Research on Regional Carbon Emission Policy and Breakthrough Green Technology Innovation Pathways: Based on the Perspective of New Quality Productivity

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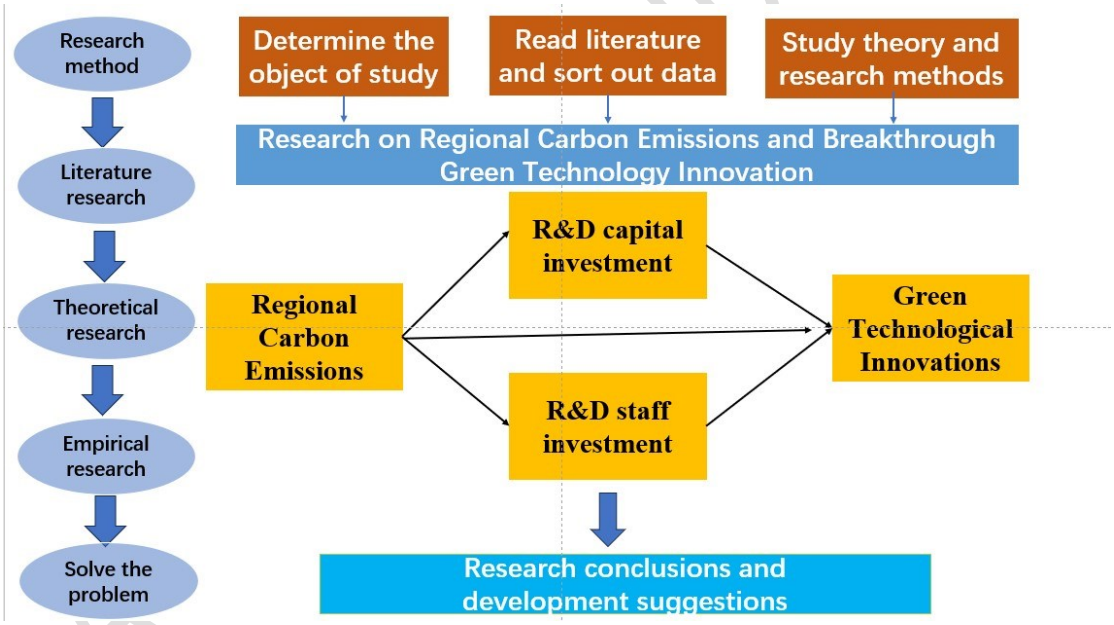
Graphical Abstract



Abstract: The driving force of new quality productivity comes from innovation, and breakthrough green technology innovation is its important engine. Breakthrough green technology innovation is the core driver of new quality productivity, and it is an important support to promote and develop new quality productivity. Based on the panel random effect model, the model of regional carbon emission policy impact on breakthrough green technology innovation is tested, and the mediating effect model is used to explore the impact and path of carbon emission on breakthrough green

technology innovation. Heterogeneity analysis shows that in the eastern, northeastern and western regions, carbon emissions policy significantly promote breakthrough green technology innovation. While in the central region, the effect is not significant. In addition, it was found that R&D capital investment partially mediated between carbon emissions policy and breakthrough green technology innovation, and the number of R&D staff investment mediated insignificantly between carbon emissions policy and breakthrough green technology innovation. Finally, recommendations are made at the levels of policy, enterprises, collaboration among research subjects, and regional development.

Keywords: Breakthrough green technology innovations; new quality productivity; carbon emissions policy; R&D investment； sustainable development.

1. Introduction

Over the past decades, innovation has attracted a lot of attention, and different support programs and policies have been developed at the global, national, or regional level to promote research, development, and innovation, and science, technology. Innovation have been widely recognized as an important driver of competitive advantage and performance improvement for organizations (Walsh et al.,2020).

In September 2023, the concept of new quality productivity was proposed for the first time, the new quality productivity by the revolutionary breakthroughs in technology, innovative allocation of factors of production, industrial transformation and upgrading of the depth of the new quality productivity, to the workers, labor materials, labor objects and their optimization of the combination of the leap as the basic connotation, with a significant increase in total factor productivity as the core mark, characterised by innovation, the key to quality and excellence, the essence is advanced productivity (Shi, 2023). Therefore, it is necessary to promote industrial innovation with scientific and technological innovation, especially with disruptive technology and cutting-edge technology to give rise to new industries, new models, new kinetic energy, and the development of new quality productivity. Innovation plays a leading role in the development of new-quality productivity, and is the new kinetic energy for fostering the development of new quality productivity(Chen,2024；

Hao,2023).

Green innovation, which refers to new processes, products, services or systems designed to reduce environmental impacts, has a double externality effect compared to non-green innovation, meaning that in addition to the positive technological spillovers usually associated with general R&D investments, green innovation generates other positive externalities that reduce external environmental costs (Lian et al.,2022). Major sustainability transitions require new forms of green innovation, as incremental improvements in technology and in the environmental efficiency of production systems may not be sufficient to achieve the fundamental changes needed for sustainable development (Capponi et al.,2022). Breakthrough innovation refers to a type of innovation that can bring about significant changes in the marketplace and disrupt the existing competitive landscape, which usually involves entirely new technologies, products or services that can solve long-standing problems or satisfy previously unmet needs, and is the key for enterprises to achieve extraordinary development, transformation and upgrading, and is a mode of innovation that fundamentally changes the original technological paradigm and market strategy (Datta & Srivastava, 2023). Breakthrough innovation has two outstanding characteristics, at the micro level, the technology is novel enough to bring significant technological progress and new value-added space for the enterprise, so that the core competitiveness of the enterprise is ahead of other competitors in the industry. At the macro level, it has a great impact on the market, and with the emergence of a series of new products and the fulfillment of new needs of the customers, it will lead to the linkage change of the industrial pattern and the transformation and upgrading of the industrial structure. Green technology innovation can be considered as a key factor of productivity, which in harmony with cost reduction and reduction of greenhouse gas emissions, energy conservation, use of cleaner technologies and better utilization of raw materials in production and processing, contributes to a further reduction of environmental impact, thus contributing to the enhancement of a company's image, the achievement of its business objectives and the enhancement of its competitive advantage. Breakthrough green technology innovation refers to breakthrough product

innovation, breakthrough process innovation or breakthrough service innovation through research on low-carbon technologies, and cutting-edge research results in the fields of carbon-free technologies, carbon-removal technologies and carbon-reducing technologies, so as to realize the goals of low energy consumption, low pollution and low emissions. Breakthrough green technology innovation is an important form of science and technology innovation, which is a necessary way for countries and enterprises to realize sustainable development, and a necessary condition for major ecological improvements, which greatly deviates from conventional practices, has the potential to reshape existing markets, create new markets, and lead to the emergence of new technological trajectories, and is an important engine for driving the development of new qualitative productive forces, which is of great significance to enterprises. Breakthrough green technology innovation requires more resources and is more uncertain and complex than incremental innovation. Therefore, breakthrough green technology innovation is an important engine of new quality productivity, while the development of breakthrough green technological innovation is a long-term arduous task.

Breakthrough green technology innovations are necessary to achieve sustainable development can change the very basis of competition. In recent years, under the guidance of the dual-carbon target, the pressure of carbon reduction has increased in various regions, and unprecedented attention has been paid to science and technology innovation, and various policies have been introduced to promote green science and technology innovation through the use of policy tools to regulate the allocation of resources, especially to advocate breakthroughs and disruptive independent innovation. Various policies have been introduced, especially promoting breakthrough and disruptive independent innovation, and investing more in R&D investment, science and technology awards and subsidies, etc., with the expectation of incentivizing individuals, enterprises, institutions, scientific research institutes, colleges and universities within the jurisdiction to carry out carbon reduction and efficiency activities, and certain results have been achieved so far. In May 2024, the State Council issued a circular on the issuance of the Action Programme for Energy

Conservation and Carbon Reduction for the period 2024-2025, which sets out key tasks in 10 areas and proposes safeguards in six areas. Although breakthrough green technology innovation has begun to attract attention, there is little research on the antecedents and driving mechanisms of breakthrough green technology innovation, and the limited research focuses mainly on enterprises. Realizing breakthrough green technology innovation is a complex issue with many conflicting problems and dilemmas. To what extent do carbon emission policies affect regional breakthrough green technology innovation? How can it have an impact? What is the role of regional R&D investment as an important means of supporting green technology innovation, and what is the role of carbon emissions policy in influencing breakthrough green technology innovation? Relevant studies are still very limited, and there is no consensus on how carbon emissions policy affect regional breakthrough green technology innovation, which needs to be further explored.

2. Literature review and research hypotheses

2.1 Literature review

There is very limited research on breakthrough green technology innovations at home and abroad, but there are more studies on breakthrough innovations or green technology innovations, which are summarized as follows.

(1) Foreign research on breakthrough green technology innovation. Green technology innovation is vital to organizations and communities, and research in this area has been on the rise in recent years, mainly focusing on the following three aspects. First, green technology innovation effect, support strategic goals, guide organizations to obtain sustainable competitive advantage. Green technology innovation contributes to cost efficiency and organizational flexibility, mitigates environmental risks, improves resource efficiency, reduces manufacturing costs, creates new opportunities for environmentally friendly practices, reduces pollution rates and improves environmental performance, improves service quality and economic performance, and brings about eco-reputation. Therefore, breakthrough green technology innovation is an important tool that can help society, organizations and businesses to achieve environmental sustainability and gain a competitive

advantage (Varanaviciu & Navikaite, 2016). Second, influences on the successful implementation of green technology innovation. The need for companies to embrace the green approach, the practice of a green corporate culture through the exchange of knowledge, experience, and skills among employees, organizational collaboration for the implementation of green technological innovations, the integration of digital technologies into industry, commitment of senior management to implement environmental regulations. Three different capabilities must be in place for breakthrough green technology innovation to occur with any degree of frequency in a company, these three different breakthrough green technology innovation capabilities are called discovery, incubation and acceleration (Frank et al.,2024). Third, there are many challenges to implementing green technology innovation, such as new green technologies and their environmental issues, risk of failure during implementation, high R&D costs, difficulties in data collection, increased workload and job dissatisfaction among employees, insufficient funding for implementing green projects, negative impact of external knowledge, lack of risk-taking in the organization, insufficient understanding of green initiatives, and ineffective government support (DiMasi et al., 2016).

(2) Domestic research on breakthrough green technology innovation. Domestic research on breakthrough green technology innovation is a little later than foreign countries, but the research trend is faster, mainly focusing on the following 2 aspects. First, driving factors of green innovation. Digital technology, green bonds, environmental protection tax, green credit policy, carbon emissions policy, environmental rights and interests trading market, government R&D subsidies and other factors have an impact on enterprise green innovation (Wu et al.,2020). Second, green innovation effect. The benefits of enterprise green innovation practice, listed companies can get green innovation premium, and effectively reduce haze pollution are green innovation effects (Wang et al., 2022).

(3) Research review. Scholars at home and abroad have studied breakthrough green technology innovation from different perspectives, and have achieved fruitful results that are worth learning from, but there are still certain deficiencies. From the

existing literature, there is relatively little literature on breakthrough green technology innovation, and previous studies mainly focused on the impact of carbon emissions policy, green credit, financing constraints and other factors on green innovation, as well as industrial policy and patent quality, etc., and there was no widely recognized identification method and measurement method of breakthrough green patents, which greatly restricts the field of breakthrough green science and technology innovation. In-depth research, there are still fewer studies on regional green innovation, and the understanding of regional breakthrough green technology innovation paths is not yet clear.

This paper intends to conduct research in the following aspects. First, study the impact of carbon emissions policy on regional breakthrough green technology innovation, to provide a new theoretical perspective for exploring the deep integration of limited resources and green development to realize the maximum benefits. Second, explore the impact of R&D investment on breakthrough green technology innovation behavior, to provide theoretical support for further development of corresponding policies. Third, analyze the mediating role of regional R&D investment under carbon emissions policy, to provide a new theoretical perspective for exploring the path of regional breakthrough green technology innovation under the perspective of new quality productivity to provide new ideas.

2.2 Research hypothesis

2.2.1 Direct mechanism of carbon emissions policy on regional breakthrough green technology innovation

Porter's hypothesis suggested that stricter environmental regulation may lead to innovation and thus competitive advantage. Carbon emissions policy have a significant pollution control effect, which can catalyze technological innovation, reconfigure the technological innovation path of enterprises, and influence the choice of enterprise innovation mode. Green technology has the characteristics of long R&D cycle, high requirements, high investment, high risk and complexity, which will lead to additional investment in innovation by enterprises, and without the guidance and support of the government, it is impossible to realize the green technological

innovation with positive externalities, and the innovation compensation effect and cost compliance effect of the environmental regulation may lead to innovation and thus bring competitive advantages. The innovation compensation effect and cost compliance effect of environmental regulations may promote or hinder green technological innovation, and government interventions will have different impacts on green technological innovation. Current research suggests that institutional pressure and environmental regulation compel firms to implement green innovations. An analysis of environment-related patents from 326 publicly traded companies in polluting industries in the United States suggests that institutional pressures can trigger green innovations, and that firms that pollute relatively more than their peers should be more sensitive to institutional pressures and respond more diligently as they look for new ways to overcome these environmental problems. Firms' decisions to engage in green innovation are influenced by a variety of factors, including technology-driven, regulatory-driven, market-pull, and firm-specific factors, and among all types of drivers, regulations remain the primary driver, with institutional pressures and environmental regulation being important institutional factors driving firms to green innovation.

However, policies introduced by the state may not have achieved the expected improvements, and the efficiency of green innovation guided by external regulations is generally low in China. Under stringent carbon emissions policy, firms are incentivized to develop new and improve existing production processes and equipment to reduce CO_2 emissions and air pollution in order to comply with environmental standards. This will motivate companies to innovate with green technologies. The core driver of new quality productivity is innovation, and breakthrough green technology innovation is an important type of innovation, and new requirements for breakthrough green technology innovation have been put forward from the national level. Therefore, based on the above analysis, the following hypotheses are proposed in this paper.

H1: In the new quality productivity perspective, carbon emissions policy has a significant positive impact on regional breakthrough green technology innovation.

2.2.2 The role of carbon emissions policy on R&D investment

There are two dominant theories used to explain the impact of carbon emissions policy on R&D investment (Fernández et al., 2018). The follow cost theory argued that environmental regulations lead to an increase in pollution control costs for enterprises. Especially in the short term, due to the limitation of the amount of capital, enterprises have to increase the input of sewage, which will inevitably lead to the reduction of R&D investment, resulting in the R&D crowding out effect. However, another theory, the Porter hypothesis, suggests that in the long run, reasonable and strict environmental regulations can promote technological practices, and the cost of carbon emissions may be partially or fully offset by the compensatory effect of innovative activities (Zhao & Sun, 2016). The hypothesis suggests that appropriate carbon emissions policy can stimulate innovation and motivate firms to increase their R&D investment in order to achieve technological innovation and green production. Firms need to seek technological innovation to reduce pollution and improve production efficiency when facing strict carbon emission policies (Yang, Tseng, & Chen, 2012). Therefore, enterprises will increase their investment in R&D to promote technological innovation and green production. Firstly, carbon emissions policy increase the operating costs of enterprises. In order to comply with environmental regulations, enterprises need to invest a lot of money in purchasing environmental protection equipment, improving production processes and reducing pollution emissions. These additional costs may compress enterprises' investment in research and development (R&D), making them have to make a trade-off between R&D and environmental governance (Van Leeuwen & Mohnen, 2017). However, this increased cost can also be seen as an incentive to innovate, prompting firms to seek more efficient and environmentally friendly production methods, thus driving their investment in R&D. Second, carbon emission policies provide new market opportunities for companies. As consumer demand for environmentally friendly products continues to grow, companies that comply with carbon emission reduction are usually able to build a good social image and enhance consumer trust. A good corporate image helps enterprises attract more external investment and provides

support for their green technology innovation (Bu, Qiao, & Liu, 2020). Enterprises that can make breakthroughs in R&D and develop new products that meet environmental standards will be able to gain a competitive advantage in the market. Furthermore, carbon emissions policy reduction also prompts enterprises to focus on technological innovation. When faced with strict carbon emission reduction policies, enterprises may realize that non-compliance will face great legal risks and economic losses. To avoid these risks, firms may increase their investment in R&D to develop products and technologies that meet environmental standards. Enterprises need to reduce pollution and improve productivity by seeking technological innovations such as new production methods, materials and processes to reduce costs and enhance competitiveness. Therefore, the carbon reduction policy will push enterprises to increase their investment in R&D to support their technological innovation activities. Such technological innovation will not only help enterprises meet the challenges posed by carbon emissions policy, but also improve their core competitiveness. In addition, government support policies also play an important role between carbon emission reduction and R&D investment (Pan et al, 2021). In order to encourage enterprises to carry out environmental technology innovation, the government usually provides support policies such as tax incentives and financial subsidies. These policies can reduce the R&D costs of enterprises and increase their R&D willingness, thus increasing R&D investment. Therefore, the government's support policies will provide a strong guarantee for enterprises to increase R&D investment under the carbon emission policy.

H2: In the new quality productivity perspective, carbon emissions policy has a significant positive effect on R&D investment.

H2a: Carbon emissions policy has a significant positive effect on R&D capital investment.

H2b: Carbon emissions policy has a significant positive effect on R&D staff investment.

2.2.3 The role of R&D investment in breakthrough green technology innovations

Breakthrough green technology innovations involve substantially new

technologies, imply a higher level of sophistication, provide greater customer benefits relative to existing products and require considerable changes in consumption or usage patterns. Therefore, based on the resource base view and the dynamic capabilities view, breakthrough innovations require significant investment and may require additional resources. There are many types of innovation, but breakthrough innovation remains the holy grail, and firms invest in breakthrough innovation because those that develop it tend to perform better and survive longer. Environmental regulation can affect green technology innovation through the moderating effect of green finance. Chen et al (2022) examined the impact of environmental regulation on green technology innovation in terms of carbon emission and air pollution using panel data of 281 prefecture-level cities in China from 2004 to 2016. The results show that, carbon emission and air pollution environmental regulations have a positive impact on urban green S&T innovation as measured by the number of green invention patent applications, the impact of carbon emission environmental regulations on green technology innovation is greater than that of air pollution environmental regulations, and human resource investment and financial investment in R&D activities of local governments positively moderates the association between environmental regulations and green technology innovation. Wang , Long and Li (2022) to A-share listed enterprises in China from 2010-2019 as a sample, classified environmental regulation into three categories: commanded environmental regulation, market-oriented environmental regulation and voluntary environmental regulation, and investigated their impacts on enterprises' green science and technology innovation, and the results showed that enterprises' R&D investment and governmental support moderated the relationship between environmental regulation and green invention. Guo et al (2018) found that direct governmental subsidies and tax incentives have a facilitating effect on green technology and innovation, and environmental regulation positively moderates the association between green science and technology innovation.

Empirical evidence from previous studies suggested that R&D investment has a significant positive effect on innovation output, and R&D investment should be the main factor in promoting green technology innovation. Increased R&D investment

accelerates technological innovation because the financial and human resources invested in R&D activities increase physical facilities such as equipment and laboratories, and increase intellectual assets through the cultivation of scientific knowledge and technological talent. These tangible and intangible factors enhance the ability of firms and organizations to discover new knowledge and develop new technologies (Qi et al.,2021). Based on the above analysis, this paper proposes the following hypotheses:

H3: In the new quality productivity perspective, R&D investment has a significant positive effect on regional breakthrough green technology innovation.

H3a: R&D capital investment has a significant positive effect on regional breakthrough green technology innovation.

H3b: R&D staff investment has a significant positive effect of on regional breakthrough green technology innovation.

2.2.4 The mediating role of R&D inputs

Research has shown that carbon emissions policy do not have a direct impact on breakthrough green technology innovations, but rather work through mediating variables. Capital investment is the first step of enterprise innovation, which is a key indicator of the success of enterprise innovation. The amount of capital investment can also reflect the importance, willingness and strength of enterprises to breakthrough green technology innovation. Capital investment is also an important factor that affects the allocation of enterprise innovation factors, improves innovation efficiency and stimulates innovation vitality. The sources of financing for breakthrough green technology innovation of enterprises mainly include endogenous financing and exogenous financing. Among them, regional R&D investment is the embodiment of endogenous financing, and government support is an important source of exogenous financing. Government support can also play a leading and demonstrative role in the capital allocation of exogenous financial institutions, further promoting the diversification of exogenous financing channels. Talent is the most active element of productivity and the source of breakthrough ideas and technologies, and its quantity and quality have a direct impact on breakthrough green science and

technology innovation. Research and development (R&D) activities often require large investments in basic equipment and instruments, as well as in specially trained personnel, which often creates barriers to innovation, especially for small enterprises. Under environmental regulatory policies, local governments typically reallocate resources, alter fiscal expenditures and provide the infrastructure needed for scientific and technological research. In addition, Governments and relevant organizations channel more funds into innovative activities by providing financial subsidies and tax incentives to enterprises that are actively engaged in green science and technology innovation. Increased R&D investment can improve the level of green innovation of enterprises, thus producing more innovations. Based on China's provincial-level panel data from 2009 to 2017, it is found that R & D investment mediates the relationship between intellectual property protection and regional green innovation performance (Asni & Agustia, 2022).

Based on the above analysis, the following hypotheses are proposed in this paper.

H4: In the new quality productivity perspective, R&D investment has a mediating role in positive carbon emissions policy influencing regional breakthroughs in green technology innovation.

H4a: R&D capital investment has a mediating role in positively influencing regional breakthrough green technology innovations in terms of carbon emissions policy.

H4b: R&D staff investment has a mediating role in positively influencing regional breakthroughs in green technology innovation.

We include an analysis of the linkage between carbon emissions policy and green technology innovation in Figure 1.

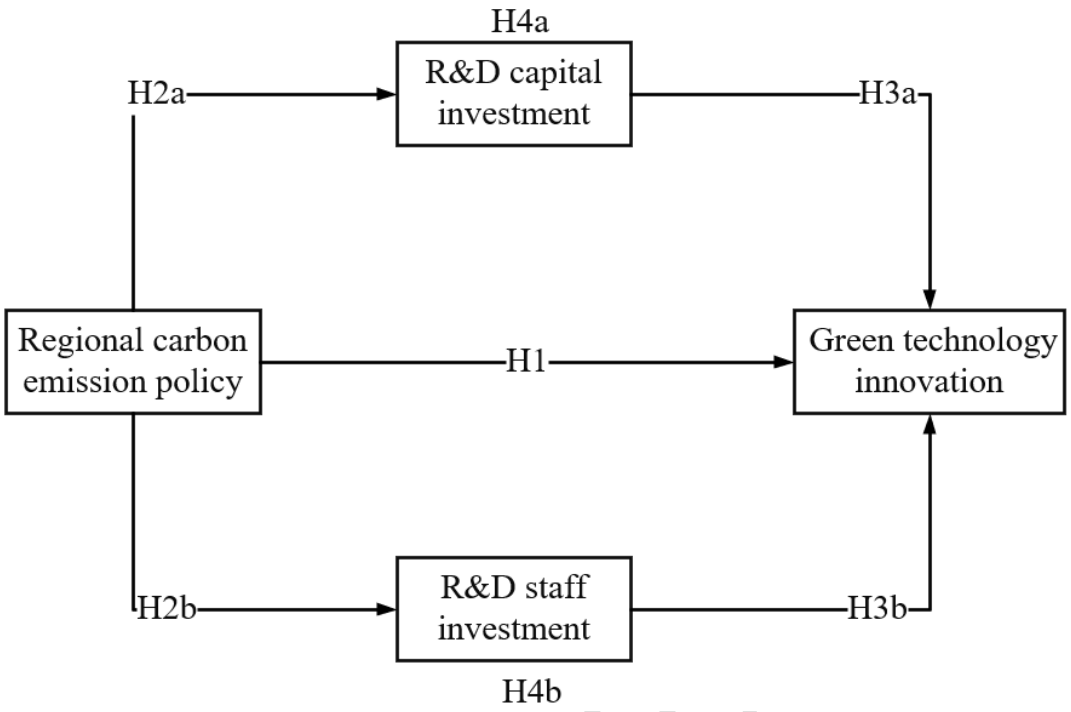


Figure 1. Conceptual model

3. Variables and regression models

3.1 Data description

The data for this study is sourced from government reports, academic journals and industry databases to ensure the comprehensiveness of the analysis. The data used in this paper are provincial panel data for the period 2006-2021, and the data covered in this paper are the most recent data currently available due to the varying channels of statistical data release.

3.2 Definition of variables

(1) Explained variables. The significance of breakthrough green technology innovations is not only reflected in their technological novelty, but also in their impact on the evolution of industrial technology paths. Patents are often used to measure the results of firms' innovation activities, and invention patents are property rights granted to inventors by the State Patent Office. The explanatory variable of this paper is breakthrough green technology innovation, and patent is a commonly used measure, among which invention patents have the highest technological content and degree of innovation, while utility models are relatively less technologically difficult, and this paper uses the number of green invention patent applications as a breakthrough green technology innovation proxy variable. According to the literature, firstly, patent

applications reflect the output of innovation activities and are a more direct measure of innovation than input indicators such as R&D expenditure. Second, patent applications tend to be a relatively timely indicator of green technology innovation compared to other output indicators such as the number of patents granted and the number of new products developed. However, due to delays caused by cumbersome processes, etc., it can take a long time (months or even years) for an applicant to get a patent approved. Firms may use patented technologies that have been patented but not yet approved in their business activities. Therefore, as green patent grants are susceptible to factors other than technology, patent application data are a more timely measure of technology innovation than patent grant data. Third, invention patents are by nature the most innovative and groundbreaking. Green invention patents are usually based on the Green List of the International Patent Classification compiled by the World Intellectual Property Organization (WIPO) in 2010. The data for this study is obtained from the China Research Data Service Platform (CNRDS).

(2) Core explanatory variables. Currently, there is no universally recognized standard for measuring carbon emissions policy in the literature. According to the literature, the main measurement approaches are as follows. First, use the private sector's pollution abatement costs and the enforcement rate of environmental regulations. Second, use energy efficiency. Third, use the ratio of pollution control investment relative to the output value or cost of the enterprise. Fourth, use the total amount of funds for pollution control in each region. Fifth, choose the emissions of one or more pollutants as a measure of the intensity of environmental regulations. In this paper, carbon dioxide (CO_2) emissions and the ratio of word frequencies related to carbon emissions policy in provincial government work reports to the total number of word frequencies in the full text of government reports are used to measure the strength of carbon emissions policy. Carbon emissions policy are the response of firms in a region to local environmental regulations. Thus, all else being equal, the higher (smaller) the carbon emissions emitted, the more lenient (stronger) the carbon emissions policy in that region. Accordingly, carbon emissions should be negatively related to the strength of carbon emissions policy. Referring to Chen, Yao and Zhong

(2022), this paper converts these measures to the corresponding inverse value, i.e., 1/log (CO_2 emissions). Meanwhile, with reference to Karim et al (2021), since the ratio of carbon emission-related word frequencies in the provincial government work report to the total number of word frequencies in the full text of the government report is positively correlated with the intensity of carbon emission policy, it is also used as a measure of carbon emission policy intensity. The carbon emission policy word frequencies include environmental protection, environmental protection, pollution, energy consumption, emission reduction, emissions, ecology, green, low carbon, air, chemical oxygen demand, sulfur dioxide SO_2, carbon dioxide CO_2, PM10, PM2.5, etc. The data of CO_2 emission is from China Carbon Accounting Database (CEADs) (https://www.ceads.net/data/province/), and the frequency of words related to carbon emission is counted with the help of Python software.

(3) Mediating variables. This paper chooses the expenditure on research and experimental development in each region and the full-time equivalent of research and experimental development personnel in each region as the mediating variables to study their mediating roles in the relationship between carbon emissions policy and regional breakthrough green scientific and technological innovation, and the data of this study come from the China Science and Technology Statistical Yearbook.

(4) Control variables. Previous studies have shown that breakthrough green technology innovation is associated with economic indicators. Therefore, in order to control the impact of omitted variables on the model estimation results, referring to Xu et al (2021), the control variables in this paper are foreign investment level, measured by the share of foreign investment direct investment in GDP, which reflects the utilization of foreign investment. Human capital level, the population of tertiary education and higher education in each region/the overall population of each region. Advanced industrial structure, output value of tertiary industry/output value of secondary industry in each region. Common wealth level, expressed by GDP per capita. The above data are from China Statistical Yearbooks of past years.

In order to eliminate the effects of heteroskedasticity and multicollinearity among variables, the explanatory variable (breakthrough green technology

innovation), the core explanatory variable (carbon emissions), and the control variable (GDP per capita) were logarithmized in all regression models. The variables are summarized in Table 1.

Table 1. Definition of variables

Variable symbol	Variable type	Variable name	Explanation
GP	Explanatory variable	Breakthrough green technology innovation	log(number of patent applications for green inventions in each region +1)
ER	Core explanatory variables	Carbon emissions policy	1/log (CO_2)
ERS	Intermediary variable	R&D capital investment	log (R&D expenditures by region)
RDP	Intermediary variable	R&D staff investment	log (number of R&D staff)
TER	Control variable	Level of human capital	Higher education population per region /overall population per region
STMVR	Control variable	Advanced industrial structure	Tertiary sector output by region/secondary sector output by region
FDIR	Control variable	Overseas foreign direct investment	Total foreign investment per region/GDP per region
PCGDP	Control variable	Mutual enrichment	log (GDP per capita)

3.3 Measurement models

(1) Random effects modeling

Random effects models assume that differences between individuals are random and that these differences can be estimated as part of the aggregate. In applications, the Hausman test is often used to determine whether to use a fixed utility model or a random effects model. When individual effects are assumed to be independent of the explanatory variables, the random effects model is the appropriate choice, characterised by a common intercept, individual effects are treated as random variables, it is capable of estimating cross-individual differences and between-group variation, and it is suitable for situations where the structure of the data is complex, while at the same time, it increases the efficiency of the estimation. In order to

mitigate the endogeneity problem, the Hausman test showed a p-value of 0.0844, indicating that the null hypothesis could not be rejected at the 5% significance level, which suggests that the random effects model is applicable in this study. Therefore, this paper uses the panel random effect model to test the estimation of the effect of carbon emissions policy on the level of breakthrough green STI.

$$GP_{it} = \beta_0 + \beta_1 ER_{it} + \lambda Control_{it} + \mu_i + \xi_{it} \quad (1)$$

In equation (1), the explanatory variable GP is the level of breakthrough green technology innovation, the core explanatory variable ER is the inverse of the logarithm of CO_2, which represents carbon emissions policy, and the control variable Control contains the level of human capital (TER), the advanced industrial structure (STMVR), foreign direct investment (FDIR), and common wealth (PCGDP). β_0 represents the intercept term, β_1, λ represents the parameters to be estimated, and the combination of μ_i and ξ_{it} represents the combined residual term.

(2) Mediating effects modeling

After the random effect model test, this paper will use the mediation effect model to explore the impact and path of carbon emissions policy (ER) on breakthrough green technology innovation (GP).

$$GP_{it} = \alpha_0 + \alpha_1 ER_{it} + \alpha_2 Control_{it} + \mu_{GP1} + \xi_{GP1} \quad (2)$$

$$Med_{it} = \beta_0 + \beta_1 ER_{it} + \beta_2 Control_{it} + \mu_{Med} + \xi_{Med} \quad (3)$$

$$GP_{it} = \gamma_0 + \gamma_1 ER_{it} + \gamma_2 Med_{it} + \gamma_3 Control_{it} + \mu_{GP2} + \xi_{GP2} \quad (4)$$

In equations (2), (3) and (4), the mediator variable Med stands for R&D capital investment (ERS) or R&D personnel investment (RDP), and the meanings of other GP, ER and Control are the same as equation (1). α_0、β_0、γ_0 represent the intercept term, α_1、α_2、β_1、β_2、γ_1、γ_2 represent the parameter to be estimated, the combination of μ_{GP1} and ξ_{GP1}, the combination of μ_{Med} and ξ_{Med}, μ_{GP2} and ξ_{GP2} represent the combined residual term.

4. Baseline empirical results

4.1 Descriptive statistics

Descriptive statistics of the variables used in the econometric model of this study are presented in Table 2. The variables involved in the panel regression contain 16 years of data from 31 provincial administrative regions, with a total of 496 observations for each variable. Breakthrough green technology innovation level (GP) is the explanatory variable with a mean of 2.911, a standard deviation of 0. 787, and a maximum value of 4.509. Carbon emissions policy (ER) is the core explanatory variable with a mean of 0. 513, a standard deviation of 0. 104, and a maximum value of 0.636.

Table 2. Descriptive statistics

Variant	N	Mean	SD	Min	Max.
GP	496	2.911	0.787	0	4.509
ER	496	0.513	0.104	0	0.636
TER	496	0.019	0.006	0.006	0.042
STMVR	496	0.011	0.006	0.005	0.053
FDIR	496	0.006	0.027	0	0.475
PCGDP	496	10.593	0.622	8.663	12.123
ERS	496	6.224	0.718	3.684	7.66
RDP	496	4.788	0.679	2.87	6.096

4.2 Analysis of regression results

This section focuses on analyzing the impact of carbon emissions policy (ER) on breakthrough green technology innovation (GP). In Table 3, the panel regression model with no control variables and no random effects in column (1) has a regression coefficient of 10.76 for carbon emissions policy, which is statistically significant at the 1% level, while the R^2 of this model is 0.334, indicating that the model explains 33.4% of the variation in the dependent variable. The regression model with control variables and no random effects in column (2) has a regression coefficient of 2.635, which is significantly positive at the 1% level, and at the same time, the model's R^2 improves to 0.693, indicating that the inclusion of these variables greatly improves the model's explanatory power. The regression model in column (3) contains control variables and contains random effects, and the regression coefficient of carbon emissions policy is 2.635, which is significantly positive at the 1% level, and at the

same time, this indicates that the introduction of regional random effects does not numerically and significantly affect the fit of the model, but may help to control for unobserved region-specific factors. All of the above panel regression results indicate that carbon emission policy (ER) can significantly reduce the level of breakthrough green technological innovation (GP). The economic significance of carbon emission policy (ER) is important in promoting breakthrough green technological innovation (GP), with each 1% growth in carbon emission policy contributing to a 2.635% increase in breakthrough green technology innovation.

Table 3. Impact of Carbon Emissions policy (ER) on Breakthrough Green Technology Innovation Levels (GP)

Serial number	(1)	(2)	(3)
Variant	*GP*	*GP*	*GP*
ER	10.76***	2.635***	2.635***
	(0.776)	(0.525)	(0.525)
control	NO	YES	YES
Region RE	NO	NO	YES
R^2	0.334	0.693	0.693
Observations	496	496	496

Note: Standard errors in parentheses,*** p<0.01, ** p<0.05, * *p<0.*1

4.3 Robustness tests

(1) Add heteroskedasticity robust standard errors

This part adds heteroskedasticity robust standard errors (Robust) to the panel regression random effects model to test the robustness of the model. The regression results show that carbon emissions policy are still significantly negative at the 1% level, which indicates that the effect of carbon emissions policy (ER) on the level of breakthrough green technology innovation (GP) still exists. Meanwhile, the significance levels of some control variables change, such as the significance of Science and Technology Market Volume (STMVR) decreases, while the significance of Foreign Direct Investment (FDIR) increases to the 10% level, which suggests that the estimation of the impact of some variables on the level of breakthrough green technology innovation (GP) becomes more robust after accounting for potential heteroskedasticity.

(2) Removal of outliers

Compared with other provinces, Tibet autonomous region is dominated by agriculture and animal husbandry, industry is less developed, and pollutant emissions and green innovation are fewer and statistics are missing. Therefore, Tibet can be excluded from the panel regression as an outlier, and this paper considers removing the data from Tibet for robustness testing. The regression results also show that carbon emission (ER) is still significantly negative at the 1% level, which indicates that the effect of carbon emissions policy (ER) on the level of breakthrough green technology innovation (GP) is still robust.

(3) Replacement of explanatory variables

In this paper, with the help of Python software, the government work report is processed by word division, and the word frequencies related to carbon emission policy in the provincial government work reports from 2006 to 2021 are counted, and the proportion of them to the total number of word frequencies in the full text of the government reports is calculated, and the proportion is used as a proxy variable for carbon emission to replace the core explanatory variable CO_2 in order to test the robustness of the findings of the panel regression. The regression results still show that carbon emission policy (ER) is still significantly negative at the 1% level, which suggests that the enhancing effect of carbon emission policy (ER) on breakthrough green technology innovation (GP) still exists.

Table 4. Robustness test

Serial number	(1)	(2)	(3)
Variant	*GP*	*GP*	*GP*
ER	2.635***	2.666***	
	(0.436)	(0.701)	
WF			19.71***
			(3.739)
control	YES	YES	YES
Region RE	YES	YES	YES
R^2	0.863	0.867	0.857
Observations	496	480	476

Note: Standard errors in parentheses,*** p<0.01, ** p<0.05, * *p<0.*1

4.4 Placebo test

This section tests the null hypothesis that the coefficients on the carbon emissions policy (ER) variables are statistically significantly different from zero due to randomness alone with the help of actual data rearrangements. This is done by comparing the original regression coefficients with the distribution of coefficients resulting from these 500 random assignments to assess whether the significance of the original coefficients could be the result of random variation alone. If the original coefficients fall in the tails of this random distribution, then it is reasonable to reject the null hypothesis and argue that carbon emissions policy (ER) do have an effect on the level of breakthrough green technology innovations (GP) that is unlikely to have arisen by chance.

In the research model, the effect of environmental risk (ER) on economic performance (GP) was validated by a placebo test with 500 Monte Carlo methods, and the results showed significant statistical significance. Specifically, the 95% confidence intervals did not include zero values, which reduces the possibility that the ER correlation coefficients are due to random fluctuations. As seen in Figure 2, the actual observed carbon emission (ER) coefficient (T(obs) = 2.63) is much higher than that of any random permutation simulation, which further demonstrates the reliability of the model regression results.

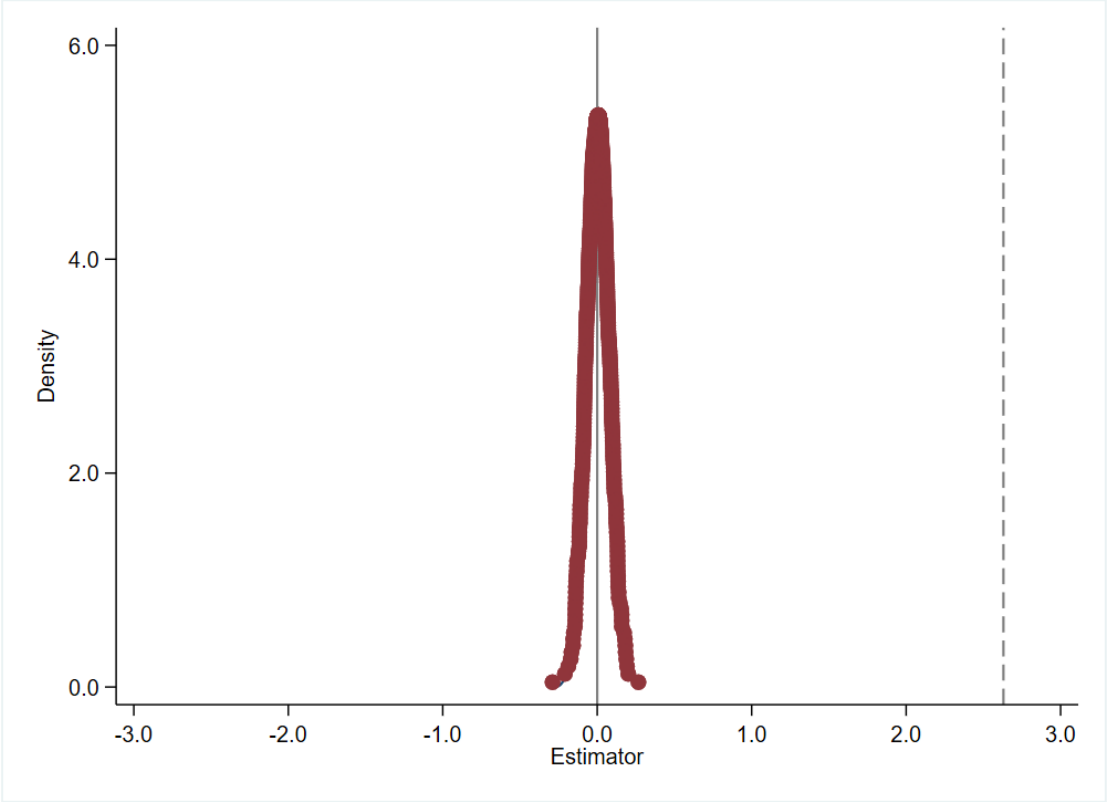


Figure 2. Placebo test results

5. Heterogeneity test

This section further explores the heterogeneity of the impact of carbon emissions policy (ER) on the level of breakthrough green technology innovation (GP) in different regions. Considering the imbalance of regional development in China, the sample is divided into four regions, namely, East, Central, West, and Northeast, based on the division of economic zones by the National Bureau of Statistics (NBS), in order to test whether there is any regional heterogeneity in the impact of carbon emissions policy on the level of breakthrough green technology innovations (GP).

As shown in Table 5, the eastern region contains provinces with more advanced economic development, and the intensity of carbon emissions policy may directly affect the region's innovation drive and capacity. According to the regression results, carbon emissions policy has a significant negative impact on breakthrough green technology innovations in the eastern region, indicating that carbon emissions policy may inhibit enterprises from engaging in more green innovation activities in more economically advanced regions. Although the central region is relatively backward in

terms of economic development level, the carrying capacity of resources and environment in this region is relatively loose compared to the eastern region. The regression results show that carbon emissions policy does not have a significant impact on breakthrough green technology innovation in the central region, which may indicate that firms in the central region do not respond as positively to carbon emissions policy as they do in the eastern region. The western region has richer natural resources and larger development space, and the implementation of carbon emissions policy may have different impacts on local green innovation. The regression results show that carbon emissions policy have a significant positive impact on breakthrough green technology innovations in the western region, which suggests that carbon emission reduction may be effective in promoting green innovation in resource-rich regions. As a traditional industrial base, carbon emission policy is important for promoting regional green transformation in the northeast region. The regression results show that carbon emissions policy also have a significant positive effect on breakthrough green science and technology innovation in the Northeast, indicating that carbon emission policy may be an important factor in promoting green transformation and innovation in traditional industrial areas.

The above analysis shows that there is regional heterogeneity in the impact of carbon emissions policy on breakthrough green technology innovation. In the eastern, northeastern and western regions, carbon emissions policy significantly promotes green innovation, while in the central region, the effect is not significant. The reason for the insignificant impact of carbon emissions policy on green technology innovation in the central region may be related to the characteristics of the region. First, enterprises in the central region are generally small in size and invest relatively little in R&D. Under the current level of carbon emissions policy, these enterprises may be more focused on following the cost principle rather than actively pursuing green technology innovation. As the intensity of carbon emissions increases, the cost of pollution control for enterprises may increase significantly, while the high cost and risk of green technology innovation may discourage enterprises, leading them to choose to crowd out the investment of innovation funds, and they may even use

certain ways to cover up their pollution behavior, thus inhibiting the improvement of green innovation efficiency. Second, the energy consumption per unit of GDP in the central region is high, and the cost pressure from rising energy prices is not conducive to corporate technological innovation. This may make enterprises more inclined to choose traditional and less costly pollution control methods rather than actively investing in green technology innovation in the face of carbon emissions policy. In contrast, the situation may be different in the eastern and western regions. In the eastern region, enterprises are larger in scale and more capable of conducting independent R&D and introducing green energy-saving technologies, so the impact of carbon emissions policy on green technology innovation may be more significant. While the western region is also small in terms of enterprise scale, its market economy dynamics are more different from that of the eastern region, and it is relatively less negatively affected by energy price fluctuations, so the impact of carbon emissions policy on green technology innovation may also be different from that of the central region. Carbon emissions policy in the Northeast significantly promotes breakthrough green technology innovation, which may be related to the region's longer history of industrialization and more urgent need for environmental protection and green innovation.

Table 5. Heterogeneity analysis of the effect of carbon emissions policy**(ER) on the level of breakthrough green technology and innovation (GP)**

Area	Eastern part	Central region	Western region	Northeastern region
Variant	GP	GP	GP	GP
ER	2.968***	-2.637	2.994***	7.606**
	(1.044)	(2.359)	(0.444)	(3.298)
TER	-12.04*	-47.31	-31.24*	-0.613
	(6.837)	(31.04)	(16.24)	(40.46)
STMVR	2.088	47.67*	14.63	24.54***
	(6.727)	(28.95)	(15.16)	(8.761)
FDIR	-0.307	-85.09	-8.589	-5.699
	(0.209)	(77.65)	(11.51)	(16.16)
PCGDP	0.929***	1.130***	0.955***	0.498*
	(0.0863)	(0.279)	(0.138)	(0.292)
Constant	-8.202***	-6.587***	-8.475***	-6.705***
	(0.570)	(2.355)	(1.180)	(0.763)
Observations	160	96	192	48

Number of region	10	6	12	3
R^2	0.849	0.787	0.480	0.858
Region RE	YES	YES	YES	YES

Note: Robust Standard errors in parentheses,*** p<0.01, ** p<0.05, * *p<0.*1

6. Mechanism analysis

As shown in Table 6, through the mediation test, this paper explores the mediating roles of R&D capital investment (ERS) and R&D staff (RDP) in the impact of carbon emissions policy (ER) on regional breakthrough green technology innovation (GP). We set two hypotheses of mediating effects, H4a and H4b, to predict the mediating roles of R&D capital investment and R&D staff on the relationship between carbon emissions policy and green technology innovation, respectively.

(1) The mediating effect of R&D funding (H4a)

In model (1), carbon emissions policy (ER) was found to have a significant positive effect on R&D capital investment (β=1.380, p<0.05), which suggests that higher carbon emission policy may promote more R&D capital investment and H2a is supported. Model (2) shows that carbon emission policy (ER) still has a significant effect on R&D capital investment (ERS) (β=0.835, p<0.01) when considering R&D capital investment (ERS), while carbon emission policy (ER) also has a significant positive effect on breakthrough green technology innovations (GP) (β=0. 667, p<0.1), but the significance is significantly lower, the literature has demonstrated that government R&D capital investment has a positive effect on green technology innovation, which suggests that R&D capital investment (ERS) has a partially mediating role in the effect of carbon emission policy (ER) on regional breakthrough green technology innovation (GP), and H4a is strongly supported. In model (3), carbon emission policy (ER) has a significant positive effect (β=2.635, p<0.01) on breakthrough green technology innovation (GP).

(2) The mediating effect of R&D staff investment (H4b)

In model (4), carbon emissions policy (ER) had a significant positive effect on R&D staff investment (RDP) (β=3.302, p<0.01), and H2b was supported, suggesting that carbon emissions policy may have promoted more R&D staff investment. When

R&D staff investment (RDP) was introduced as a mediating variable in model (5), the relationship between R&D staff investment (RDP) and regional breakthrough green technology innovation (GP) was also significant (β=0.309, p<0.01), while the coefficient of carbon emission (ER) was slightly reduced but remained significant (β=-2.664, p<0.01), which indicated that R&D staff investment (RDP) may not be another mediating pathway for carbon emission (ER) to influence regional breakthrough green technology innovation (GP), which is not strongly supported by H4b.

Summarizing the above analysis, the data in this paper support hypothesis H4a, but not H4b, that is, R&D capital investment funds play a mediating role between carbon emissions policy and regional breakthrough green technology innovation, but R&D staff investment does not necessarily have a mediating role. This suggests that carbon emissions policy not only directly promotes regional breakthrough green technology innovation, but also indirectly promotes breakthrough green technology innovation by influencing R&D capital investment. These findings provide insights for policymakers that reducing R&D inputs by enhancing carbon emissions policy may be an effective way to stimulate regional breakthrough green technology innovation.

Table 6. Mechanism analysis of the impact of carbon emissions policy (ER) on the level of breakthrough green technology innovation (GP)

Serial number	(1)	(2)	(3)	(4)	(5)
Variant	ERS	GP	GP	RDP	GP
ER	1.380**	0.667*	2.635***	3.302***	2.664***
	(0.610)	(0.372)	(0.436)	(0.567)	(0.354)
ERS		0.835***			
		(0.086)			
RDP					0.309***
					(0.0696)
TER	0.948	-12.30**	-16.94**	-8.377	-6.009
	(2.586)	(5.384)	(7.068)	(6.769)	(6.963)
STMVR	7.197**	5.708	8.562	-3.883	12.37**
	(2.996)	(5.106)	(6.562)	(5.792)	(5.896)
FDIR	0.231**	-0.525***	-0.345*	-0.465**	-0.447***
	(0.0945)	(0.176)	(0.184)	(0.230)	(0.150)
PCGDP	0.584***	0.351***	0.884***	0.765***	0.570***

	(0.0277)	(0.0849)	(0.0659)	(0.0784)	(0.117)
Constant	-0.773**	-6.173***	-7.586***	-4.803***	-5.995***
	(0.308)	(0.560)	(0.603)	(0.849)	(0.862)
Observations	496	496	496	496	496
R^2	0.654	0.913	0.693	0.655	0.826
Region RE	YES	YES	YES	YES	YES

Note: Robust Standard errors in parentheses,*** p<0.01, ** p<0.05, * *p<0.*1

7. Conclusions and recommendations

Based on the above research, this paper draws the following conclusions. This study verifies that carbon emissions policy (ER) have a significant positive impact on regional breakthrough green technology innovation (GP), and hypothesis H1 is supported. Meanwhile, R&D capital investment (H3a) and R&D staff investment (H3b) also have a significant positive effect on regional breakthrough green technology innovation (GP), which confirms that technology innovation requires the investment of both capital and staff. Carbon emission significantly affects R&D capital investment (H2a) and R&D staff investment (H2b). Further analysis shows that R&D investment mediates the relationship between carbon emissions policy (ER) and regional breakthrough green technology innovation (GP), and H4a is supported. The mediating effect of R&D staff investment is not as significant as expected, probably because financial investment is more critical to the direct impact on innovation outcomes, and thus H4b is not supported.

To develop new quality productivity, it is necessary to promote breakthrough green technology innovation as a means of generating new industries, new models and new dynamics. In order to generate breakthrough green technology innovation, this paper suggests.

（1）The Government should encourage enterprises to increase their investment in research and development (R&D) under carbon emission policy, thereby promoting the development of breakthrough green innovations. Measures such as setting up a green technology R&D fund, providing tax incentives and financial subsidies should be taken to reduce the R&D costs of enterprises and stimulate their innovation. At the same time, the policy should also guide enterprises to optimize resource allocation

and invest more resources in green technology R&D, so as to improve their green innovation capability. For breakthrough green innovation, the government should increase its support. A green innovation reward mechanism can be set up to recognize and reward enterprises that have made significant breakthroughs in the field of green technology, so as to stimulate the innovation drive of enterprises. In addition, it should also promote cooperation between industry, universities and research institutes, and strengthen cooperation and exchanges between universities, research institutes and enterprises, so as to jointly overcome green technological problems and promote breakthroughs and development of green technologies. The government should continue to strengthen carbon emission reduction, and incentivize enterprises to carry out green technology innovation, especially breakthrough green technology innovation, by formulating stricter environmental protection standards and carbon emission policies. It should also strengthen enforcement of carbon emissions policy to ensure that enterprises comply with environmental regulations. Enterprises that violate environmental regulations should be severely punished in accordance with the law to form an effective deterrent. At the same time, it should also strengthen the environmental protection publicity and education, improve public awareness of environmental protection, and jointly promote green development.

（2）Enterprises should respond positively to the carbon emission reduction policy and should recognize that carbon emissions policy are not only a challenge, but also an opportunity for transformation and upgrading. By increasing investment in R&D, enterprises can develop more environmentally friendly and efficient products and production processes, reduce environmental pollution and resource consumption, and thus comply with carbon emission requirements. Breakthrough green innovation can not only bring technological leadership for enterprises, but also enhance their brand image and market competitiveness. Enterprises should increase R&D investment in green technology, explore new environmentally friendly technologies and materials, and promote the development of their products in a greener and more environmentally friendly direction. At the same time, enterprises should also strengthen internal management and collaboration. By optimizing the R&D process,

strengthening team building, and improving the environmental awareness of employees and other measures, the overall innovation ability of the enterprise can be improved. In addition, enterprises should also actively cooperate with universities, scientific research institutions and other external organizations to jointly develop green technology and share the results of innovation. With the increasing awareness of environmental protection, consumer demand for green products is also increasing. Enterprises should follow the market trend, develop green products that meet consumer demand, satisfy market demand, and realize win-win economic and social benefits. They should increase capital investment in R&D and attract and train high-quality R&D talents in order to improve the capability and efficiency of breakthrough green technology innovation.

(3) Considering the differences in the level of economic development, industrial structure and resource endowment among regions, enterprises in each region should take into account their own characteristics and formulate reasonable strategies according to local conditions. Enterprises in regions with high levels of economic development should increase their R&D investment and explore innovations and breakthroughs in green technologies. These regions have more funds and resources to better support R&D activities. In regions with relatively low levels of economic development, the government should provide financial support and tax incentives to reduce the R&D costs of enterprises and encourage them to gradually transform to green technology innovation. For regions dominated by heavy industries and highly polluting industries, enterprises should actively adjust their industrial structure and shift to green industries with low energy consumption and low pollution. At the same time, they should increase their investment in green technology R&D for these industries and promote their green transformation. For regions dominated by service and light industries, enterprises should continue to strengthen the R&D and application of green technologies, improve the green content of their products and services, and meet consumer demand for green products. In regions with rich resource endowments, enterprises should make full use of local resource advantages to develop green industries and promote the sustainable utilization of resources. At the same time,

strengthen the green technology research and development of resource-based industries to improve resource utilization efficiency and reduce environmental pollution. In regions with relatively scarce resource endowments, enterprises should strengthen the R&D and application of energy-saving and emission reduction technologies to improve energy utilization efficiency and reduce production costs. At the same time, they should actively introduce and absorb external green technologies to make up for their own shortcomings of insufficient resources.

This study has some limitations that need to be further explored. First, due to the limitation of available data, this study did not fully consider the impact of other factors on breakthrough green innovation. In order to broaden the research field and increase the reliability of the study, internal and external factors such as enterprise digitization, non-governmental organizations, international inter-cooperation, and consumers should be considered in future research. Second, new quality productivity will give rise to new industries, and future research can focus on the effects of carbon emissions policy and R&D investment on breakthrough green innovation of enterprises under the conditions of different new industries and different forms of enterprise organization, so as to provide more useful information for the policy guidance of governmental departments.

Future research could focus on how to design more refined and targeted carbon emission reduction policies under the theoretical framework of new quality productivity to promote the research, development and application of green technologies. Meanwhile, attention will be paid to the development dynamics of the international carbon trading market to explore its potential impact on China's green technology innovation and industrial development. Through interdisciplinary and multi-angle research, we will provide theoretical support and practical guidance for the construction of a low-carbon and efficient green economic system.

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