Frontiers in Business, Economics and Management
ISSN: 2766-824X | Vol. 10, No. 1, 2023

Carbon Emissions Trading and Corporate Green Technology Innovation

-- Empirical Evidence from Chinese Listed Companies

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Abstract: Green technology innovation is the cornerstone of achieving green and high-quality development and an important guarantee for China to achieve the goals of "carbon neutrality" and "carbon emission reduction". As a market-oriented environmental policy, the carbon emission trading policy can affect the behavior of enterprises, and its impact on green technology innovation of enterprises deserves in-depth study. Based on the green patent data of A-share listed companies from 2008 to 2021, taking the carbon trading pilot policy as a quasi-natural experiment, this paper establishes a multi-point difference-in-differences model to explore the impact of carbon trading policy on green technology innovation of enterprises and discusses the regulatory role from the perspective of the carbon price, carbon market liquidity, and carbon market size. Finally, we also conduct a heterogeneity analysis based on the differences in the micro-characteristics of enterprises. The results show that the carbon trading policy significantly promotes the green technology innovation activities of enterprises; The role of carbon emission rights in facilitating enterprises to expand their green technology innovation is stronger for those with higher carbon price, as well as larger carbon trading scale. The market mechanism measured by the liquidity of the carbon market partially explains the promotion role of green technology innovation. Further heterogeneity analysis shows that the promotion effect of carbon trading policy on green technology innovation is mainly reflected in non-high-tech enterprises, low-carbon enterprises, and enterprises with high internal control quality. Therefore, we should give play to the incentive role of the carbon price and carbon trading scale, optimize the design of the carbon market system, provide targeted green innovation support for enterprises, and help to achieve carbon emission reduction and green high-quality development.

Keywords: Carbon emission trading, Green technology innovation, Carbon price, Carbon market liquidity, Carbon trading scale.

1. Introduction

Climate issues, especially global warming caused by greenhouse gases, have become critical to human survival and development, posing a great threat to the sustainable development of the global economy. In recent years, market-incentivized environmental regulation measures have received increasing attention. Since the introduction of the Kyoto Protocol, carbon trading mechanisms have been implemented in several countries (Wang et al., 2011). For example, the European Union developed a carbon trading mechanism and a low-carbon economy, and the carbon cap-and-trade mechanism in the U.S. was first implemented in Chicago, followed by the establishment of state-level carbon trading markets. In 2011, China also announced carbon emissions trading pilots in seven provinces and cities, including Beijing, Shanghai, Tianjin, Chongqing, Guangdong, Hubei, and Shenzhen, and officially launched the first carbon trading pilot in 2013. At present, China's carbon market has covered more than twenty industries such as electricity, cement, and steel. A growing number of empirical studies have shown that carbon markets have great potential to promote industrial structure upgrading and carbon emission reduction (Jiang et al., 2021), and thus the carbon emissions trading pilot has achieved the expected results.

In September 2020, the Chinese government made a solemn commitment to the world to achieve "carbon peaking" by 2030 and "carbon neutrality" by 2060. General Secretary Xi has repeatedly mentioned that "both green water and green mountains are needed, as well as golden mountains", and that the goal of "carbon peaking" and "carbon neutrality" should be incorporated into the construction of ecological civilization. In order to promote the high-quality development of "ecological priority and low-carbon", green technology innovation, especially the carbon emission trading mechanism, needs to play a unique role (Yao and Zeng, 2019). Existing literature has explored the relationship between carbon trading policies and corporate green technology innovation from the perspective of quota allocation methods and carbon price signals (Song et al., 2021). However, in addition to carbon price, will indicators of carbon market operation status, such as carbon market liquidity and carbon trading scale, also stimulate firms to engage in green technology innovation? In order to explore the impact of carbon trading policy on enterprises' green technological innovation from a more comprehensive perspective, taking A-share listed companies from 2008-2021 as research objects, this paper uses carbon trading pilot policy as a quasi-natural experiment and treats enterprises included in carbon trading pilot and those not included in carbon trading pilot as treatment and control groups respectively, and constructs a multi-point difference-in-difference model. The study also examines the role of carbon trading policy on enterprises' green technological innovation and elaborates on the regulation role from a more comprehensive perspective of carbon market mechanism, including carbon price, carbon market liquidity, and carbon trading scale, and finally analyzes the heterogeneity by differences in enterprises' micro characteristics.

2. Literature Review

2.1. The connotation of green technology innovation and its influencing factors

Green technology innovation is an important part of technological innovation. Traditional innovation is mainly to bring economic benefits to enterprises, while green technological innovation emphasizes the unity of economic and environmental benefits. Regarding the connotation of green technological innovation, Braun and Wield (1994) first proposed that green technological innovation refers to technologies that can improve energy efficiency and reduce environmental pollution; Lv et al. (1994) considered that green production processes, energy utilization, and product output are the carriers of green technological innovation. With the development of the economy and society, the connotation of green innovation has been evolving and enriched. In 2011, based on the goal of sustainable development, the European Commission defined green technological innovation as a major innovation that can avoid, reduce or even eliminate environmental impacts and make more efficient use of natural resources. The European Commission defines green technology innovation as a major innovation that avoids, minimizes, or even eliminates environmental impacts and enables more efficient use of natural resources （Commission of European Union, 2011）.

Factors that influence firms' green technology innovation include both external macro factors and internal micro factors. At the macro level, various factors such as economic, technological, and policy factors can have an impact on green innovation, such as the study by Xu (2012) and others, which showed that the government can drive firms to engage in green technology innovation. Qi et al. (2018) argued that environmental equity trading can induce green innovation in polluting industries by the triple difference method. lv et al. (2021) found that the degree of financial development can promote green innovation by examining the relationship between financial development and green technology innovation, and environmental regulation plays a positive moderating role in it. From the public perspective, Qin (2022) concluded that public participation and environmental regulation can influence corporate green innovation when combined. At the micro-firm level, internal factors such as the level of digitalization, corporate social responsibility, and firm size can have a significant impact on green technology innovation (Xu et al., 2022). Song et al. (2022) used a sample of listed companies in the heavy pollution industry and found that the digitalization of heavy polluting firms can significantly promote their green technology innovation, while Yang (2022) explored the impact of corporate social responsibility on green technology innovation and found that internal social responsibility can promote green innovation, while external social responsibility can inhibit green innovation.

2.2. Environmental regulation and green technology innovation

With the deterioration of environmental problems, the relationship between environmental regulation and technological innovation has become one of the hot issues studied by scholars. Regarding the impact of environmental regulation policies on firms' technological innovation, existing studies are mainly divided into two views. One is based on the traditional neoclassical theory, which takes a static perspective and argues that under the assumptions of constant technology level, resource allocation and consumption demand, environmental protection, although improving the overall welfare of society, will weaken the level of firms' technological innovation at the cost of increased costs to manufacturers. The excessive costs resulting from environmental protection will hinder the productivity of manufacturers and reduce market competitiveness (Jaffe, 1995). This additional cost, caused by internalizing the negative externalities of corporate pollution, will squeeze out the funds for green innovation, which is known as the "crowding out effect"（Kneller et al. 2012）. Another viewpoint is that environmental regulations increase the production cost of manufacturers, but also have a certain incentive effect on technological innovation, and the famous "Porter hypothesis" is proposed (Porter M, 1991). According to Porter's hypothesis, sound environmental regulations can promote technological innovation (Porter and Linde, 1995). Strict and appropriate environmental regulations can force enterprises to make more green innovations in energy conservation and environmental protection, which is manifested as a "compensating effect" and improves the productivity and market competitiveness of enterprises.

2.3. Carbon trading policy and green technology innovation

Early studies on carbon trading policies mainly focused on the European Union Emission Trading System (EU ETS). Calel (2016) studied the impact of carbon trading on corporate green technology innovation in the EU carbon market and showed that the level of green technology innovation in carbon trading covered companies increased by 10%. Qi and Zhang found that in the first phase of the EU ETS, which was dominated by the historical method, renewable energy technology innovation in member countries was significantly insufficient. Hasan et al. (2021) developed a model under the carbon tax, cap-and-trade, and carbon cap regimes and found that under the carbon cap regime, the profits gained by firms were proportional to the investment in green technology innovation.

Research on carbon trading systems in China has only begun in recent years, and studies on the impact of carbon trading policies on green technology innovation begin to increase.

Chen et al. (2021) find that Porter's "weak" hypothesis is not fully realized in the carbon market, and the pilot carbon trading policy inhibits green innovation, and this inhibition is a lagged effect; Zhang et al. (2022) found that carbon trading policies squeeze out R&D investment and inhibit green innovation at this stage, but significantly reduce carbon emissions and carbon intensity.

Most studies have shown that carbon trading policy as a market-based instrument can significantly promote green technology innovation of enterprises, and the existing literature mainly elaborates on the mechanism of action from the perspectives of policy expectations, quota allocation methods, and carbon price signaling. Using a synthetic control method, Wang (2020) found that carbon trading in pilot regions can significantly promote low-carbon technology innovation activities from the perspectives of policy expectations and signaling mechanisms (Wang et al.,2019). Song et al. (2021) discuss the impact of carbon emissions trading on enterprises' green technology innovation in terms of allowance allocation methods, and conclude that the benchmark method has a stronger incentive effect on enterprises' green innovation activities, and is conducive to motivating enterprises with more green innovation accumulation in the early stage to engage in green innovation activities, while the historical method will weaken the motivation of enterprises with higher green innovation level in the early stage to engage in green innovation, resulting in the "whipping the fast cow" effect. Zhu et al. (2019) also elaborate on the impact mechanism from the perspective of quota allocation structure and find that the incentive effect of carbon trading policy on green innovation is more significant for firms with large-scale allocation, which is better than that of firms with ratio allocation.

From the carbon price signaling perspective, L et al. (2019) explore the role and influence of carbon price level in the carbon market and find that a carbon price at a low level cannot bring any significance, and a carbon price with corresponding carbon subsidy policy can play a carbon emission reduction effect and promote enterprises' green technology innovation; Wei et al. (2021) find that carbon emissions trading can significantly promote enterprises' green technology innovation, and this promotion effect is more significant when the carbon price is higher. The carbon price, as a carbon market mechanism, can stimulate the green technology innovation behavior of enterprises, while other indicators to measure carbon market mechanism include carbon market liquidity and trading scale, etc. This paper will explore the regulatory role of carbon price, market liquidity, and carbon trading scale in the process of policy play from three perspectives respectively, and enrich the existing perspective of mechanism elaboration.

3. Theoretical Analysis and Research Hypothesis

Apparently, there are two opposing views of scholars on the relationship between environmental regulation and green technology innovation. Since green technology innovation has "double externalities", i.e., emissions cause negative externalities to society and the environment, while technology innovation generates knowledge spillovers, which are positive externalities. This special nature leads to a lack of incentive for green innovation in the absence of policy intervention. As a result, a growing body of research suggests that various government regulatory tools are considered necessary to promote green innovation (Shao et al., 2020). National policies related to energy and environmental regulation can have a significant positive impact on green technology innovation (Wang and Zhao, 2019), especially the market-oriented environmental regulation policies that have a stronger promotion effect on green technology innovation.

As a market-based environmental regulation measure, carbon emissions trading policy has a reasonable price formation mechanism and a tight government control mechanism, which will promote enterprises' green technology innovation activities in the long run. On the one hand, when enterprises carry out green technology innovation, they can improve energy use and production efficiency, reduce the procurement cost of carbon emission allowances and the production burden of enterprises, and bring excess revenue for those enterprises with surplus carbon emission allowances. This allows companies to have more funds to participate in innovation activities, forming a positive circular development model. On the other hand, carrying out green technology innovation activities can establish a good image for enterprises to take social responsibility. Accordingly, this paper proposes hypothesis 1:

H1: Carbon emissions trading policy can promote green technology innovation of enterprises.

In 2011, the National Development and Reform Commission (NDRC) issued the Notice on the Piloting of Carbon Emissions Trading, and since then carbon emissions trading pilots have been carried out in Beijing, Shanghai, Tianjin, Chongqing, Hubei Province, Guangdong Province and Shenzhen during 2013-2014, with Fujian Province added as a carbon trading pilot in 2016. The establishment of eight pilots also marked the formation of eight carbon markets, so did market mechanisms play a role in the promotion of corporate green technology innovation by carbon trading policies?

Currently, the eight carbon markets are functioning well, and the carbon price, as the core of the efficient operation of the carbon market, reflects the supply and demand of carbon quotas by transmitting price signals to guide enterprises' emission reduction behavior and green innovation decisions (Qi et al., 2020). The existing literature has partially elaborated the mechanism of carbon trading policy from the perspective of carbon price signals, while the number of trading days and trading size of the carbon market can also measure the market mechanism and reflect the operation of the carbon market (Yi et al., 2018). This paper selects the carbon price, the number of trading days in the carbon market, and the scale of carbon trading as indicators of the market mechanism, in order to explore the impact of the operation of the carbon market in promoting green technology innovation from these three aspects in a more comprehensive perspective.

In the case of a high enough carbon price, a high carbon price increases the cost pressure in environmental regulation for enterprises with high marginal abatement costs, thus forcing them to make green technological innovation; for enterprises with low marginal abatement costs, a higher carbon price will drive them to sell carbon quotas for excess profits, so it will also promote their green technological innovation. When the carbon market is inefficient, the number of trading days is reduced, the scale of trading is reduced or even if there is no trading, the demand for carbon quotas is reduced, and the profit space for enterprises to carry out green technology innovation is squeezed, and the willingness of enterprises to carry out green innovation activities is not strong; while when the carbon market is relatively active and the operation is good, the number of trading days and the scale of trading are at a high level, and the willingness of enterprises to sell carbon quotas to obtain excessive returns and carry out green innovation is also increased. Based on the above analysis, this paper proposes hypothesis 2:

H2: The better the carbon market operation, such as the higher the carbon price, the more carbon trading days, and the larger the trading scale, the stronger the promotion effect of carbon trading policy on enterprises' green technology innovation.

Different firms differ in their tolerance of environmental regulations and their reliance on technological innovation due to different micro characteristics, and these micro characteristics will make the impact of carbon emissions trading on their green technological innovation also differ to some extent. In terms of the reliance on technological innovation, high-tech enterprises conduct more frequent technological innovation activities and invest more in technological innovation, and the promotion effect of carbon trading policy on green innovation may be heterogeneous among high-tech enterprises and non-high-tech enterprises. From the perspective of tolerance to environmental regulation, there is a difference in the response to environmental policies between firms with high tolerance and those with low tolerance due to the difference in environmental adjustment costs. From the perspective of the quality of internal control, since the quality of internal control is closely related to management's decision-making, thus different quality of internal control will lead managers to make different technological innovation decisions and affect the green technological innovation of the firm. Therefore, this paper proposes hypothesis 3:

H3: Differences in the micro characteristics of firms, such as the degree of reliance on technological innovation, the degree of tolerance to environmental regulations and the quality of firms' internal controls, result in heterogeneity in the promotion of green technological innovation by carbon trading policies.

4. Research Design

4.1. Sample selection and data sources

At present, most of the industries included in the carbon trading pilot in China are industrial industries, mainly involving eight industries, such as chemical, petrochemical, electric power, non-ferrous, iron and steel, building materials, paper and aviation, etc. Therefore, this paper mainly selects the A-share listed companies in the above eight industries in China from 2008 to 2021 as the research sample, and does the following treatment on the initial sample: exclude ST or PT companies; exclude the sample of companies with missing financial data. Corporate financial status, carbon market information and other related indicators were obtained from the Guotaian database. After screening, a total of 20,100 observation samples were obtained.

4.2. Model Building

The multi-point DID model is a commonly used policy evaluation method, which uses the double difference between cross-sectional and time series generated by exogenous public policies to judge the policy effects. The carbon trading pilot policy can be considered as a quasi-natural experiment, and since the carbon trading pilot is established in batches, this paper adopts a multi-point double difference model, which is constructed as follows:

$$green\_patent_{it} = \beta_0 + \beta_1 DID_{it} + \beta_2 \delta_{it} + \gamma_t + \lambda_r + \varepsilon_{it} \quad (1)$$

In equation (1), the subscript i denotes the firm and the subscript t denotes the year. $green\_patent_{it}$ is the explanatory variable, i.e., the firm's green technology innovation. DID_{it} is the core explanatory variable, $DID_{it} = treat_i \times post_{it}$, $treat_i$ represents the treatment and control groups, $post_{it}$ represents before and after policy implementation. δ_{it} represents a set of control variables that may affect green technology innovation, γ_t represents year-fixed effects, λ_r represents industry-fixed effects, and ε_{it} is the residual term.

4.3. Variable Definition and Description

(1) Explained variable. Denoted by green technological innovation ($green\_patent$). In this paper, we refer to the green technology innovation index construction of Wei (2021) and Zhang (2022) and use the sum of green technology invention patents and green utility model patent applications to represent the green technology innovation level of enterprises.

(2) Core explanatory variable. Carbon emissions trading policy (DID). DID is 1 if the enterprise's region starts a pilot carbon trading in year t, otherwise DID takes 0.

(3) Control variables. Considering that the factors affecting the green innovation of enterprises are both micro-level factors of the enterprises themselves and macro-level regional factors, this paper refers to Qi et al. (2018) to select some economic characteristics indicators at the enterprise level as control variables and Xu et al. (2020) to select some city-level indicators as control variables.

①Enterprise scale. Measured by the total assets of the company, expressed as lnsize after taking the logarithm. ② Age of the enterprise. The age of an enterprise reflects the maturity of the firm, measured by the length of time the firm has been on the market and expressed as lnage after taking the logarithm. ③Social wealth creativity of enterprise. The ratio of the enterprise's asset value to capital replacement cost is the value of TobinQ. The larger TobinQ indicates that the enterprise creates more social wealth, so this indicator is expressed as TobinQ after taking the logarithm, i.e. lnTobinQ. ④Financial leverage for enterprise. Measured as the ratio of total corporate liabilities to total assets, expressed as lev. ⑤ Cash holding ratio. Measured as cash assets as a percentage of total assets, expressed as cash. ⑥Return on Total Assets. Return on total assets is measured by the ratio of a firm's net income to its total assets and is expressed as ROA. ⑦ Enterprise investment level. The investment level of an enterprise is the ratio of cash paid for the acquisition of fixed assets, intangible assets and other long-term assets to total assets, expressed as inv_level. ⑧Relevant control variables at city level. Considering that city-level indicators such as regional openness, regional industrial structure, and economic development level can have an impact on enterprises' green technology innovation (Yu Yongze et al., 2022), this paper also selects urbanization rate, foreign investment share, industrial structure, and fiscal dependence as control variables. Urbanization rate is the ratio of urban household population to total household population, denoted by ur; foreign investment share is the proportion of total foreign investment to GDP, denoted by FDI; industrial structure is the proportion of GDP of secondary industry to regional GDP, denoted by ind_str; fiscal dependence is the ratio of local general public budget revenue to regional GDP, denoted by rely.

(4) Adjustment variables. Carbon trading market mechanism. In this paper, we refer to Wu et al. (2021) to select carbon price, carbon market liquidity, and carbon market size as the moderating variables to measure the carbon market mechanism. Among them, carbon price is the annual average

price of daily closing price, which is expressed by lnprice after taking logarithm; carbon market liquidity is measured by the annual non-zero trading days, which is expressed by lnday after taking logarithm; carbon market size is the total annual trading volume, which is expressed by lnscale after taking logarithm.

The main variables are defined and described in Table 1:

Table 1. Definition and description of main variables

Variable Type	Variable Name	Variable Symbol	Variable Description
Explanatory variable	Carbon Emissions Trading Policy	DID	DID is 1 if the enterprise's region starts a carbon trading pilot in year t, otherwise DID takes 0.
Explained variable	Corporate Green Technology Innovation	$green\_patent$	The sum of the annual number of green invention patent and green utility model patent applications by enterprises
Adjustment variables	Carbon Price	ln price	Logarithm of the annual average of daily closing prices
	Carbon Market Liquidity	ln day	Logarithm of the number of non-zero trading days per year
	Carbon Market Size	$\ln scale$	Logarithmic value of total carbon trading in the year
Control variables	Enterprise Scale	$\ln size$	Logarithmic value of total corporate assets
	Age of the Enterprise	$\ln age$	Logarithmic value of the length of time a company has been listed
	Social wealth creativity of enterprise	$\ln TobinQ$	Logarithmic value of Tobin's q value for the enterprise
	Financial leverage for enterprise	lev	Total liabilities/total assets
	Cash holding ratio	$cash$	Cash assets/total assets
	Return on Total Assets	ROA	Net profit/total assets
	Enterprise investment level	inv_level	Acquisition of fixed assets, intangible assets and other long-term assets/total assets
	urbanization rate	ur	Urban household population/total household population
	industrial structure	ind_str	GDP of the secondary sector / regional GDP
	foreign investment share	FDI	Total foreign investment/regional GDP
	fiscal dependence	$rely$	Local general public budget revenue/regional GDP

5. Empirical Results and Analysis

5.1. Descriptive statistical results of the main variables

Table 2 reports the results of descriptive statistics for the main variables. The mean value of corporate green patents is 9.138 and the standard deviation is 51.51, showing that the level of green technology innovation varies widely among enterprises. The mean value of *DID* is 0.242, indicating that 24.2% of enterprises are included in the carbon trading pilot area. *Price*, *day*, and *lnscale* all have large differences between the maximum and minimum values, indicating that the operation of the carbon market varies widely among different carbon trading pilot regions.

Table 2. Descriptive statistics results

Variables	Sample size	Mean	Standard deviation	Min	Max
DID	20100	0.242	0.428	0	1
green_patent	20100	9.138	51.51	0	1577
lnsize	20100	22.11	1.340	17.64	28.64
lnage	20100	2.781	0.403	0.0136	4.154
lnTobinQ	20100	0.749	0.578	-0.904	4.806
lev	20100	0.420	0.205	0	0.997
ROA	20100	0.0487	0.0622	-0.194	0.969
cash	20100	0.179	0.133	0	0.911
Inv_level	20100	0.0549	0.0486	0	0.504
ur	20100	0.638	0.131	0.219	0.896
FDI	20100	0.0230	0.0142	0.000100	0.121
Ind_str	20100	0.419	0.0836	0.160	0.620
rely	20100	0.112	0.0320	0.0569	0.245
price	4826	33.36	19.63	4.360	91.81
day	399	189.8	47.50	87	244
lnprice	4826	3.330	0.614	1.472	4.520
lnday	399	5.208	0.293	4.466	5.497
lnscale	4826	15.00	1.983	7.863	17.63

5.2. Parallel trend test and analysis of policy dynamic effects

Before applying the multi-point double difference model, a parallel trend test is required to verify whether there are systematic differences among firms before the policy is implemented, and the double difference model can be used only after it is passed. Considering that the timing of the inclusion of carbon trading pilots is not entirely consistent across firms, this paper draws on McGovack's (2020) research framework to test the parallel trend hypothesis using event analysis and to analyze the policy dynamic effects. In this paper, we take the four years before the launch of the carbon trading pilot as the comparison benchmark, and construct the cross-product terms of the year dummy variables and the corresponding policy dummy variables three years before, at the launch, and five years after the launch of the carbon trading pilot, and the model is as follows:

$$green\_patent_{it} = \beta_0 + \sum_{n=1}^{3} \beta_{pre\_n} D_{pre\_n} + \beta_{current} D_{current} + \sum_{n=1}^{5} \beta_{post\_n} D_{post\_n} \beta_2 \delta_{it} + \gamma_t + \lambda_r + \varepsilon_{it} \quad (2)$$

In equation (2), D_{pre_n}, $D_{current}$ and D_{post_n} represent the cross product terms of the year dummy variables and the policy dummy variables before, at and after the policy launch, respectively, β_{pre_n}, $\beta_{current}$ and β_{post_n} represent the corresponding coefficients, and the meanings of the other symbols are the same as in Eq. (1). Table 3 and Figure 1 report the results of the parallel trend test. The results show that none of the coefficients are significant, i.e., there is no systematic difference between the green technology innovation of firms in the treatment and control groups before the implementation of the carbon trading pilot policy, and the parallel trend hypothesis is satisfied. Although $\beta_{current}$, β_{post_1} and β_{post_2} are not significant, they show some increasing trend and the corresponding coefficients for all three years after the policy initiation are significant, and the significance increases year by year. These indicates that the implementation of carbon emissions trading policy can promote green technology innovation of enterprises, but this promotion shows a lagged effect, with the promotion effect only appearing in the third year after the launch of the policy and increasing year by year thereafter. Therefore, it can be considered that the parallel trend test is passed.

Table 3. Parallel trend test

Variables	Corporate Green Technology Innovation
	green_patent
pre3	-1.7174
	(2.0476)
pre2	-.4283
	(2.7731)
pre1	-1.8192
	(2.7022)
current	-2.5651
	(2.5305)
post1	.0128
	(2.6389)
post2	1.6272
	(2.7206)
post3	6.2922*
	(3.4291)
post4	8.0283**
	(3.5208)
post5	9.5692***
	(3.3251)
Control variables	Yes
Year fixed effect	Yes
Industry fixed effect	Yes
Sample size	20100
R^2	0.0539

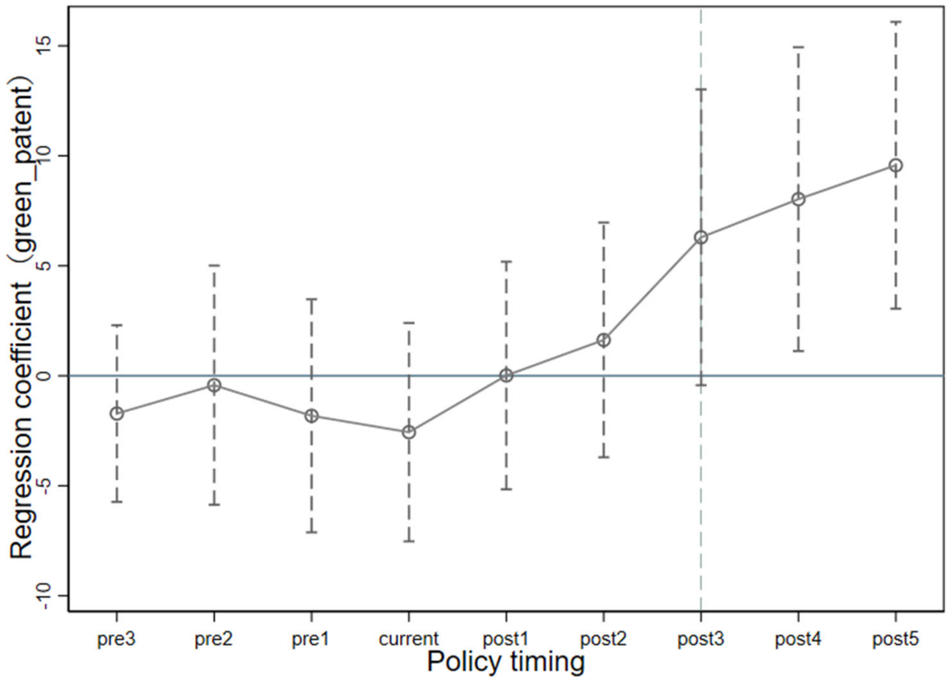

Figure 1. Parallel trend test

5.3. Baseline regression results

Based on the model (1) established in the previous section, table 4 presents the results of the impact of carbon trading on green technology innovation. All regressions control for year fixed effects, no control variables are added in column (1), control variables are added in column (2), and industry fixed effects are further added in column (3).

From the results, it can be seen that the DID coefficients of all three columns are significant at the 1% level, indicating that there is a significant increase in the level of green technology innovation in the enterprises that have been included in the carbon emission trading pilot, and hypothesis 1 is verified. The logic can be interpreted as that, after the implementation of carbon trading policy, the internalization of the emission costs of enterprises creates cost pressure, thus driving them to invest more in green technology innovation in order to reduce costs and generate potential benefits. Firms will be more willing to engage in green technology innovation activities driven by profit maximization.

Table 4. Baseline regression results

Variables	green_patent		
	(1)	(2)	(3)
DID	9.6339***	7.5372***	7.3961***
	(3.2651)	(2.8123)	(2.8126)
Control variables	No	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Industry fixed effect	No	No	Yes
Sample size	20100	20100	20100
R^2	.0357	.05	.0522

5.4. Robustness tests

(1) Excluding the effects of special samples

Among the eight carbon trading pilot regions, Chongqing is the only pilot region located in the west. Given that the specificity of economic development in the western region may affect the regression results, this paper excludes the companies located in Chongqing to re-run the regression. Fujian province was included in the carbon trading pilot in 2016, which is later compared to several other pilots, and the paper also excludes the enterprises located in Fujian province to re-run the regression. After excluding the samples from Chongqing and Fujian respectively, the regression results are shown in columns (1) and (2) of Table 5. DID coefficients are still significantly positive at the 1% level, and the coefficients are not significantly different from the original results, indicating that the original results are somewhat robust.

Table 5. Robustness test results excluding special samples

Variables	(1) Exclude Chongqing	(2) Exclude Fujian
DID	7.8498***	8.7163***
	(2.9903)	(3.2617)
Control variables	Yes	Yes
Year fixed effect	Yes	Yes
Industry fixed effect	Yes	Yes
Sample size	19840	19598
R^2	.0524	.053

(1) Sample subinterval model estimation

Considering that the global financial crisis in 2008 and the outbreak of the new crown pneumonia epidemic in 2020 may have an impact on the level of green technology innovation of enterprises, this paper excludes the sample data of 2008, 2009 and the epidemic in 2020 and 2021 and re-regresses them. The results reported in column (1) of Table 6 shows that the significance level of the DID coefficient is 5%, and although the significance decreases, the coefficient is still positive, indicating the robustness of the original results.

(3) Alternative explanatory variables model estimation

Considering that the number of green patent applications may not represent the real green innovation level of enterprises, this paper uses the sum of green technology invention patents and green utility model patents granted to replace the original explanatory variables for robustness testing, and the results are shown in column (2) of Table 6, and the DID coefficient is significantly positive at the 5% level, which is consistent with the original findings.

(4) Change time series

Considering that the formation of green patents takes some time, the regression is re-run here by considering the impact of enterprises included in carbon emissions trading in the current period on green technology innovation in the next period. The results reported in column (3) of Table 6 show that the regression results are still significantly positive at the 5% level, which is consistent with the original findings.

Table 6. Results of the remaining robustness tests

Variables	(1) Sample subinterval model estimation	(2) Alternative explanatory variables	(3) Change time series
DID	5.0747**	5.5462**	7.8457**
	(2.1724)	(2.2275)	(3.5248)
Control variables	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes
Sample size	14262	20100	17134
R^2	.0597	.062	.0602

5.5. Analysis of Moderating Effects

According to the previous paper, the operation of the carbon market will have an impact on the green technology innovation of enterprises. This paper introduces carbon price, carbon market liquidity, and carbon trading scale as indicators to measure the operation of carbon market, and constructs a moderating effect model to further analyze the impact of carbon market operation on enterprises' green technology innovation, as follows:

$$green\_patent_{it} = \beta_0 + \beta_1 DID_{it} + \theta DID_{it} \times mark_{it} + \beta_2 \delta_{it} + \gamma_t + \lambda_r + \varepsilon_{it} \quad (3)$$

In equation (3), $mark_{it}$ is a measure of market mechanism, representing carbon price, carbon market liquidity, and carbon trading scale, respectively, and other symbols have the same meaning as model (1). The results of the moderating effect are reported in Table 7. When the carbon market mechanism is measured by the carbon price, the coefficient θ of the carbon price and the cross DID multiplier term is significantly positive at the 10% level, indicating that the carbon price promotes the green technology innovation of enterprises, and the higher the carbon price, the higher the level of green technology innovation of enterprises. At this point, considering the influence of the main explanatory variable *DID* on enterprises' green technology innovation, we can get $\Delta green\_patent / \Delta DID = \beta_1 + \theta \ln price$ from model (2), and the values of *Lnprice* all greater than 1.472, so the influence of on enterprises' green technology innovation is positive, which is consistent with the results of the previous paper.

When the market mechanism is measured by carbon market liquidity, the coefficient θ of the cross-product term does not show significance, but the *DID* coefficient is significant at the 5% level and decreases compared to the previous benchmark regression, suggesting that the market mechanism measured by market liquidity explains the green technology innovation of firms to some extent.

When the market liquidity is measured by the scale of carbon trading, the coefficient of the cross-product term is significantly positive at the 5% level, indicating that the larger the scale of carbon trading, the higher the level of green technology innovation of enterprises. At this time, considering the influence of *DID* on enterprise green technology innovation, still from model (2), we get $\Delta green\_patent / \Delta DID = \beta_1 + \theta \ln scale$, and the minimum value of *Lnscale* is 7.863, so for any *Lnscale*, the influence of *DID* on enterprise green technology innovation is positive, and the same result as the previous paper. Based on the above analysis, hypothesis 2 is verified.

Table 7. Regulating role of carbon market operation status

Variables	(1)	(2)	(3)
	green_patent		
DID	-4.0636	7.182**	-5.0371
	(7.2418)	(2.97)	(4.3975)
c.DID#c.lnprice	4.1197*		
	(2.3637)		
c.DID#c.lnday		.1643	
		(.3368)	
c.DID#c.lnscale			.9056**
			(.427)
Control variables	Yes	Yes	Yes
Year fixed effect	Yes	Yes	Yes
Industry fixed effect	Yes	Yes	Yes
Sample size	20100	20100	20100
R^2	.0502	.0523	.053

6. Further Analysis

The impact of carbon emissions trading policy on enterprises' green technology innovation is not only regulated by the market mechanism, but also the micro characteristics of enterprises themselves may cause different degrees of impact. In this paper, we further analyze the heterogeneous impact in terms of firms' reliance on technological innovation, tolerance to environmental regulations, and internal control quality according to their micro characteristics.

6.1. Heterogeneity Analysis of High-Tech and Non-High-Tech Firms

According to the degree of reliance on technological innovation, enterprises can be classified as high-tech enterprises and non-high-tech enterprises. In this paper, according to the Statistical Classification Catalogue of High Technology Industries issued by the National Bureau of Statistics, combined with the Guideline on Industry Classification of Listed Companies (2012 Revision) issued by the China Securities Regulatory Commission, the pharmaceutical manufacturing industry, special equipment manufacturing industry, railroad, ship, aerospace and other transportation equipment manufacturing industry, electrical machinery and equipment manufacturing industry, computer, communication and other electronic equipment manufacturing industry, instrumentation manufacturing Enterprises in pharmaceutical manufacturing, special equipment manufacturing, railway, ship, aerospace and other transportation equipment manufacturing, electrical machinery and equipment manufacturing, computer, communication and other electronic equipment manufacturing, and instrumentation manufacturing are classified as high-tech enterprises, while enterprises in other industries are non-high-tech enterprises.

Table 8 reports the results of heterogeneity between high-tech and non-high-tech enterprises. The results show that the DID coefficient is 7.5083 in the group of non-high-tech enterprises, which is significant at the 1% level, while it is not significant in the group of high-tech enterprises, which indicates that the promotion effect of carbon emissions trading on green technology innovation is mainly reflected in non-high-tech enterprises. This may be due to the fact that the technological innovations of high-technology firms involve a wider and more diverse range of fields, while the technological innovation fields of non-high-technology firms are relatively narrower and have fewer technological innovation activities. After the introduction of the carbon emissions trading policy, stimulated by this market-based environmental regulation measure, non-high-technology firms are able to allocate their resources more precisely to green technological innovation activities.

Table 8. Results of the test for heterogeneity of high-tech/non-high-tech enterprises

Variables	high-tech enterprises	non-high-tech enterprises
	green_patent	*green_patent*
DID	6.9577	7.5083***
	(6.2220)	(2.5033)
Control variables	Yes	Yes
Year fixed effect	Yes	Yes
Industry fixed effect	Yes	Yes
R^2	0.0522	0.0563
N	7792	12343

6.2. Analysis of the heterogeneity of high-carbon and low-carbon enterprises

Based on the differences in firms' tolerance to environmental regulations and environmental regulation costs (Deng and Wang, 2020), firms are classified as high-carbon firms and low-carbon firms. In this paper, referring to Liu et al. (2017), enterprises belonging to 17 polluting industries such as the ferrous metal smelting and rolling processing industry, nonferrous metal smelting and rolling processing industry, paper and paper products industry, and pharmaceutical manufacturing industry are classified as high-carbon enterprises, and enterprises in other industries are low-carbon enterprises.

The heterogeneity results are shown in Table 9, the DID coefficient is 11.0379 in low carbon enterprises, which is significant at the 5% level, while the DID coefficient is not significant in the high carbon enterprise group, indicating that the promotion effect of carbon trading policy on green technology innovation is stronger and more significant in low carbon enterprises.

The reason may be that high-carbon firms have higher emission costs and higher adjustment costs, and are slower to respond to green technology innovation under the incentive of carbon trading policy, while low-carbon firms have low environmental technology adjustment costs and are more likely to respond to green technology innovation after the policy is implemented.

Table 9. Results of the heterogeneity test for high-carbon enterprises/low-carbon enterprises

Variables	high-carbon enterprises	low-carbon enterprises
	green_patent	*green_patent*
DID	2.3689	11.0379**
	(2.4988)	(4.7068)
Control variables	Yes	Yes
Year fixed effect	Yes	Yes
Industry fixed effect	Yes	Yes
R^2	0.0185	0.0866
N	9510	10625

6.3. Heterogeneity analysis of internal control quality

The quality of a company's internal controls affects management's decisions, which in turn affects technology innovation decisions and ultimately has an impact on green innovation activities. This paper measures the quality of internal control of companies by using the Dibble Internal Control Index and divides the sample into high internal control group and low internal control group based on the average of the internal control index. Table 10 reports the results of the grouped regressions. The DID coefficients of the group with higher quality of internal control are significantly positive, while the DID coefficients of the group with lower quality of internal control are not significant, indicating that the promotion effect of carbon trading policy on corporate green technology innovation is mainly manifested in the companies with higher quality of internal control. This may be due to the fact that firms with higher quality of internal control have more scientific management decisions and are able to formulate more long-term corporate development strategies after the carbon trading policy is launched, thus attaching importance to the investment in green technology innovation. On the other hand, enterprises with high internal control also have relatively low risk in conducting green innovation, and are able to better deploy resources and control risks under the pressure of environmental regulation costs to promote green innovation activities.

Table 10. Results of group testing of internal control heterogeneity

Variables	High quality of internal control	Low quality of internal control
	green_patent	*green_patent*
DID	7.7236**	-2.4280
	(3.0145)	(2.1390)
Control variables	Yes	Yes
Year fixed effect	Yes	Yes
Industry fixed effect	Yes	Yes
R^2	0.0537	0.1256
N	18466	1669

7. Conclusion and Insights

Taking the green patent data of listed companies as the research object and adopting the carbon emission trading pilot policy as a quasi-natural experiment, this paper constructs a multi-point double difference model to study the impact of carbon trading policy on the green technology innovation of enterprises and elaborates the regulating role of market mechanism in this process from the perspectives of carbon price, carbon market liquidity, and carbon market size. We also further analyze the differences between high-tech enterprises and non-high-tech enterprises, high-carbon enterprises and low-carbon enterprises, and high-internal-control enterprises and low-internal-control enterprises with respect to the micro characteristics of enterprises.

The findings of this paper suggest that: (1) carbon trading policy can significantly promote enterprises' green technology innovation, and this promotion effect still holds after the robustness test; (2) the higher the price of carbon and the larger the scale of carbon trading, the stronger the impact of carbon emission rights on enterprises' green technology innovation, and the market mechanism measured by carbon market liquidity partially explains the promotion effect of green technology innovation; (3) further analysis shows that the promotion effect of carbon trading policy on enterprises' green technology innovation is mainly manifested in non-high-tech enterprises, low-carbon enterprises, and enterprises with high internal control.

Based on the above findings, this paper proposes the following implications:

For the government, it should continue to promote the construction of the national carbon emission trading market and expand the green innovation effect of carbon trading policy. The results have shown that carbon emission trading policies have made significant contributions to the green and sustainable development of enterprises, while the national carbon trading market is still in its initial stage, the exploration of initial allocation, market trading, supporting services and other systems should be accelerated to promote the development and improvement of supporting policies and expand the enterprises included in the carbon trading system so that the policies can play a greater role.

At the same time, the government should optimize the carbon market environment and system design. At present, there are large differences in carbon prices, carbon market liquidity and carbon trading scale among the eight major carbon markets in China, and it is necessary to adhere to market orientation and give full play to the incentive role of market mechanism. It is necessary to implement the principle of moderately tight carbon quota allocation, reasonably allocate carbon quotas, effectively promote carbon prices, and convey positive green innovation investment signals to enterprises; at the same time, establish and improve the financial derivatives trading mechanism of the carbon market, activate the carbon market, expand the trading scale and number of trading days, and more efficiently play the role of the carbon market in promoting green innovation.

Government departments should provide differentiated policies for enterprises with different micro characteristics and strengthen the regulation of the carbon market. For high-tech enterprises and high-carbon enterprises, they should be reasonably guided to carry out green innovation activities, improve their green innovation awareness and increase their green innovation investment level; for non-high-tech enterprises and low-carbon enterprises, government departments should strengthen support for their technological innovation and optimize their green innovation investment environment. At the same time, a perfect carbon market supervision system should be established to reduce the risk and uncertainty of green innovation investment by enterprises.

For enterprises, micro business entities should improve their internal management systems. Corporate entities should improve the quality of internal control to adapt to the changing macro environment and focus on the harmonization of external macro policies and corporate development strategies. As China's ecological civilization construction and green development construction continue to strengthen, enterprises should more green development strategy into their own long-term development strategy, strengthen the main position of green technology innovation, to achieve green high-quality development.

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