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Research on the Impact Mechanism of ETS on Green Innovation in China's High-Carbon Industries: A Perspective of Enterprise Heterogeneity

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Abstract: Green technology innovation is an important driving force for low-carbon development of enterprises. As a market-based environmental policy to promote greenhouse gas emission reduction, whether carbon emission trading scheme (ETS) can encourage enterprises to carry out green technology innovation under the background of "dual carbon" goal deserves further research. Taking Chinese A-share listed enterprises in the five major sectors as samples, this study constructed a modified Difference-in-Differences (DID) model to test the causal effect of ETS on green innovation in high-carbon industries. Three significant results can be summarized from the empirical study. Firstly, the ETS has a significant promoting effect on green innovation of high-carbon enterprises. And it can effectively promote high-carbon enterprises to achieve an average of a 13.24–19.56% increase in low-carbon innovation capabilities. Secondly, enterprises with different characteristics have heterogeneity in the impact of ETS implementation on green innovation. Secondly, the implementation of ETS exerts heterogeneous effects on green technology innovation across enterprises that possess diverse characteristics. Enterprises with a large capital scale (low equity concentration) have a more significant promoting effect than those with a small capital scale (high equity concentration). Thirdly, the green innovation effect of ETS exhibits significant heterogeneity across different types of industries. In the mining, manufacturing, and construction sectors, the ETS has effectively stimulated green innovation to a certain extent. There has been no significant change in green innovation in the sector of electricity, heat, gas, and water production and supply. In particular, after the implementation of the ETS, green innovation has actually been weakened in the transportation sector. As such, for policy makers, differentiated ETS policies should be implemented based on the actual situation of different industries and types of carbon-emitting enterprises.

Keywords: ETS; green innovation; DID; heterogeneity; high-carbon enterprises

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1. Introduction

As the world's largest greenhouse gas emitter and a responsible major country, after the proposal of the dual carbon target (carbon peak by 2030 and carbon neutral by 2060), various industries have successively introduced a series of environmental laws, policies, regulations and other measures to implement this commitment [1]. Of which, the Emission Trading Scheme (ETS) has long been regarded as the most effective tool for controlling greenhouse gas emissions and achieving carbon neutrality. Basically, ETS is a way of clearly defining the subject of emission rights, marketizing carbon emission rights, and controlling total carbon emissions within an appropriate range [2]. Therefore, the ETS is also known as the cap and trade policy.

Compared to developed countries such as the European Union and the United States, China's implementation of the ETS policy was relatively late. In October 2011, the National

Development and Reform Commission (NDRC) approved seven regions to launch a pilot carbon emissions trading scheme. In 2013, Shenzhen took the first step to implement the pilot scheme, followed by the other six regions. In 2016, Fujian province joined the carbon trading pilot scheme. Thereafter, in 2017, the NDRC promulgated the National Carbon Emissions Trading Market Construction Plan (Power Generation Sector), which marked the official launch of the national carbon emissions trading market. Currently, the carbon trading market in China has more than 2000 key emission units in the power generation industry, with carbon emissions exceeding 4 billion tons, surpassing the EU ETS and becoming the world's largest emissions trading scheme [3]. The ETS has made initial progress in energy conservation and emission reduction in recent years, providing valuable experience for the large-scale promotion of the policy across the country [4].

ETS policies mainly generate economic incentives through market mechanisms, which in turn stimulate enterprises to adopt innovative technologies and methods to achieve carbon emissions reduction. However, factors such as emission costs can also impose certain constraints on the implementation of environmental regulatory policies. Whether the implementation of ETS policies can promote economic growth while protecting the environment has become a hot research topic. The existing research on the effectiveness of ETS policies mainly focuses on the evaluation of environmental-economic effects, and there is relatively few in-depth analysis of the impact mechanism behind this effect. This leads to three issues that need further research: (1) Is the implementation of ETS policies effective in reducing carbon emissions and improving corporate green innovation capabilities? (2) What are the specific impact pathways of ETS policies? (3) Is there significant heterogeneity in the implementation effect of ETS among different types of emission enterprises? Taking Chinese A-share listed companies in the five major sectors from 2010 to 2019 as samples, this study constructed a multi-period Propensity Score Matching Difference-in-Differences (PSM-DID) model to empirically test the environmental and economic effects of ETS policy, and further explore the impact path and heterogeneity of this policy on the green innovation effect of high car-bon enterprises.

The possible marginal contribution of this study lies in the following three aspects: (1) in terms of research content, the evidence for the validity of the Porter hypothesis in China's environmental regulation reform mostly remains at the macro level, and the conclusions have not reached a consensus. This study delves into the micro-enterprise level, focusing on the impact of ETS on green innovation of enterprises, confirming that China's market-oriented environmental regulation reform can achieve the Porter hypothesis. (2) In terms of research methodology, this study constructs a multi-period PSM-DID method, which can effectively weaken the endogeneity of the sample selection. Thus, a meticulous and scientifically sound evaluation of the influence of ETS net policies on green technology innovation in enterprises can be conducted. In addition, this study innovatively starts from various dimensions such as firm size, equity concentration, and industry categories to further examine the heterogeneity of the impact of ETS. (3) In reality, the government has proposed the construction of a nationwide carbon emissions trading market. This study will help identify problems in a timely manner, formulate corresponding policy measures, and better promote the continued implementation of the policy nationwide.

2. Literature Review

Global warming caused by the increase in carbon dioxide (CO_2) concentrations has led to serious impacts on the human living environment, such as frequent extreme weather and air pollution [5]. According to the International Energy Agency (IEA), by the end of 2022, the CO_2 emissions generated by fossil energy consumption were 36.8 billion tons, setting a new historical high [6]. To address the negative externalities of carbon emissions, environmental regulations have been widely applied. There has been a heated debate over the impact of existing environmental regulations on their effectiveness. Neoclassical economics believes that environmental regulations can lead to additional costs for businesses and have a negative impact on the country's economic growth. Meanwhile, the Porter hypothesis

suggests that reasonable and strict environmental regulations are conducive to incentivizing companies to engage in innovative activities, reducing their additional environmental costs, and achieving a win–win situation for both the environment and the economy.

According to the types of environmental regulations, existing studies on the relationship between environmental regulation and corporate green technology innovation can be divided into three categories. One is administrative command based environmental regulation, which mainly achieves established environmental goals through mandatory intervention. The second type is the market-oriented environmental regulation, which mainly emphasizes the role of market allocation of resources to achieve environmental goals. The third type is the emerging voluntary environmental regulation. Environmental issues are negative externalities caused by market participants. To solve environmental problems, it is necessary for participants who cause negative externalities to make compensation, and this compensation can precisely compensate for the negative behavior they have caused to society. Relatively, market-based environmental regulation is more flexible than administrative command based environmental regulations, and more restrictive than voluntary environmental regulations. Market-based environmental regulation can better leverage the resource allocation function of the market.

As one of the representative policies of market-oriented environmental regulation, ETS policy has gradually become one of the effective policies for controlling environmental pollution. The core of ETS policy is the allocation of enterprise emission quotas based on total quantity control. Emission rights can be freely traded in the market, and high emission enterprises can purchase excess emissions and sell them to increase their profits, thereby utilizing market forces to achieve effective resource allocation. On the one hand, by setting emission quotas for enterprises, ETS policies can achieve the effect of carbon reduction. Sun et al. [6] studied the impact of ETS on carbon intensity and its mechanism, and found that the policy reduces carbon intensity by adjusting industrial structure, while energy structure and energy intensity have not played a role. In addition, in the research by Fang et al. [7], China's ETS was simulated through a non-linear programming. They found that implementing a carbon emissions trading system is economically meaningful in achieving the dual goals, as it will reduce China's emission reduction costs by 61.41–80.33% from 2016 to 2030.

On the other hand, the effective implementation of ETS policies is not only about reducing emissions, but also about promoting green economic development. Wu and Zhu [8] reviewed the impact research of ETS from four aspects: emissions reduction, economic performance, competitiveness, and innovation. The main goal of ETS is to reduce emissions, while the other long-term goal is to promote innovation. In order to keep their carbon emissions within the stipulated cap, enterprises have to take effective measures to cope with this policy [9]. Most scholars, after model derivation or empirical analysis, believe that ETS has a positive promotion effect on green technology innovation [10–12]. Representative studies included Liu and Sun [13], which empirically found that China's ETS pilot can significantly promote the increase in green technology innovation, and the effect of China's ETS pilot on green technology innovation will gradually increase over time. However, a few scholars have found that ETS policies experienced a crowding-out effect on innovation and confirmed this phenomenon through mechanism analysis.

Overview of existing studies, scholars have achieved fruitful results. Nevertheless, no consensus has been reached on the impact of any environmental regulation on innovation. Further analysis can still be expanded in the following two aspects. Firstly, most studies have examined the green innovation effects of environmental policy implementation from the perspective of policy makers at the macro level, but lacked research on how ETS affect enterprises' green innovation at the micro-perspective. Overall CO_2 emissions can only be reduced radically by finding ways to enable individual micro-enterprises to develop green innovations on their own. Secondly, it is particularly important to clarify how ETS affect the direction of technological change in enterprises. Instead of a one-size-fits-all emissions control policy, policy makers should propose feasible green innovation solutions suitable

for different types of enterprises to cope with environmental regulation policies. Therefore, this study explores the impact of China's carbon emissions trading pilot policies on green innovation in high-carbon enterprises. This will help to discover the practical strategies that different emission control companies tend to adopt when responding to policies, and explore the real motivations behind the increase in green innovation in enterprises.

3. Theoretical Analysis and Research Hypotheses

3.1. The Impact of ETS on Green Innovation

The impact of environmental regulation on green innovation has been fully investigated in the existing literature. For enterprises, the enhancement of green technology innovation comes from two aspects: firstly, enterprises add additional funds, fixed assets investment and human resources on the basis of existing innovation activities to specifically support green technology innovation, so that existing innovation activities have a "leverage effect" on green innovation [14]; Secondly, enterprises will optimize the allocation of internal resources, using resources originally intended for other innovative or business activities for green technology innovation [15]. This not only promotes green technology innovation, but also has a certain "crowding out effect" on other innovative behaviors of the enterprise.

As a market-oriented environmental regulation measure, ETS policy may affect the choice of corporate behavior in the following three ways: firstly, market participants will see carbon emissions trading policy as a signal for the government to strengthen environmental regulation, and enterprises will gradually realize their emission problems in operation, thereby strengthening technological innovation in emission control [16]. Secondly, the introduction of carbon emissions trading policies has reduced the policy uncertainty for enterprises to invest in emission control [17]. Various continuous environmental regulations have made enterprises realize the necessity of emission control and continuously eliminate their concerns about low or even no returns on investing funds in the emission control field. This can motivate enterprises to make long-term investments, which plays a promoting role in innovative behavior. Finally, environmental regulations are widely implemented for enterprises, which can create a fair competitive market environment [18]. Moreover, the carbon emissions trading mechanism relies on the market, and the allocation of resources is more flexible and effective, which is undoubtedly more conducive to guiding enterprises towards green technology innovation choices. In general, ETS can promote corporate green technology innovation through a "leverage + crowding out" approach.

This study focuses on the impact of carbon ETS on green innovation in high-carbon enterprises to confirm whether the innovation compensation effect can offset the innovation crowding out effect caused by compliance costs. In other words, aiming at profit maximization, enterprises may adjust their practices in the face of environmental regulations to meet emission standards at lower costs. Thus, environmental regulation may stimulate innovation in a particular area. As Levinson and Taylor [19] pointed out, high-carbon enterprises invest more factors in technological research and development after the government adopts environmental regulation. Responding to environmental regulations through a green innovation approach requires that enterprises have sufficient funds to invest in R&D so that they can improve the energy efficiency of their processes and production equipment, or else they must pay the prescribed costs of non-compliance [20,21]. As a market-based environmental regulatory tool that stimulates the advanced and pushes the backward, the carbon ETS is equally applicable, leading to the following hypothesis:

H1. The carbon ETS can effectively promote high-carbon enterprises to promote green innovation.

3.2. Heterogeneity of the Impact

Generally, it is recognized that the higher the quality of a firm's innovation, the more competitive advantage it has in the marketplace [22]. However, considering that it takes time for enterprises to adjust their innovation strategies, enterprises can carry out appropriate technological application innovation within the existing technological framework in the short term. This can not only avoid the uncertainty risk brought by original technological innovation, but also enable enterprises to enjoy the innovation compensation effect brought by application innovation more quickly [23]. This adjustment of innovation strategy may be different for different enterprises, thus the impact effect of ETS on enterprises' green innovation differs between different types of enterprises [24]. This leads to Hypothesis 2:

H2. The promotion effect of the ETS on green innovation exhibits heterogeneity in different enterprises.

The differences between enterprises are often reflected in three aspects: capital size, equity concentration, and industry category. As such, the heterogeneity of promotion effect of the carbon ETS on green innovation can also be analyzed in three aspects, i.e., the capital size, the equity concentration, and the industry category.

Firstly, capital size of an enterprise not only reflects the enterprise's production scale, but also represents the difficulty of its endogenous and exogenous financing [25]. The resource dependence theory suggests that organizations form a demand for external resources, establish connections with the outside world, and thus obtain resources from the outside world. The stronger this demand, the closer the connection between the organization and the outside world. Enterprises with larger capital scales exhibit a stronger capacity for obtaining external financing. Sufficient capital can greatly enhance the enterprise's ability to resist risks, and the close connection with the external market enables it to accelerate the pace of its own technological progress. In this way, enterprises can maintain a comparative advantage in fierce market competition and obtain excess profits. In contrast, enterprises with smaller capital scales may face tight financial constraints and be unable to withstand the risks associated with R&D failures [26]. Moreover, small capital scale enterprises generally still be in the phase of increasing returns to scale. Instead of investing their funds in technology innovation with uncertain outcomes, it is optimal for them to expand their production scale. Therefore, the following hypothesis is proposed in this study:

H2a. The implementation of carbon ETS has a more significant promoting effect on the green innovation level of enterprises with larger capital scales.

Secondly, according to the principal-agent theory, differences arise between company operators and investors in major aspects related to the long-term development. For example, due to conflicting interests and information asymmetry, the business decisions often have differences. The concentration of corporate equity reflects this principal-agent relationship. Specifically, when the concentration of equity in a company is low, company managers have to accept external supervision from multiple parties. They often adopt aggressive strategies to enhance the company's value, thereby attracting more individual and institutional investors [27]. With the gradual increase in equity concentration, controlling shareholders tend to maximize their own interests by encroaching on the interests of other minority shareholders. There is even a motivation to "empty" the assets of listed companies that attract investors, creating a so-called "trench defense effect" [28]. Therefore, this study believes that companies with lower equity concentration have more open, transparent, and diversified corporate governance pattern. This can increase their investment in green technology and significantly increase green innovation when implementing the carbon ETS. Conversely, companies with relatively higher equity concentration are more dependent on

the decisions of management representatives, who represent the interests of major shareholders. They are more focused on short-term interests rather than long-term development, it is improbable that these companies will embark on green innovation endeavors due to the existence of the ETS. As such, we propose the following hypothesis:

H2b. The implementation of ETS has a more significant promoting effect on the green innovation level of enterprises with lower equity concentration.

Thirdly, low-carbon green production should not only be implemented in every product and every industrial process, but also from the source and throughout the entire industrial chain of production. As production methods and energy use may vary among industries and enterprises, the emission reduction methods may vary greatly among different industries and the aspects of innovation may also differ [29]. The ETS policy has different effects on green innovation incentives among different industries, which puts forward new requirements for policy strength and schemes in different industries. Therefore, this study believes that even in the pilot enterprises, there exists industry heterogeneity in the promotion effect of ETS on green innovation. As such, this study proposes the following hypotheses:

H2c. The implementation of ETS has different promoting effect on the green innovation level of enterprises in different industries.

4. Research Design and Sample Selection

4.1. The PSM-DID Method

This study focused on the impact of carbon ETS on green innovation in high-carbon enterprises, aiming to investigate the change in the green innovation level of enterprises before and after the implementation of ETS. In reality, however, there are no two identical companies, one that implements ETS policies and the other that does not. The difference in difference (DID) method divides the target enterprises into a treatment group and a control group by constructing a quasi-natural experiment [30]. The control group is used to simulate the situation of enterprises in the treatment group without implementing ETS, which is to solve the problem of "counterfactual". Meanwhile, the DID method requires the selection of the experimental sample is randomized. However, the selection of pilot provinces, cities, and emission control enterprises in China is not random, but closely related to regional development level, carbon emission level, and the characteristics of the enterprises themselves. Therefore, using DID alone to estimate the average processing effect cannot meet the framework of counterfactual reasoning models. This might lead to serious sample selection bias and endogeneity problems [31]. Propensity Score Matching (PSM) is to replace multiple covariates with a single score, thereby achieving balance in the distribution of these covariates across the treatment and control groups [29]. This can perform a randomized equilibrium treatment on confounding factors in non-randomized studies to reduce selection bias.

In addition, with the continuous development of ETS, there are differences in the processing time points among enterprises participating in ETS. The traditional PSM-DID with a single processing time point is not applicable here. As such, referring to Liu and Liu [29], this study constructs a year-by-year PSM-DID method to estimate the actual treatment effect of ETS policies on enterprises' green innovation. Based on the theoretical analysis mentioned earlier, a fixed-effects model should be used, the benchmark regression model is as follows:

$$\ln(Patent)_{it} = \alpha + \beta ETS_i \times Period_t + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (1)$$

where i and t represent the company and the year, respectively. The logarithm of the number of green patents $\ln(Patent)_{it}$ is the explained variable, representing the green innovation level of company i in year t; α represents the constant term in the regression; the interaction

term $ETS_i \times Period_t$ represents the explanatory variable of policy implementation or not; and its fitted regression coefficient β reflects the impact effect of ETS policy on green innovation; Z_{it} represents the matrix of relevant control variables, which contains scale, profit, management, and maturity.

Among them, the enterprise scale is reflected by the size of capital (logarithm of the net assets, lnK) and employees (logarithm of the number of employees, lnL); profit is described by book value per share (BPS) and earnings per share (EPS); management is described through shareholding ratio of major shareholders (SR) and leverage ratio (LR); maturity is mainly reflected by the age of the enterprise (Age) and Tobin q value (TobinQ). Specifically, TobinQ mainly reflects the relationship between the market value of enterprise assets and their replacement costs. It is an important indicator for measuring whether a company's market value is overvalued or undervalued. The parameter of γ represents the fitted regression coefficient matrix of each control variable, μ_m, v_n and ν_t represent the fixed effects of region, industry and year, respectively. Meanwhile, ε_{it} is a random disturbance term that varies with individual and time.

4.2. Samples and Data Description

Given the ETS pilot policy's implementation timeframe primarily spanning 2013–2016, this research opted for a sample period spanning 2010 to 2019. Post-2019 data were deemed unsuitable due to the unforeseen disruptions caused by the global COVID-19 pandemic in 2020, which introduced unpredictable external factors affecting enterprises worldwide [32]. On the other hand, in 2010, the world gradually emerged from the impact of the US subprime crisis and the European debt crisis, and the production and operation of enterprises gradually returned to normal [33]. Therefore, the period from 2010 to 2019 is a reasonable and acceptable research time interval.

The carbon emission trading market in our country is mainly established on the basis of five major industries, namely: mining industry (S1), manufacturing industry (S2), electricity, heat, gas and water production and supply industry (S3), construction industry (S4), and transportation, warehousing and postal industry (S5). And these industries include enterprises participating in the pilot program, so we selected panel data of A-share listed companies in five high-carbon industries as the research field. During the preliminary screening of sample companies, we excluded listed firms exhibiting financial irregularities, including those marked with ST, PT, and *ST status, to ensure data integrity and reliability. In addition, companies with severe missing variables, delisted from the stock exchange during the study period, as well as those listed after 2006, were also excluded to maintain consistency in the sample and ensure comparability across firms. Although some financial and service enterprises are also included in the list of emission control enterprises, their production and emission reduction models differ greatly from traditional high-carbon enterprises and are not suitable for discussion together. After the above screening, the final dataset of this study includes 19,280 samples from 1928 listed companies from 2010 to 2019. Of which, the treatment group comprises 1260 samples sourced from 126 listed companies.

The number of green patents data is downloaded and classified from the Inco-Pat patent database. The other data of control variables mainly come from the Wind and CSMAR databases. The explained variable and the enterprise scale related control variables (net assets and the number of employees) have been logarithmically treated to reduce the possibility of covariance and heteroscedasticity. Table 1 shows the descriptive statistical results of the sample.

Table 1. Descriptive statistics of samples.

Variables	Non-Pilot Enterprises (N = 18,020)				Pilot Enterprises (N = 1260)			
	Mean	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
ln(Patent)	0.31	0.75	0.00	2.71	0.56	2.29	0.01	2.77
BPS	5.04	9.14	0.01	19.32	5.37	1.99	0.01	18.63
EPS	1.06	1.00	0.01	5.99	0.97	1.00	0.01	5.46
SR	36.17	16.61	8.26	76.13	39.61	17.29	7.66	65.33
lnL	8.10	1.49	2.56	15.85	9.27	1.61	2.56	16.46
lnK	22.33	1.67	18.29	26.59	23.11	2.59	17.66	25.33
Age	24.02	5.85	9	43	31.25	5.14	10	42
LR	51.39	115.91	37.89	150.63	50.55	24.00	36.55	127.86
TobinQ	3.58	13.56	0.15	8.96	5.13	0.81	0.16	7.98

5. Empirical Research Results and Analysis

5.1. Baseline Regression Analysis

This study conducted a multi-period PSM on enterprises that participated in the pilot program from 2013 to 2016. According to the analysis of the significance of standard deviation and *t*-test, all absolute values of standard deviation were relatively large. Before applying PSM, the *p*-values derived from the *t*-test conducted between the treatment and control groups were strikingly proximate to zero, suggesting the presence of notable disparities in the covariates within the initial dataset. Nevertheless, the biases were significantly reduced and the *p*-values were not significant after PSM. This suggests the null hypothesis that after PSM, no statistically significant difference exists between the treatment and control groups. Consequently, the validity of the Propensity Score Matching process is affirmed. Utilizing panel data spanning from 2010 to 2019 of A-share listed companies across five key industries in China, this study delves into the influence of ETS on fostering green innovation within high-carbon enterprises.

The fixed-effects model can solve the problem of omitted variables that do not change with time or individuals through intra group dispersion information, partially addressing endogeneity issues. Therefore, this study uses the fixed-effects model in the regression model of DID. Due to the carbon ETS being implemented in pilot provinces and cities, targeting some high-carbon industries, macro shocks may mainly come from both provincial and industry levels. In addition, adding fixed effects at the enterprise level may excessively eliminate the differences in the implementation effects of pilot area enterprises [34,35]. Therefore, this study incorporates fixed effects of time province industry into the main regression model. Table 2 presents the results:

Table 2. Results of PSM-DID regression.

Variables	ln(*Patent*) M1-OLS	ln(*Patent*) M2-OLS	ln(*Patent*) M3-Tobit	ln(*Patent*) M4-Wei	ln(*Patent*) M5-Sup
ETS × *Period*	0.1956 ***	0.1401 ***	0.1324 ***	0.1825 ***	0.1936 ***
	(6.0224)	(5.1172)	(2.6850)	(3.6501)	(3.6501)
BPS		0.0104 ***	0.0104 ***	0.0125 *	0.0125 *
		(4.3351)	(4.6774)	(1.6542)	(1.6782)
EPS		−0.0216	−0.0214	−0.0103	−0.0103
		(−1.3312)	(−1.2678)	(−0.0953)	(−0.0953)
SR		−0.0025 ***	−0.0025 ***	−0.0038 **	−0.0038 **
		(−3.7729)	(−3.9858)	(−2.5462)	(−2.5324)

Table 2. *Cont.*

Variables	ln(*Patent*) M1-OLS	ln(*Patent*) M2-OLS	ln(*Patent*) M3-Tobit	ln(*Patent*) M4-Wei	ln(*Patent*) M5-Sup
ln *L*		0.1614 ***	0.1110 ***	0.1615 ***	0.1615 ***
		(18.7646)	(15.0076)	(6.4527)	(6.4527)
ln *K*		0.1008 ***	0.0987 ***	0.1106 ***	0.1107 ***
		(11.4538)	(10.9986)	(4.3386)	(4.3386)
Age		−0.0010	−0.0010	0.0021	0.0021
		(−0.3653)	(−0.3637)	(0.7095)	(0.7095)
Lev		0.0010 *	0.0010 **	0.0013 *	0.0013 *
		(1.3627)	(2.6789)	(1.8802)	(1.8024)
TobinQ		−0.0001	−0.0001	−0.0365 *	−0.0365 *
		(−0.1028)	(−0.3846)	(−1.9906)	(−1.9906)
Constant	0.5266 ***	−2.3687 ***	−2.3672 ***	−3.1416 ***	−3.2456 ***
	(9.3406)	(−15.6028)	(−18.3651)	(−8.1090)	(−9.001)
Adj R^2	0.1106	0.1835	-	0.2302	0.2302

Note: the values in parentheses are t-values; *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

As shown in Table 2, different methods were applied to estimate the results. The coefficient of the policy interaction term $ETS_i \times Period_t$ is significantly positive under different methods, indicating that ETS has an increasing effect on the green innovation of high-carbon enterprises. This verifies the conjecture of Hypothesis 1 and the rationality of the theoretical derivation in H1.

In Column (1), there is no control variable added to the OLS regression model but after the three levels of fixed effects were controlled. Its coefficient of the interaction item was the largest among Columns (1)–(3), which may be due to the omission of important variables. So we added the eight control variables mentioned above in Columns (2)–(5). In Column (2), the coefficient of the DID estimator revealed that the green patents of the regulated industrial firms increased by 14.01% as compared with the non-pilot industrial firms. Among all control variables, size of capital (ln *K*), size of employees (ln *L*), book value per share (*BPS*) showed significant positive correlations with the green innovation of the enterprise. This indicates that, under the environmental regulation policies, some differential factors related to the enterprise itself have been effectively controlled. This result is consistent with the research by Hang et al. [36], that is, the size of the firm will amplify its impact on the output of green innovation.

Meanwhile, Column (2) shows that the shareholding ratio of the major shareholders inhibited the improvement of green technological innovation. A possible reason is that enterprises with a high SR tend to leave decision-making in the hands of a few top leaders, and therefore it is a smarter choice to purchase high value-added fixed assets rather than increasing R&D investment in the long term. Column (3) shows the results of a Tobit model used to estimate the effects of the ETS on a firm's green patents because the values of the dependent variable are mostly zero. This estimation result is roughly consistent with the OLS estimation. In Column (4), we refined the sample by excluding instances with zero matching weights, retaining only those with non-zero weights. Conversely, in Column (5), we augmented the sample by expanding the pool to include cases where the matching weights exceeded unity. Across both approaches, the empirical findings consistently demonstrated that the implementation of the ETS pilot policy had a markedly positive impact on promoting green technological innovation within industrial enterprises.

5.2. The Robustness Test

5.2.1. The Parallel Trend Test

The validation of the parallel trend assumption test for the estimated results of the model is noteworthy. This indicates that prior to policy implementation, pilot and non-pilot enterprises followed similar trends in green innovation development, thereby confirming

the validity of employing the PSM-DID model. This lends credibility to the analytical approach used and enhances the robustness of the findings regarding the effects of the ETS on green innovation development. The following regression model can be used to estimate whether exist the parallel trends between the treatment and control groups:

$$\ln(Patent)_{it} = \alpha + \sum_{k=-6}^{6} \beta_k \cdot DID_{it}^{k} + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (2)$$

where DID_{it}^{k} is a series of dummy variables indicating whether the policy has occurred or not. The coefficient β_k for each year is the dynamic effect of the policy, and its significant change trend is the focus of this article. The specific results are shown in Table 3:

Table 3. The parallel trend test for the whole sample.

Period	ln(*Patent*) M3-Tobit		ln(*Patent*) M4-Wei		ln(*Patent*) M5-Sup	
	Coefficients	**t-Values**	**Coefficients**	**t-Values**	**Coefficients**	**t-Values**
Before-6	0.0324	−0.8628	0.0324	−0.8637	−0.0281	−0.3157
Before-5	0.0745	−1.0004	0.0745	−1.0982	0.0094	−0.1615
Before-4	0.0586	−0.9272	0.0586	−0.9174	−0.0092	−0.1146
Before-3	0.0701	−1.0795	0.0701	−1.1864	0.0201	−0.1494
Before-2	0.1473 **	−2.6373	0.1473 **	−2.663	0.0801	−1.3992
Before-1	0.1389 **	−2.5169	0.1389 **	−2.1617	0.0624	−1.1784
Current	0.1981 ***	−4.07462	0.1981 ***	−4.07968	0.1320 ***	−2.91346
After-1	0.1811 ***	−3.45642	0.1811 ***	−3.45103	0.1026 **	−2.35202
After-2	0.1364 ***	−3.47578	0.1364 ***	−3.4705	0.1186 **	−2.38326
After-3	0.1526 ***	−3.13467	0.1526 ***	−3.12983	0.1124 *	−2.07614
After-4	0.1226 **	−2.29955	0.1226 **	−2.29603	0.0627	−1.2936
After-5	0.1895 ***	−3.04546	0.1895 ***	−3.04084	0.1131 *	−2.09077
After-6	0.1465 **	−2.53902	0.1465 **	−2.53506	0.0815	−1.6445
Constant	−1.9626 ***	−26.7094	−2.6638 ***	−23.0069	−1.3288 ***	−17.3586
Adj R^2			0.1238		0.1139	

Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 3 presents the regression results of the dynamic effects of the ETS. Based on M3-Tobit and M4-Wei, this study evaluates the dynamic innovation effect of ETS using Tobit model and OLS fixed-effects model, respectively. All other control variables except for employee size (ln *L*) are included, because the employee size statistics in the database are based on the number of employees at a time point, not changing over time. These two regressions have reached similar conclusions, that is, before the implementation of the ETS, there was no significant difference in the level of green innovation between the two groups of enterprises. Meanwhile, in the year of implementation and subsequent years, it became significantly positive at a 5% level. Based on M5-Sup, all the control variables were added to the regression model, and the coefficients are not significant before the pilot projects in various provinces and cities start in batches. This is consistent with the fact. However, the coefficients of After4 and After6 are not significant, which may be due to the innovation activity gradually encounters bottlenecks during this period. In conclusion, the results presented in Table 3 indicate that the basic model of the ETS on green innovation for high-carbon enterprises has passed the parallel trend test.

5.2.2. The Placebo Test

The above results have made it clear that enterprises participating in the ETS have a relatively higher level of green innovation, which raises the question of whether this difference is gradually emerging based on the implementation of the ETS. Therefore, a placebo test with random years was conducted to reverse verify whether the observed increase in green innovation level occurred after the implementation of the ETS. Considering the

gradual implementation characteristics of ETS, the time point for unified verification is not applicable. Therefore, this article adopts the following strategies for research:

Firstly, we conducted a random sampling simulation on the pilot enterprises. In the sampling process, we randomly selected a year for each pilot enterprise and assumed that this year was the implementation year of the ETS policy.

Secondly, set this year and subsequent years as simulated processing years, within which we assume that the enterprise has been affected by ETS. And the years before this year are considered as simulated unprocessed years, assuming that the enterprise has not been affected by ETS during these years.

Thirdly, based on this division, we constructed a new policy time dummy variable to simulate the potential impact of ETS on enterprises at different time points. To ensure the reliability and non-accidental nature of the simulation, this experiment was conducted 500 times, and the kernel density and *p*-value distribution of each estimated coefficient are shown in Figure 1 below.

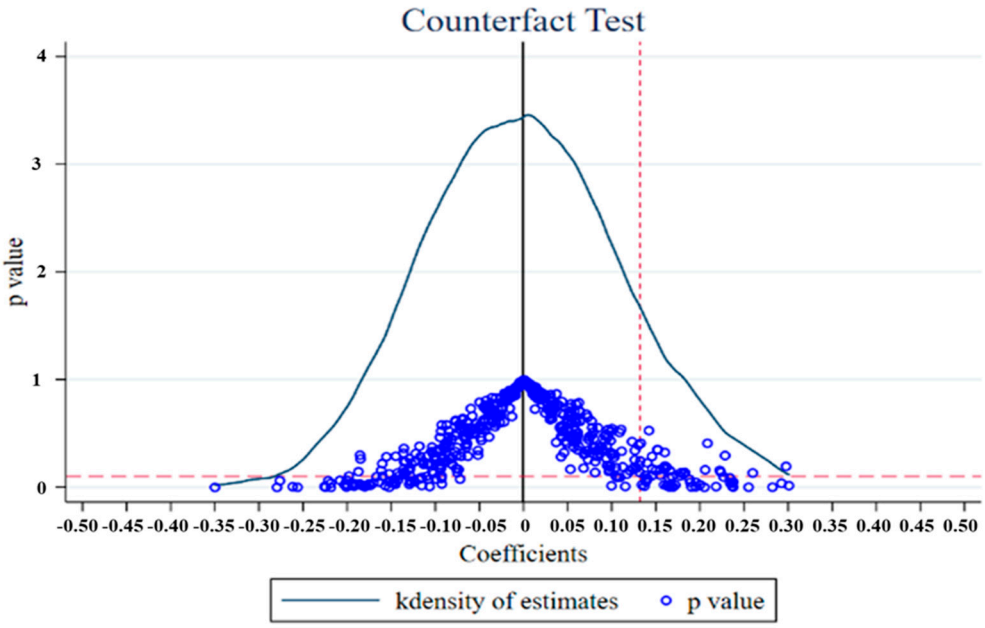


Figure 1. Results of the placebo test.

As shown in Figure 1, the vertical dashed line at x = 0.1401 signifies the actual estimated coefficient derived from the baseline regression analysis utilizing the M2-OLS methodology. The horizontal dashed line at y = 0.1, on the other hand, denotes the threshold for statistical significance, as indicated by the *p*-value boundary. From the regression results of 500 simulations, Figure 1 shows that the results estimated by the randomized year placebo test are significantly different from the actual estimated coefficient, and most of the *p*-values represented by the small circle are above 0.1. The above results indicate that the selection of occurrence time nodes for ETS in the basic study is not accidental, strengthening the robustness of the estimated results.

5.2.3. The Instrumental Variable Method Test

Because the selection of carbon emission trading pilot areas may be affected by other potential factors, which may interfere with the estimation results, the existence of random disturbance terms may make the estimation results inaccurate. In order to further overcome the influence of endogeneity, this study uses the instrumental variable method to deal with the endogeneity problem. The selection of effective instrumental variables needs to satisfy two conditions that are related to endogenous variables but not to random perturbation terms.

Following the idea of Zhang and Xi [35], this study chooses air circulation coefficient as the instrumental variable for implementing ETS pilot policies. The reason is that: firstly, when the total amount of carbon emissions is constant, the smaller the air circulation coefficient in an area, and the higher concentration of carbon dioxide. Therefore, environmental departments are more likely to choose high-carbon emission areas as pilot areas. Thus, this instrumental variable satisfies the assumption of correlation. Secondly, the air circulation coefficient is determined solely by meteorological and geographical conditions and is unrelated to random disturbances. Hence, this instrumental variable satisfies the assumption of exogeneity. The air circulation coefficient is represented by the product of wind speed and boundary layer height for each unit. Based on the atmospheric quantity model, this study constructs variables for air mobility indicators at the prefecture level in China.

As shown in Table 4, column (1) presents the first stage regression results of instrumental variables, where *iv* represents the natural logarithm of the annual mean air circulation coefficient of the city where the industrial enterprise is located. The coefficient of the interaction term $iv \times Period$ is significant, indicating a high correlation between instrumental variables and policy variables. In the second stage regression, the coefficient of the interaction term between the fitted policy variables is also significant, and it is almost consistent in direction and magnitude with the innovation effect of ETS policy in the benchmark regression, which is 14.01%. This indicates that after eliminating the endogeneity problem of non-random factors in policy selection, ETS policy can still significantly promote the improvement of green innovation level in industrial enterprises, which further verifies the robustness of the benchmark regression results.

Table 4. Results of the instrumental variable method test.

	ETT* × *Period **(1)**	**ln(*Patent*)** **(2)**
$iv \times Period$	0.0716 *** (163.0028)	
$ETS \times Period$		0.1422 *** (4.5687)
Constant	−0.0066 (−0.3125)	−1.3258 *** (−27.1628)
Time fixed effect	Y	Y
Province fixed effect	Y	Y
Industry fixed effect	Y	Y
Control variable	Y	Y
Adj R^2	0.4954	0.1343

Note: the values in parentheses are t-values; *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

5.3. Heterogeneity Analysis

The effects of ETS pilot programs may vary in practice for different companies. This study focuses on the characteristics of companies implementing ETS pilot programs, and study the differences in green innovation strategies among different types of companies based on three factors: capital size, equity concentration, and industry category. Following the idea of moderating effects, the interaction terms between heterogeneity variables and policy variables are constructed and put into the model for regression. Grouping all samples for regression analysis, rather than performing regression analysis on a subset of samples, can help eliminate inconsistencies in regression estimates and make the regression results more convincing. Therefore, in order to test the heterogeneous impact of ETS on the green innovation of different enterprises, namely the theoretical H2 proposed above, we construct heterogeneous research models as follows:

$$\ln(Patent)_{it} = \alpha + \beta_1' ETS_i \times Period_t + \beta_2' k_i \times ETS_i \times Period_t + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (3)$$

$$\ln(Patent)_{it} = \alpha + \beta_1'' ETS_i \times Period_t + \beta_2'' sr_i \times ETS_i \times Period_t + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (4)$$

$$\ln(Patent)_{it} = \alpha + \beta_1''' IndB \times ETS_i \times Period_t + \beta_2''' IndC \times ETS_i \times Period_t + \beta_3''' IndD \times ETS_i \times Period_t + \beta_4''' IndE \times ETS_i \times Period_t + \beta_5''' IndG \times ETS_i \times Period_t + \gamma Z_{it} + \mu_m + v_n + \nu_t + \varepsilon_{it} \quad (5)$$

where k is a grouping variable representing the capital scale in Equation (3), with $k = 1$ representing a larger scale of corporate capital, higher than the median of all corporate capital scales, and $k = 0$ representing the remaining enterprises. The variable of sr represents a grouping variable for corporate equity concentration in Equation (4), measured by the shareholding ratio of major shareholders, also using the median shareholding ratio of major shareholders as the division standard. The term $sr = 1$ represents a company with lower equity concentration and more diversified corporate governance, while $sr = 0$ represents a company with more centralized corporate governance. In Equation (5), $IndB$, $IndC$, $IndD$, $IndE$ and $IndG$ respectively represent the five major national economic sectors involved in the research sample companies.

As such, in Equation (3), β_1' represents the magnitude of the increase or decrease in the level of green innovation in enterprises with lower capital scale under the influence of the ETS. If β_2' is significantly different from zero, it indicates that under the ETS, the level of green innovation varies among enterprises with different capital scale levels. The explanation of sr in Equation (4) is similar. In Equation (5), the policy interaction term was divided into five interaction terms according to the classification of national economic industries, representing the green innovation effects of ETS in the five industries. The coefficients in front of each term represent the magnitude of the increase or decrease in the level of green technology innovation in the industry under the influence of the ETS. The coefficients (i.e., β_1''', β_2''', β_3''', β_4''', and β_5'''), respectively, represent the extent to which the green innovation level of enterprises in the corresponding industry has increased or decreased under the action of ETS pilot policies. The regression results are shown in Table 5:

Table 5. Heterogeneous effects of ETS pilot policy on green innovation.

Variables	ln(*Patent*)	ln(*Patent*)	ln(*Patent*)
$ETS \times Period$	−0.2081 ***	0.1001	
	(−4.073)	(1.2483)	
$k \times ETS \times Period$	0.3962 ***		
	(8.2452)		
$sr \times ETS \times Period$		0.2031 ***	
		(5.7261)	
$IndB \times ETS \times Period$			3.1594 ***
			(12.0456)
$IndC \times ETS \times Period$			0.3390 ***
			(3.4855)
$IndD \times ETS \times Period$			0.1801 *
			(0.1743)
$IndE \times ETS \times Period$			0.4833 **
			(3.0813)
$IndG \times ETS \times Period$			−0.4410 ***
			(−3.8460)
Constant	−0.6962 ***	−3.1415 ***	−2.2151 ***
	(−15.2431)	(−13.9124)	(−15.7623)
Adj R^2	0.1536	0.1522	0.1304

Note: the values in parentheses are t-values; *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

From the perspective of capital scale heterogeneity, enterprises with different capital scales often have different responses to innovation even when facing the same environmental regulation system. As shown in Table 5, the estimated coefficient values of β_1' and β_2' in Equation (3) are −0.2081 and 0.3962, respectively, and both have passed the 1% significance test. This indicates that enterprises with lesser capital tend to curtail their green innovation endeavors by approximately 20.81% as a means to comply with emission reduction targets, whereas those with ample capital exhibit significantly different behavior patterns in this regard. When facing the ETS, large enterprises tend to carry out 39.62% more green innovation than small enterprises. This means that under the pressure of market-oriented environmental regulations, large enterprises can choose to strengthen 18.81% of green innovation on their own, rather than purchasing emission quotas. On the one hand, large enterprises demonstrate strong mortgage guarantee capabilities through their sound financial management system, which greatly promotes the diversification of their financing channels and significantly enhances their ability to diversify and resist innovation risks. On the other hand, large enterprises have gained strong bargaining power in the supply chain due to their economies of scale and market dominance, further consolidating their market influence. In contrast, small-scale companies are often unwilling to increase their green innovation investment in order to alleviate financial and cost pressures. This result further suggests that implementing ETS for enterprises with larger capital scales is more conducive to the generation of green innovation, and the innovation compensation effect can be achieved. However, for enterprises with small capital scales, the compliance costs are too high, resulting in a crowding-out effect of green technology innovation.

From the perspective of equity concentration heterogeneity, enterprises with different equity concentration often have different responses to innovation even when facing the same environmental regulation system. As shown in Table 5, the estimated coefficient values of β_1'' and β_2'' in Equation (4) are 0.1001 and 0.2031, respectively. This means the ETS pilot policy has promoted green innovation in 10.01% and 20.31% of companies with higher and lower equity concentration, respectively. Specially, companies with low equity concentration are more inclined to invent green innovation, with a 10.30% increase in green innovation output compared to companies with high equity concentration companies. Companies with high equity concentration, the division of labor and checks and balances within the governance layer are not clear or superficial. The power holders may only rely on their own judgment of current environmental regulation policies to adjust production scale, which may underestimate the long-term benefits of green technology innovation. In contrast, companies with low equity concentration have a relatively significant modular division of labor, which reduces the degree of information asymmetry and eases the relationship between delegation and agency. In the process of strategic choice, companies with low equity concentration tend to have a longer-term perspective and may place more emphasis on the importance of green technology innovation.

In the context of industrial heterogeneity, it is evident that various industries possess distinct production methodologies and strategies for achieving emission reductions, each tailored to their unique circumstances. Table 5 shows the detailed impact of ETS on green innovation in five major industries. In S1, S2, and S4, ETS has played positive roles in stimulating green innovation to some extent. There is no significant change in green innovation in S3, while in S5, after implementing ETS, green innovation level has actually decreased. Specially, S1, S2, and S4 are all high-carbon-emitting industries, accounting for more than 70% of the nation total CO_2 emissions. A larger emissions volume naturally requires more green emission reduction technologies to achieve the goal of carbon emission reduction. Otherwise, only expensive quotas or production cuts can be purchased, which brings considerable costs and consequences. This creates a virtuous cycle in innovation input-output for these industries. The poor green innovation effect of the ETS policy in S3 may be due to nearly half of the industry's innovation expenditure being directed towards the procurement of machinery, equipment, and software, rather than internal research and development. On the contrary, the ETS has had a negative impact on the green innovation

of S5. This is because the industry mainly relies on advanced transportation equipment and reasonable scheduling to save energy and reduce emissions, thus performing poorly in green technology innovation.

With limited financial resources, companies divert spending that would otherwise have been spent on innovation into the acquisition of machinery and software, thereby reducing long-term investment in green technology research and development and innovation. This "crowding out" effect of capital allocation causes resources that might otherwise be used for green technology innovation to be replaced by other more urgent expenditures, thus inhibiting the green technology progress of enterprises in related industries. Therefore, on the one hand, the government should encourage and support enterprises to obtain funds through diversified financing channels, so as to reduce the financial pressure of enterprises and make them have more resources to invest in green technology innovation. On the other hand, further improve the carbon trading market mechanism to ensure fair, transparent and efficient operation of the market. Through reasonable carbon price signals, enterprises are guided to actively carry out energy conservation and emission reduction and green technology innovation, and achieve a win–win situation of economic and environmental benefits.

6. Conclusions and Limitations

6.1. Conclusions

Green technology innovation is an important driving force for low-carbon development of enterprises. As a market-based environmental policy to promote greenhouse gas emission reduction, whether carbon emission trading scheme (ETS) can encourage enterprises to carry out green technology innovation deserves further study. Utilizing a comprehensive dataset of Chinese A-share listed companies spanning five key sectors from 2010 to 2019, this study employs a multi-period PSM-DID model to rigorously examine the causal nexus between ETS and green innovation within high-carbon industries. Additionally, a nuanced heterogeneity analysis is undertaken, delving into the differential impacts across three pivotal dimensions: capital intensity, equity concentration, and industrial classification. The core findings of this study are succinctly encapsulated as the following two aspects:

Firstly, the ETS has a significant promoting effect on green innovation in high-carbon enterprises, with an increase of 14.01% even after adding control variables at the enterprise level. In addition, under different regression methods, the results are consistent. In order to further test the robustness of the results, this study adopts the parallel trend test, the placebo test of random years, and the instrumental variable method test. The above tests showed that ETS has indeed a significantly positive impact on green technology innovation of high-carbon enterprises. That is to say, the innovation compensation effect considered in Porter's hypothesis does exist in enterprises implementing ETS, and the effect of innovation compensation effect is greater than that of innovation crowding-out effect.

Secondly, enterprises with different characteristics have heterogeneity in the impact of ETS implementation on green technology innovation. Specifically, enterprises with smaller capital scales have reduced some green innovations when subjected to market-oriented environmental regulation policies, while enterprises with larger capital scales have increased their output of green innovation. The level of green innovation in enterprises with lower equity concentration is significantly better than that in enterprises with higher equity concentration. Moreover, the green innovation effect of ETS is also diverse in different industries. In S1, S2 and S4, ETS has positive stimulating effects on green innovation to a certain extent. Moreover, there is no significant change in green innovation in the S3. However, the S5, on the other hand, experienced a decrease in green innovation after ETS implementation.

After clarifying the transmission mechanism and the impact of ETS on enterprises' green innovation, this study puts forward the following policy recommendations.

Firstly, due to the fact that ETS can effectively promote high-carbon enterprises to promote green innovation. Regulated enterprises should consolidate their market competitiveness through green innovation, promptly and precisely adjust their development strategies and positioning, and transform their previous disadvantage of high emissions into the advantage of green production. For instance, such enterprises can actively shift to industries with low pollution and emissions, e.g., renewable energy. For enterprises that are not under the supervision for the time being, they should learn from the advanced green technologies of industry leaders, actively participate in the ETS market. Through attracting external investments, they should promote a transition towards more advanced and resource-saving production modes. Furthermore, they should actively seek cross-regional cooperation with enterprises in different regions to strengthen the regional spillover effect of green technologies, thereby making the positive impact of green technologies more extensive and profound.

Secondly, due to the fact that the promotion effect of the ETS on green innovation exhibits heterogeneity in different enterprises. For different types of enterprises, practical and feasible green technology innovation solutions should be proposed to cope with ETS policies, rather than a one size fits all approach. In industries such as mining (S1), manufacturing (S2), and construction (S4), the coverage of ETS should be further expanded to maximize the proactive role of these enterprises in green innovation. For enterprises in naturally monopolistic industries like electricity, heat, gas, and water production and supply (S3), they can increase investment in green innovation by applying for government policy support, such as tax incentives and green innovation funds. For enterprises in transportation, warehousing, and postal services (S5), due to their apparent innovation crowding-out effect, staff should be provided with training related to carbon accounting to gain insights into their production processes and energy consumption. This will enable them to formulate mid-to-long-term carbon emission plans. In the short term, enterprises should ensure that their carbon emissions match the quotas allocated by the government; in the long term, they should strive to achieve additional revenue by selling quotas. Meanwhile, when making strategic choices for green innovation, enterprises need to further improve the equity allocation system, and reduce the agency problems caused by information asymmetry.

6.2. Limitations

This study takes enterprise heterogeneity as the starting point to analyze whether EST can promote green innovation in high-carbon industries and its impact mechanism. However, there are still some limitations. Due to the lagging nature of policy effects and limitations in data, this study did not explore the impact of policy lag on green innovation. With further improvement of data in the future, the impact of policy lag on corporate green innovation should also be explored and studied. At the same time, due to the availability of corporate data, the analysis of corporate heterogeneity in this study is not very comprehensive. In the future, we will continue to collect data at the enterprise level to explore the impact mechanism of EST on green innovation and the impact of enterprise heterogeneity from more dimensions.

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