greenwashing" practices may exist. To address this, the study integrates the specific objectives of CETS and applies a carbon emission intensity index (CEI):

$$CEI_{i,t} = \frac{\text{Carbon Emissions}_{i,t}}{\text{Operating Income}_{i,t}/10,000} \tag{6}$$

The regression results reported in column (2) of Table 6 indicate that, after substituting the quantitative indicators, the DID coefficient is −0.0646 and statistically significant at the 5% level. This suggests that the policy has effectively prompted firms to reduce their carbon emission intensity while achieving substantive improvements in GT, thereby mitigating potential measurement errors associated with the benchmark indicators.

Table 6. Results of PSM-DID estimation and alternative dependent variable tests.

Variables	PSM-DID	Carbon Intensity	Total Profit
DID	0.1391 * (0.0731)	−0.0646 ** (0.0269)	0.4093 ** (0.1789)
Controls	Yes	Yes	Yes
Province FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
Observations	6063	4531	6063
R-squared	0.4188	0.7528	0.5389

Note: Standard errors are given in parentheses: ** significance at 5% level, * significance at 10% level.

To further verify the robustness of the benchmark regression results, this study replaces the dependent variable of GT with the enterprise total profit indicator for regression analysis. The total profit of enterprises serves as an indicator of changes in their economic performance and adjustments in profitability following CETS implementation. In the regression results presented in column (3) of Table 6, the DID coefficient is 0.4093 and statistically significant at the 5% level. This finding indicates that, after the implementation of the CETS, the total profit of the affected enterprises has increased substantially. The result further suggests that the CETS not only encourages firms to engage in strategic investments in green technology but also incentivizes continuous green production and investment, thereby enhancing the economic sustainability of GT initiatives. In addition, the total profit replacement test eliminates the possible interference of the benchmark regression caused by index construction errors. Even if the enterprise profitability is used as the measurement standard, the policy effect is still robust, which further enhances the reliability of the research conclusion.

6. Discussion and Conclusions

6.1. Discussion

A persistent debate in environmental economics revolves around whether stringent emission regulations stifle corporate competitiveness or stimulate strategic upgrading. Empirical analysis in this study validates the first hypothesis, providing clear micro-level evidence that China's CETS goes beyond serving as a simple administrative penalty. By internalizing the environmental costs of carbon, the trading scheme fundamentally shifts the cost–benefit calculus for energy-intensive firms. Rather than passively absorbing compliance costs, management is compelled to reallocate internal resources toward long-term carbon asset optimization, capturing the economic premium of surplus quotas to fuel operational transformation.

Furthermore, the effectiveness of such market-based environmental policies is far from automatic. Validating the second set of hypotheses, the results open the "black box" of policy transmission to reveal that organizational friction often dictates a firm's adaptive success. It is found that robust internal control systems are vital in suppressing managerial myopia. Without such governance, management might resort to short-term financial maneuvering rather than committing to the structural shifts required for genuine transformation. On the technical front, a firm's pre-existing baseline of green technology determines its transformation efficiency. This technological readiness allows them to upgrade their production processes at a substantially lower cost, thereby accelerating their overall GT.

Finally, confirming the third set of hypotheses, the findings illustrate that the impact of CETS is highly context-dependent. A particularly interesting dynamic emerges in highly competitive markets: when firms lack the pricing power to shift carbon compliance costs onto downstream buyers, survival pressure pushes them to accelerate GT to carve out a differentiated competitive edge. Moreover, in the face of the massive financing gaps often created by these structural shifts, a firm's historical GI acts as a crucial strategic buffer. This intangible capital effectively lowers information asymmetry with external stakeholders, smoothing the path for deep-level green investments.

6.2. Conclusions

This study investigates the China Carbon Emission Trading System (CETS) by analyzing 529 listed firms from six major energy-intensive industries over the period 2007–2024. A multi-period difference-in-differences (DID) approach is applied to empirically examine the driving effects and operational mechanisms of CETS on enterprises' green transformation (GT). The main research findings are summarized as follows.

First, the evidence indicates that CETS effectively promotes firms' GT. Empirical results show that CETS, through the price discovery mechanism and cost constraints, significantly prompts energy-intensive enterprises to achieve GT. After a series of robustness tests, including parallel trend test, PSM-DID, placebo test, and substitution of dependent variables, this conclusion remains robust.

Second, internal control and green technological innovation (Ginn) strengthen the effect of CETS on GT. Internal control, as the core of micro-level governance, significantly amplifies the positive impact of CETS on GT by reducing agency costs and optimizing the environmental decision-making process. This suggests that strong "governance precision" serves as a critical mechanism for translating policy pressure into GT's momentum. Ginn, as the "technical foundation" for enterprises to cope with carbon quota constraints, significantly enhances the driving efficacy of the policy. Enterprises with strong technological innovation reserves can better hedge against carbon costs through technological iteration and achieve higher-quality GT.

Third, the effect of CETS is heterogeneous across industry competition levels and GI profiles. The effectiveness of CETS varies under different competitive scenarios. In industries with intense competition (where the HHI is low), enterprises have a stronger motivation to seek "differentiated competition" through GT, thus they are more responsive to policy signals. GI, as an important reputation capital for enterprises, can play a positive guiding role. Enterprises with a good green reputation can more effectively alleviate financing constraints when facing policy shocks, thereby demonstrating a significant effect on the GT path.

6.3. Policy Recommendations

Based on the above findings, this article puts forward the following suggestions, aiming to provide a reference for the further reform of the CETS.

First, the government should further optimize the quota allocation schemes for the six major energy-intensive industries, ensuring that the carbon price signal can effectively penetrate industry barriers and reach the decision-making levels of enterprises. At the same time, targeted green transition monitoring indicators should be established to prevent enterprises from using information asymmetry to engage in "greenwashing".

Second, encourage energy-intensive enterprises to enhance their environmental compliance while improving the quality of internal control to optimize resource allocation and increase financial support and patent protection for green technologies in key areas, enabling enterprises to achieve the transition from "passive compliance" to "active transformation" through technological means.

Third, when implementing the carbon trading policy, attention should be paid to the imbalance of the industry competition environment. More support for GT should be provided to low-competitive industries. At the same time, enterprises should be guided to establish environmental credit files, and the green reputation premium mechanism should be utilized to attract social capital to flow towards energy-intensive enterprises with outstanding GT performance.

6.4. Limitations and Future Research

Although this study provides robust empirical evidence, several main limitations must be acknowledged to inform future research.

There are methodological limitations associated with the robustness checks. While the PSM-DID strategy is appropriately employed to mitigate sample selection bias, its validity intrinsically depends on the strict satisfaction of parallel trends, the quality of PSM-DID, and the comprehensive selection of observable control variables. Due to current limits on corporate environmental disclosure, the potential interference of unobservable confounding factors cannot be entirely eliminated. Future studies could leverage more granular internal corporate micro-survey data or quasi-natural experiments from future policy rollout phases to further isolate the net policy effects.

Second, limitations remain regarding the sample coverage of this study. As discussed previously, while A-share listed companies are the primary targets of CETS and account for a substantial share of carbon emissions, they do not encompass the entire corporate population. Non-listed small and micro-sized energy-intensive enterprises, which often face fundamentally different financial constraints and technical capacities, are currently excluded due to data limitations. Future research could incorporate data from these entities to evaluate whether the mechanisms identified in large listed firms universally apply across a broader range of industries and enterprise types.

In addition, this paper primarily investigates the direct operational effects on focal enterprises. How the compliance pressure from the carbon market is transmitted through the supply chain to upstream and downstream partners, and whether this dynamic leads to "pollution transfer" or "collaborative emission reduction", such questions still require in-depth exploration. Furthermore, with the ongoing expansion of the national carbon market, subsequent research should track the impact of carbon assetization on the long-term strategic behavior of enterprises to uncover more sustainable green development momentum.

Author Contributions: Conceptualization, R.L. and Z.L.; methodology, R.L. and H.H.C.; software, R.L. and H.X.; validation, R.L. and Z.L.; formal analysis, H.X. and Z.L.; investigation, H.H.C. and H.X.; resources, H.H.C. and G.L.; data curation, R.L.; writing—original draft, R.L. and H.X.; writing—review and editing, H.H.C.; visualization, G.L.; supervision, H.H.C.; project administration, H.H.C. and G.L. All authors have read and agreed to the published version of the manuscript.

Funding: This study does not receive financial support from any funds or organizations.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request. The data are not publicly available due to the strict licensing agreements of the commercial databases used, which require institutional subscription and explicitly prohibit the public sharing of raw data.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

CETS	Carbon Emissions Trading System
GT	Green Transformation
GI	Green Image
DID	Difference-in-Differences
PSM	Propensity Score Matching
HHI	Herfindahl–Hirschman Index
TWFE	Two-Way Fixed Effects
ICL	Internal Control Level
Ginn	Green Technological Innovation
ROA	Return on Assets
CR	Current Ratio
Top1	Largest Shareholder Ownership Ratio
PC	Pollution Control
MM	Monitoring Management
PI	Publicity Initiatives
SC	Strategic Concepts
TI	Technological Innovation

Appendix A

Table A1. Covariate balance diagnostics before and after matching.

Variables	Sample	Treated	Control	Bias (%)	Bias Reduction (%)	t	*p*
Intangible	Unmatched	0.043	0.038	0.6		0.157	0.875
	Matched	0.043	0.044	−0.1	83.33	−0.008	0.994
Size	Unmatched	23.093	22.445	46.6		11.644	0.000
	Matched	23.093	23.042	3.3	92.92	0.204	0.843
CR	Unmatched	1.943	2.190	−11.5		−3.001	0.003
	Matched	1.943	1.955	−0.6	94.78	−0.155	0.877
ROA	Unmatched	0.042	0.035	3.9		0.213	0.831
	Matched	0.042	0.041	0.9	76.92	0.006	0.995

Table A1. *Cont.*

Variables	Sample	Treated	Control	Bias (%)	Bias Reduction (%)	t	*p*
Age	Unmatched	19.169	18.665	5.7		1.343	0.180
	Matched	19.169	19.473	−3.4	40.35	−0.319	0.755
Tobin Q	Unmatched	1.492	1.730	−27.5		−7.889	0.000
	Matched	1.492	1.511	−2.6	90.55	−0.055	0.956
Top 1 (%)	Unmatched	37.784	35.583	13.6		3.268	0.001
	Matched	37.784	37.512	4.6	66.18	0.253	0.805

References

1. Zhang, M.; Ge, Y.; Liu, L.; Zhou, D. Impacts of carbon emission trading schemes on the development of renewable energy in China: Spatial spillover and mediation paths. *Sustain. Prod. Consum.* **2022**, *32*, 306–317. [CrossRef]
2. Hu, J.; Huang, N.; Shen, H. Can market-incentive environmental regulation promote corporate innovation? A natural experiment based on China's carbon emissions trading mechanism. *J. Financ. Res.* **2020**, *1*, 171–189.
3. Hongbin, Y.; Hongmei, Y.; Cifuentes-Faura, J.; Rauf, A. The role of carbon trading in enhancing enterprise green productivity and ESG performance: A quasi-natural evidence from China. *Bus. Strategy Environ.* **2025**, *34*, 1691–1707. [CrossRef]
4. Zhao, X.; Shang, Y.; Ma, X.; Xia, P.; Shahzad, U. Does carbon trading lead to green technology innovation: Recent evidence from Chinese companies in resource-based industries. *IEEE Trans. Eng. Manag.* **2022**, *71*, 2506–2523. [CrossRef]
5. Du, R.; Zhang, M.; Zhang, N.; Liu, Y.; Dong, G.; Tian, L.; Kong, Z.; Ahsan, M. Evaluation of key node groups of embodied carbon emission transfer network in China based on complex network control theory. *J. Clean. Prod.* **2024**, *448*, 141605. [CrossRef]
6. Sun, Y.; Shen, S.; Zhou, C. Does the pilot emissions trading system in China promote innovation? Evidence based on green technology innovation in the energy sector. *Energy Econ.* **2023**, *126*, 106984. [CrossRef]
7. Wei, H.; Zhang, J.; Yuan, K. Accelerating green transition in high-carbon firms: The role of carbon trading, subsidy design, and marketization. *Energy Strategy Rev.* **2025**, *62*, 101938. [CrossRef]
8. Jia, X.; Guang, W. The impact of the digital economy on carbon emissions based on regional development imbalance. *Systems* **2024**, *12*, 291. [CrossRef]
9. Wang, Q.; Xu, Y. Can industry competition stimulate enterprises ESG performance? *Int. Rev. Financ. Anal.* **2025**, *104*, 104274. [CrossRef]
10. Ma, J.; Shang, Y.; Liu, L. Green image, digital transformation, and corporate green innovation. *Int. Rev. Financ. Anal.* **2025**, *106*, 104518. [CrossRef]
11. He, C.; Zhang, W. The impact of carbon emission trading on the financing constraints of high-emission enterprises: Evidence from China. *Financ. Res. Lett.* **2024**, *67*, 105927. [CrossRef]
12. Mobaraki, A.; Nikoofam, M.; Mobaraki, Z.; Hosseinzadehfard, E.; Mobaraki, B. Implementing an intelligent monitoring system to enhance energy efficiency and support decarbonization in sustainable buildings. *Smart Des. Polic. J.* **2025**, *2*, 19–30. [CrossRef]
13. Porras, R.; Mobaraki, B.; Liu, Z.; Muñoz, T.; Lozano, F.; Lozano, J.A. Assessment of Low-Cost Sensors in Early-Age Concrete: Laboratory Testing and Industrial Applications. *Appl. Sci.* **2025**, *15*, 8701. [CrossRef]
14. Jiang, J.; Xie, D.; Ye, B.; Shen, B.; Chen, Z. Research on China's cap-and-trade carbon emission trading scheme: Overview and outlook. *Appl. Energy* **2016**, *178*, 902–917. [CrossRef]
15. Borghesi, S.; Cainelli, G.; Mazzanti, M. Linking emission trading to environmental innovation: Evidence from the Italian manufacturing industry. *Res. Policy* **2015**, *44*, 669–683. [CrossRef]
16. Xi, B.; Jia, W. Research on the impact of carbon trading on enterprises' green technology innovation. *Energy Policy* **2025**, *197*, 114436. [CrossRef]
17. Chen, J.; Geng, Y.; Liu, R. Carbon emissions trading and corporate green investment: The perspective of external pressure and internal incentive. *Bus. Strategy Environ.* **2023**, *32*, 3014–3026.
18. Gu, Q.; Wang, Y.; Wang, J. Low-carbon transition and corporate debt financing--evidence from the low-Carbon City pilot policy in China. *Environ. Dev. Sustain.* **2026**, 1–24. [CrossRef]
19. Jin, M.; Li, X.; Liu, B.; Li, J. Management myopia and green investment: Evidence from China. *Manag. Decis. Econ.* **2024**, *45*, 5290–5305. [CrossRef]
20. Li, N.; Li, R.; Yu, S. Managerial myopia and enterprise green total factor productivity: Perspectives on the supervisory effect and incentive effect. *Sustainability* **2024**, *16*, 7144. [CrossRef]
21. Zhang, S.; Lai, Y.; Li, H.; Wang, S.; Ru, X. Does digital transformation drive enterprise green investment? Evidence from Chinese listed firms. *J. Environ. Plan. Manag.* **2026**, *69*, 124–157.

22. Marrucci, L.; Daddi, T.; Iraldo, F. The circular economy, environmental performance and environmental management systems: The role of absorptive capacity. *J. Knowl. Manag.* **2022**, *26*, 2107–2132.
23. Borah, P.S.; Dogbe, C.S.K.; Marwa, N. Green dynamic capability and green product innovation for sustainable development: Role of green operations, green transaction, and green technology development capabilities. *Corp. Soc. Responsib. Environ. Manag.* **2025**, *32*, 911–926.
24. Ji, H.; Yu, Z.; Tian, G.L.; Wang, D.H.; Wen, Y. Market competition, environmental, social and corporate governance investment, and enterprise green innovation performance. *Financ. Res. Lett.* **2025**, *77*, 107057. [CrossRef]
25. Arrow, K.J. Economic welfare and the allocation of resources for invention. In *Readings in Industrial Economics: Volume Two: Private Enterprise and State Intervention*; Springer: Berlin/Heidelberg, Germany, 1962; pp. 219–236.
26. Beneito, P.; Coscollá-Girona, P.; Rochina-Barrachina, M.E.; Sanchis, A. Competitive pressure and innovation at the firm level. *J. Ind. Econ.* **2015**, *63*, 422–457. [CrossRef]
27. Shi, J.; Zhou, Y.; Wang, Q. Is green an effective signal for investors? Impacts of corporate environmental performance on debt financing cost. *J. Environ. Manag.* **2025**, *389*, 126152. [CrossRef]
28. Li, Z.; Liao, G.; Albitar, K. Does corporate environmental responsibility engagement affect firm value? The mediating role of corporate innovation. *Bus. Strategy Environ.* **2020**, *29*, 1045–1055.
29. Cao, Y.; Myers, J.N.; Myers, L.A.; Omer, T.C. Company reputation and the cost of equity capital. *Rev. Account. Stud.* **2015**, *20*, 42–81.
30. Li, J.; Lian, G.; Xu, A. How do ESG affect the spillover of green innovation among peer firms? Mechanism discussion and performance study. *J. Bus. Res.* **2023**, *158*, 113648. [CrossRef]
31. Fosu, E.; Fosu, F.; Akyina, N.; Asiedu, D. Do environmental CSR practices promote corporate social performance? The mediating role of green innovation and corporate image. *Clean. Responsible Consum.* **2024**, *12*, 100155. [CrossRef]
32. Cheng, Z.; Wu, Y. Can the issuance of green bonds promote corporate green transformation? *J. Clean. Prod.* **2024**, *443*, 141071. [CrossRef]
33. Yan, J.; Hu, H.; Hu, Y. Does internal control improve enterprise environmental, social, and governance information disclosure? Evidence from China. *Corp. Soc. Responsib. Environ. Manag.* **2024**, *31*, 4980–4994. [CrossRef]
34. Jia, L.; Zhang, X.; Wang, X.; Chen, X.; Xu, X.; Song, M. Impact of carbon emission trading system on green technology innovation of energy enterprises in China. *J. Environ. Manag.* **2024**, *360*, 121229. [CrossRef]
35. Meng, L.; Wang, K.; Su, T.; He, H. Carbon emission trading and corporate financing: Evidence from China. *Energies* **2022**, *15*, 5036. [CrossRef]
36. Wu, X.; Li, Z.; Tang, F. The effect of carbon price volatility on firm green transitions: Evidence from Chinese manufacturing listed firms. *Energies* **2022**, *15*, 7456. [CrossRef]
37. Feng, J.; Wang, Y.; Xi, W. Does green technology transformation alleviate corporate financial constraints? Evidence from Chinese listed firms. *Heliyon* **2024**, *10*, e27841. [CrossRef] [PubMed]
38. Goodman-Bacon, A. Difference-in-differences with variation in treatment timing. *J. Econom.* **2021**, *225*, 254–277. [CrossRef]