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Study on the Emission Reduction Effect of Green Technology Innovation

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Abstract

Green technology innovation is one of the important ways to achieve carbon emission reduction targets. Based on the STIRPAT (Stochastic Impacts by Regression on Population, Affluence and Technology) model and the fixed-effects model, we measured CO_2 emissions by region using regional panel data from 2005 to 2021 at provincial level in China and explored the CO_2 emission reduction effect. Based on this, we analyzed heterogeneity of green technology innovation and the mechanism of the effect. The results show that green technology innovation has a significant effect on carbon emission reduction, achieving a 5% reduction. Second the CO_2 emission reduction effect of green technology innovation varies according to differences in economic, scientific and technological human resources, and environmental management inputs. It shows that green technology innovation has a significant CO_2 emission reduction effect in economically developed regions, regions with sufficient scientific and technological human resources, and regions with high environmental management inputs. Third, green technology innovation mainly achieves CO_2 emission reduction by improving the level of cleanliness.

JEL classification numbers: P28, O14, O15, O18.
Keywords: Green technology, Carbon emissions, STIRPAT model, Means to reduce emissions.

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1. Introduction

Climate change poses a serious threat to the sustainable development of human societies and is a challenge that countries around the world need to tackle together. Large amounts of carbon dioxide will not only lead to natural disasters such as melting glaciers, floods and rising sea levels, but also threaten human health (Jacobson et al., 2019). As the world's largest energy consumer and the country with the highest carbon emissions (Guan et al., 2018), China has actively set emission reduction targets and taken responsibility for mitigating the problem of excessive CO_2 emissions. For example, during the Eleventh Five-Year Plan period (2006-2010), the Chinese government proposed a 20% reduction in energy consumption per unit of GDP compared to the Tenth Five-Year Plan period (2001-2005). Subsequently, binding targets for carbon emissions and energy intensity control were set in the 12th and 13th Five-Year Plans (Shao et al., 2019). On 22 September 2020, China made a solemn commitment to the world to "strive to achieve carbon peaking by 2030 and carbon neutrality by 2060". Later, at the Leaders' Climate Summit in 2021, China incorporated the goals of "carbon peaking" and "carbon neutrality" into the layout of its ecological civilization.

In order to achieve carbon emission reduction targets, China has actively adopted various types of environmental regulatory instruments such as government regulation, market incentives and technological innovation to promote emission reduction. Among them, government regulation mainly uses compulsory means to control the total amount and intensity of energy; market incentives mainly use market-based mechanisms such as trading (e.g., carbon emission rights (Kevin et al., 2019)), subsidies (e.g., renewable energy subsidies (Qi et al., 2023)) and taxes (e.g., environmental protection tax (Gao et al., 2022)) to increase the cost of high-polluting industries. Technological innovation is an indispensable means of reducing emissions by improving the utilization and conversion of resources (Guan et al., 2018), and plays an essential role in improving the climate problem (Jacobson et al., 2019). Among them, green technology innovation is the fundamental way to achieve greenhouse gas emission reduction, and gradually become an important force to promote low carbon development (Guan et al., 2018). Although green technology innovation has gradually become an important means of carbon reduction in the international arena, China's green technology research and development and application capabilities have some room for improvement. Its role in environmental protection is relatively limited (Qi et al., 2023). Current low-carbon and negative-emission technologies are unlikely to help China achieve its goal of carbon neutrality by 2060 (Gao et al., 2022). Therefore, in order to emphasize the positive role of green technology innovation for low carbon development, it is necessary to study the carbon reduction effects of green technology innovation in China's provincial regions. The study of heterogeneity and transmission pathways can guide the development of green technology in each region in a targeted manner and provide theoretical support for China to achieve its carbon reduction targets and develop green technology.

2. Literature review

There is no consensus among academics on the definition of green technology. In a narrow sense, green technology is considered to be a general term for technologies and processes that reduce environmental pollution, raw materials and energy consumption, and in a broader sense, it also includes related organizational, management and institutional innovations (Yu et al., 2021). Currently, processes or products that are innovative, value-based, resource-saving and environmentally friendly are considered 'green technologies' (Lin and Long, 2021). When studying the environmental impact of green technology innovations, there were three broad categories of measures of green technology innovation. The first was to express green technology innovation in terms of R&D expenditure. For example, Churchill et al. (2019), using a sample of G7 countries, found that the relationship between R&D expenditure and carbon emissions had different characteristics over time. Ganda (2019), focusing on OECD economies, pointed out that there was a negative relationship between R&D expenditure and carbon emissions. The second was the use of the number of green patent applications as a measure of green innovation. For example, Wang et al. (2023) used Chinese green patent data to find that green technology innovation could significantly reduce PM2.5 emissions. Li et al. (2021) examined patent data from 32 economic sectors in China and found that there was an "inverse U" relationship. The third type focused on a specific area of technological innovation, such as environmental innovation, energy technology innovation, etc. For example, Mensah et al. (2019) focused on environmental innovation and found that the number of environmental patent applications contributes to the reduction of carbon emissions. In contrast, Mongo et al. (2021) concluded differently that there was a rebound effect of environmental innovation on carbon emissions. Lin and Zhu (2019) focused on energy technology innovation and found that renewable energy technology innovation promoted carbon reduction and the effect of renewable energy technology in curbing CO_2 emissions increased as the proportion of renewable energy generation increases.

Intuitively, green technologies can improve the quality of the environment. A number of scholars have found that green technology innovations have a positive impact on improving the environment. For example, Zhou et al. (2022) concluded that when green technology innovation was greater than 9.32, it could effectively curb SO2 emissions in the thermal power industry. Du et al. (2019) found that in developed economies, green technology innovation had substantially reduced carbon emissions. Xu et al. (2021) found that green technologies had a positive impact on the carbon emission performance of Chinese cities. Existing research suggested that green technology innovation affected carbon emissions in three main ways. The first was through direct technology effects. Liu et al. (2019) refined green technology innovation into product and process innovation. They believed that with improved manufacturing materials and processes, companies could directly reduce environmental pollution by producing more environmentally friendly products. Wang and Zhu (2020) argued that advanced energy technologies were beneficial to expanding energy supply and saving energy use. The second was the indirect structural effect. Xu et al (2021) studied a sample of Chinese prefecture-level cities and found that green technology innovation could promote the rationalization of industrial structure to achieve carbon reduction. The third was the technology spillover effect. Pan et al. (2021) found that inter-regional green technology spillover could lead to a reduction in energy intensity in neighboring regions, but the absorption capacity varied between regions. Yang et al. (2021) also suggested that technology spillovers could lead to emission reductions. They further showed that the impact of different forms of technology spillovers on CO_2 emission reduction was optimal when the value of intellectual property protection was below 8.169.

However, there is no consensus in the existing literature on the relationship between green technology innovation and carbon emissions. While many scholars argued that green technology innovation could reduce carbon emissions, some studies suggested otherwise, arguing that the emission reduction effect of green technology innovation was not significant. For example, Ding et al. (2016) argued that in Italy, green innovation had no significant effect on CO_2 emission reduction. Lin et al. (2022) pointed out that in 264 urban case studies in China, the emission reduction effect of green technology was not significant. Braungardt et al. (2016) also pointed out that due to the rebound effect, green technology innovation lead to an increase in energy consumption.

From the above review, it can be seen that there are already rich results on green technology innovation in the academic community, but there is still room for further research: (1) Most of the existing literature accounts for CO_2 emissions from the energy perspective, and less consideration is given to the impact of inter-regional power transfer to and from the region on CO_2 emissions. (2) The existing literature has not yet reached a consensus on the relationship between green technology innovation and CO_2 emissions, and studying the carbon emission reduction effect of green technology innovation would help to expand the relevant literature. (3) Few studies have explored the carbon reduction heterogeneity of green technology innovation from the perspective of provincial-level regions in China under the characteristics of different levels of economic development, talent pools, and environmental governance inputs. The possible marginal contributions of this paper are: accounting for regional CO_2 emissions by considering both energy consumption and inter-regional electricity transfers in and out, and studying the carbon reduction effects of green technology innovation from a provincial-level regional perspective in China. The heterogeneity of the regional impact is analyzed for different levels of economic development, different talent pools and different environmental management inputs. It further explores the carbon reduction pathways of green technology innovation and provides empirical evidence for the emission reduction effects of green technology innovation, with a view to vigorously promoting technological innovation.

3. Methods and Data

3.1 Model

This paper selects the STIRPAT model, which is an evolutionary optimization of the IPAT model by Richard et al (2003) and is now widely used to study environmental influences. the standard form of the IPAT model is:

$$I = aP^{b}A^{c}T^{d}e \tag{1}$$

Where I, P, A and T denote environment, population, property and technology levels respectively, the STIRPAT model logs the variables to eliminate the effect of heteroskedasticity to some extent:

$$lnI = lna + blnP + clnA + dlnT + lne \tag{2}$$

In this paper, following the idea of the STIRPAT model, carbon dioxide emissions are selected to characterize the environment I, the number of resident population to characterize the population P, GDP per capita to characterize the wealth level A, and the number of green patent applications to characterize the technology level T. In addition to this, the STIRPAT model is extended by introducing energy structure, industrial structure, energy intensity, openness to the outside world and forest cover as control variables to construct an econometric model of the carbon reduction effect of green technological innovation, with the following expressions:

$$\begin{aligned} lnCE = lnc + a_1 lnGP_{it} + a_2 lnGDPP_{it} + a_3 lnPOP_{it} + a_4 lnEI_{it} \\ + a_5 lnES_{it} + a_6 lnIS_{it} + a_7 lnFOR_{it} + a_8 lnOP_{it} + \mu_i + \mu_t + \varepsilon_{it} \end{aligned} \tag{3}$$

Where the subscript i denotes province and t denotes year. CE denotes CO_2 emissions, which is the explanatory variable in this paper, and GP denotes green technology innovation, which is the core explanatory variable in this paper. The control variables in this paper include: GDP per capita (GDP), number of resident population (POP), energy intensity (EI), energy mix (ES), industrial mix (IS), forest cover (FOR) and openness to the outside world (OP).

3.2 Data

3.2.1 Data descriptions

This paper constructs a provincial panel data of 30 provinces and municipalities in China from 2005 to 2021. We select CO_2 emissions as the explanatory variable. Currently, most scholars use the IPCC method to account for CO_2 emissions (Su et al., 2023). The IPCC method is to calculate the sum of CO_2 produced by the consumption of various types of energy, and this method is closer to the real value. In this paper, we also refer to the method provided by the IPCC to account for the CO_2 emissions of each province in China. The calculation method is shown in formula (4).

$$CE_{en} = \sum_{i=1}^{n} E_i \times NCV_i \times CEF_i \times COF_i \times \frac{44}{12} \tag{4}$$

where CEen is CO_2 emission; i represents the type of energy, including the consumption of coal, diesel, gasoline, paraffin, crude oil, fuel oil, coke and natural gas; E represents the energy consumption; NCV represents the average low-order calorific value of an energy, referring to the "General Principles for the Calculation of Comprehensive Energy Consumption (GB/T2589-2020)"; CEF represents the carbon content per unit of calorific value of an energy and COF is the carbon oxidation factor of an energy, referring to the "Guidelines for the Preparation of Provincial Greenhouse Gas Inventories"; 44/12 represents the molecular mass ratio of CO_2 to carbon.

In this paper, we consider the transfer of electricity in and out on the basis of the IPCC method for accounting for CO_2 emissions in each region. From the perspective of social responsibility, although the transfer of electricity from other provinces does not produce actual CO_2 emissions, the electricity is used for production and living in the region and should be included in the CO_2 emissions of the region. The net transfer in of electricity is multiplied by the baseline emission factor of the national regional grid for the year to obtain the CO_2 emissions of electricity, as follows:

$$CE_{ele} = TRANS \times OM \tag{5}$$

Where, CEele represents the local CO_2 emissions that should be accounted for in the process of power transfer in and out; TRANS refers to the local net power transfer in, which is the local power transfer in minus the local power transfer out, and the data comes from the China Energy Statistical Yearbook; OM refers to the power CO_2 emission factor, and the data comes from the China Regional Grid Baseline Emission Factor.

Therefore, this paper considers both energy consumption and electricity transfer in and out to account for regional CO_2 emissions, as follows:

$$CE = CE_{en} + CE_{ele} \tag{6}$$

We select green technology innovation as the core explanatory variable. The sum of the number of green invention patent applications and the number of green utility patent applications is used to characterize green technology innovation.

In this paper, the share of clean energy (SCE) is chosen as a mediating variable and is characterized by the share of gas consumption in energy consumption.

Finally, we select GDP per capita (GDPP), population size (POP), energy intensity (EI), industrial structure (IS), energy structure (ES), forest cover (FOR) and degree of external openness (OP) as control variables. The specific meaning of all the variables, their respective symbols and measurements are illustrated in Table 1.

Table 1: Variable selection and description

	Symbol	Variable	Description	Unit
Dependent variable	CE	CO_2 emissions	CO_2 emissions	10 thousand ton
Independent variable	GP	green technology innovation	green patent applications	pieces
	GDPP	GDP per capita	GDP/total population	%
	POP	population size	total population	10 thousand people
	EI	energy intensity	energy consumption/GDP	%
	ES	energy structure	coal consumption/energy consumption	%
	IS	industrial structure	secondary industry value added/GDP	%
	FOR	forest cover	forest coverage rate	%
	OP	degree of external openness	foreign direct investment/GDP	%
Intermediate variables	SCE	share of clean energy	gas consumption/energy consumption	%

3.2.2 Data Sources

The sample of this paper is 30 provinces (excluding Tibet, Hong Kong, Macau and Taiwan), and the time period is from 2005 to 2021. Data on GDP, value added of secondary industry, resident population and forest coverage rate are obtained from the China Statistical Yearbook. Energy consumption, coal consumption, diesel consumption, gasoline consumption, paraffin consumption, crude oil consumption, fuel oil consumption, coke consumption, electricity consumption and gas consumption are from the China Energy Statistical Yearbook. Full-time equivalent of R&D personnel and patent applications come from the China Science and Technology Statistical Yearbook. Green patent applications are from CNRDS database. Foreign direct investments are obtained from China Outward Direct Investment Statistical Bulletin of previous years.

3.2.3 Descriptive statistics

Table 2 gives descriptive statistics; CE represents CO_2 emissions, GP represents the number of green patent applications, GDPP represents GDP per capita, POP represents the number of urban residents, EI represents energy intensity, ES represents energy structure, IS represents industrial structure, FOR represents forest cover, OP represents openness to the outside world, and SCE represents cleanliness. The maximum value of CE is more than 100 times larger than the minimum value, indicating that the spatial and temporal distribution of CO_2 emissions in Chinese cities varies greatly. The maximum value of GP is 63,361, while the minimum value is only 11. This indicates that there is a large difference in the number of green patents between regions in China, and also reflects the wide gap in the level of green technology innovation between regions. The mean value of SCE is 0.06, which indicates that the average cleanliness level of Chinese production is low and there is some room for improvement.

Table 2: Descriptive statistic of the variables

Variable	Obs	Mean	Std.	Min	Max
CE	510	395.56	300.38	15.46	1660.14
GP	510	5234.62	8734	11.00	63361.00
GDPP	510	4.52	3.02	0.52	18.75
POP	510	4518.96	2773.33	543.00	12684.00
EI	510	1.32	0.94	0.17	5.56
ES	510	0.52	0.16	0.01	0.83
IS	510	0.43	0.08	0.16	0.62
FOR	510	33.47	17.97	4.00	66.80
OP	510	221.96	178.78	0.61	1010.83
SCE	510	0.06	0.06	0.00	0.38

4. Main Results

4.1 Panel unit root test

Before setting up the model and estimating the parameters, the core explanatory variables, the explanatory variables, the control variables and the mediating variables are tested for stationarity in order to increase the credibility of the regression results and to avoid pseudo-regressions. In this paper, unit root tests are carried out using the LLC test. As shown in Table 3, the original hypothesis of "existence of unit root" is rejected at the 1% level for all variables, indicating that the original data are all stationary of order zero and the variables are stationary.

Table 3: Results of stationarity test

Variable	t	P
lnCE	-6.240	0.000
lnGP	-4.226	0.000
lnGDPP	-4.869	0.000
lnPOP	-6.775	0.000
lnEI	-8.673	0.000
lnES	-2.018	0.022
lnIS	-2.792	0.026
lnFOR	-3.424	0.003
lnOP	-4.911	0.000
lnSCE	-7.634	0.000

4.2 Impact of green technology innovation on carbon emission reduction

In this paper, through the Hausman test and F-test, the fixed-effects model is optimal among the fixed-effects, random-effects and mixed-effects models, so the fixed-effects model is chosen to be used for the baseline regression.

Column (1) of Table 4 controls for province fixed effects and column (2) controls for both province and time fixed effects to analyze the carbon reduction effects of green technology innovation. The results in both columns (1) and (2) are significant. The coefficient of the explanatory variable (GP) is -0.05, which is significant at the 10% level when controlling for both time and region. It indicates that each unit increase in green technology innovation can reduce CO_2 emissions by 5%. In addition, the fixed effects regression model passes the F-test at a significance level of 1%, indicating that the linear relationship between the explanatory variables and all the explanatory variables in the model is significant in general.

For the control variables, the signs, absolute values and significance levels of the variables remained largely consistent across all regression results. As GDP per capita rises, the size of the resident population increases, and energy intensity increases, CO_2 emissions also increase significantly. Both GDP per capita and population growth can lead to increased consumption and urban expansion. It not only directly increases the demand for energy, but also indirectly consumes resources by expanding facilities and increasing the demand for other goods or services, thus leading to an increase in CO_2 emissions. An increase in energy intensity can significantly lead to an increase in CO_2 emissions. This is mainly due to the insufficient coverage and level of development of green technologies. This also shows the importance of paying attention to technological progress and innovation in the development of green technologies.

Table 4: Baseline regression results

	Dependent variable: lnCE				
Variable	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
lnGP	-0.019* (-1.97)	-0.050* (-1.82)	-0.066* (-1.85)	-0.078** (-2.75)	-0.052* (-1.74)
lnGDPP	1.052*** (17.02)	0.881*** (6.64)	0.851*** (7.24)	0.910*** (5.46)	0.899*** (6.32)
lnPOP	1.267*** (6.12)	1.171*** (6.91)	1.092*** (6.78)	1.399*** (4.96)	1.189*** (6.50)
lnIS	-0.067 (-0.68)	0.043 (0.37)	0.033 (0.25)	-0.008 (-0.06)	0.037 (0.33)
lnES	0.057 (1.50)	0.055 (1.42)	0.059 (1.49)	0.041 (1.15)	0.053 (1.33)
lnEI	1.208*** (8.83)	1.186*** (9.40)	1.169*** (9.32)	1.225*** (9.09)	1.191*** (8.78)
lnFOR	0.133 (1.33)	0.078 (0.63)	0.144 (1.03)	-0.113 (-0.42)	0.060 (0.49)
lnOP	0.020* (1.82)	0.016 (1.25)	0.013 (1.14)	0.030 (1.58)	0.021 (1.33)
Constants	-1.901 (-1.02)	-0.631 (-0.42)	-0.520 (-0.35)	-1.636 (-0.73)	-0.723 (-0.45)
Number of observations	510	510	510	360	480
R^2	0.888	0.895	0.896	0.736	0.867
Individual fixed effects	Yes	Yes	Yes	Yes	Yes
Time fixed effects	No	Yes	Yes	Yes	Yes
F	0.000	0.000	0.000	0.000	0.000

4.3 Robustness tests

4.3.1 Changing the measure of the core explanatory variable

This paper changes the measure of the explanatory variables and uses the relative value of green patent applications, i.e. the share of green patent applications in the number of patent applications, to characterize them. The fixed effects regression is still used and the results are shown in column (3) of Table 4. The coefficient on the explanatory variable (GP) is -0.066, which is significant at the 10% level. The above results are consistent with the empirical results in the previous section, indicating that this paper has more robust results.

4.3.2 Changing the time interval

In this paper, we change the time interval and select the data from 2010 to 2021, and still use fixed effects regression. The results are shown in column (4) of Table 4. The coefficient of the explanatory variable (GP) is -0.078, which is significant at the 5% level, which is consistent with the above empirical results and indicates that the results are robust.

4.3.3 Lagged variables

In this paper, the green technology innovation variable is lagged by one period. A fixed effects model regression is taken and the results are shown in column (5) of Table 4. The coefficient of the explanatory variable (GP) is -0.052, which is significant at the 10% level and remains consistent with the baseline regression results. This indicates that the carbon reduction effect of green technology innovation is robust.

4.4 Heterogeneity analysis

4.4.1 Analysis of heterogeneity across levels of economic development

The level of economic development affects the development and introduction of green technologies. In this paper, the regressions are grouped according to the GDP per capita of each province in 2021. The 30 provinces are divided into economically developed (GDP per capita greater than CNY 66,000) and economically underdeveloped (GDP per capita less than CNY 66,000) regions, using CNY 66,000 as the dividing line. As shown in Table 5, column (1) shows the regression results for economically developed regions and column (2) shows the regression results for economically underdeveloped regions. We can find that the coefficient of the explanatory variable (GP) for economically developed regions is -0.041, which is significant at the 10% level. This indicates that green technology innovation plays a significant role in reducing emissions in this region. The core explanatory variable (GP) for economically underdeveloped regions failed to pass the significance test. This indicates that in economically underdeveloped regions, green technology innovation has not yet demonstrated significant emission reduction effects.

Possible reasons for this result are: firstly, the poor level of economic development means that factor remuneration is low and the ability to gather scientific and technological talent is weak. This can affect the carbon reduction effect of green technology innovation. Second, the level of economic development is directly related to the ability of fiscal spending on science and technology. The lower level of fiscal revenue in economically underdeveloped regions leads to their weaker ability to invest in R&D. The limited investment in R&D technology can hardly make a significant impact in the short term.

4.4.2 Analysis of the heterogeneity across levels of human resource reserves

Human capital is seen as an important driver of technological innovation, and is distinguished from general labor by its ability to bring greater value-added to firms through its knowledge and skills (Canto et al., 1999). Pavel and Chirantan (2017) argue that public companies with more talented people can consistently engage in green innovative behavior and achieve higher quality. The mechanism by which technological human capital drives technological innovation lies in the accumulation of knowledge and experience by talented people, resulting in intelligent thinking that can improve productivity and technology. This kind of thinking can lead to knowledge spillover, collective learning, and idea transformation for companies thus driving the introduction of technology, learning and the ability to innovate on their own.

Based on the above analysis, the quantity and quality of human capital directly affects the output and level of regional technological innovation. This paper therefore regresses the provinces into groups according to the full time equivalent of R&D personnel in 2021. Using a threshold of 120,000 people, they are divided into regions with high reserves of science and technology human resources (R&D personnel full-time equivalent greater than 120,000) and regions with low reserves (R&D personnel full-time equivalent less than 120,000) to explore the differences in the impact of green technology innovation under different innovative human resource reserves. As shown in Table 5, column (3) indicates the regression results for regions with a rich reserve of technological human resources, while column (4) indicates the regression results for regions with a low reserve of technological human resources. We find that green technology innovation can reduce CO_2 emissions by 5.7% in regions with a rich pool of scientific and technological human resources. The core explanatory variable for the regions with less technological and human resources fails the significance test. This indicates that the effect of green technology innovation on emission reduction is not significant in regions with low human resources in science and technology. Researchers are the main force in green technology research and development, and the number of scientific and technological human resources in a region directly affects its green technology innovation capacity and the level of transformation of results. This agglomeration effect of scientific and technological human resources can bring significant positive externalities and enhance the effect of emission reduction.

4.4.3 Analysis of the heterogeneity across levels of environmental governance inputs

Government environmental governance investment can be seen as an expenditure-based environmental regulation tool, which is an economic expression of the government's performance of environmental governance functions (Huang et al, 2019). Government environmental investment can stimulate green technology innovation in three ways. The first is to help enterprises increase access to funding for research and development. Environmental protection investment as a financial subsidy, on the one hand, can directly increase the enterprises' green technology research and development funds (Eduardo et al., 2020). On the other hand, it has a policy guidance role, showing a positive signal of good development trends and attracting investors to invest in enterprises (Wu, 2017). The second is to raise the environmental awareness of enterprises. According to government intervention theory, when relevant government departments issue environmental protection investment policies, it stimulates enterprises to pay attention to technological innovation. It will also increase management's awareness of protecting the environment and taking environmental factors into account in the behavioral functions of firms' production decisions (Barbieri et al., 2020). The third is to improve the failure of the market for green technology innovation. At present, as China's intellectual property rights system needs to be further improved, the high level of investment in R&D and the vulnerability of enterprises to theft have led to a market failure in which the benefits of green technology innovation for enterprises are less than those for society, and the effective supply is lower than the demand (Wang and Yu, 2021). Environmental investment can not only focus on infrastructure development and create a better environment for technological research and development, but can also stimulate the development of regional green industries, expand the market for green products and increase the expected return on the application of green technologies by enterprises (Wu and Hu, 2020).

Through the above analysis, it is concluded that environmental protection investment can motivate enterprises to green technology. Therefore, this paper divides the provinces into regions with high investment in environmental governance (environmental protection investment greater than 16 billion yuan) and low investment (environmental protection investment less than 16 billion yuan) according to the amount of local fiscal expenditure on environmental protection in 2021, using 16 billion yuan as the threshold to examine the carbon reduction differences of green technology innovation under different environmental governance investment. As shown in Table 5, column (5) indicates regions with high investment in environmental governance and column (6) indicates regions with low investment in environmental governance. We find that green technology innovation can reduce carbon emissions by 4.9% in regions with high environmental governance inputs. The core explanatory variables for regions with low environmental inputs fail the significance test. This indicates that green technology innovation has no significant emission reduction effect in areas with low environmental governance investment. This empirical result is consistent with the theoretical analysis that environmental governance input is a financial input based on pollution control in different environmental media, and its level of input has an impact on the clean technology innovation of pollution-intensive enterprises and the accelerated development of green and low-carbon industries. This can stimulate some enterprises to increase the research, development and introduction of green technologies and bring into play the carbon emission reduction effect.

Table 5: Heterogeneity test

	Dependent variable: lnCE					
Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
lnGP	-0.041* (-2.14)	-0.013 (-0.30)	-0.057** (-2.47)	-0.060 (-1.17)	-0.049** (-2.25)	-0.044 (-1.04)
lnGDPP	1.040*** (15.95)	0.771*** (3.37)	0.795*** (3.96)	0.945*** (4.69)	0.846*** (5.40)	0.871*** (3.97)
lnPOP	1.064*** (7.38)	0.502 (1.04)	1.213*** (3.58)	0.977*** (3.03)	1.428*** (3.83)	0.976*** (3.51)
lnIS	-0.076 (-1.30)	0.139 (0.76)	0.371 (1.00)	0.006 (0.04)	0.488 (1.28)	0.144 (0.38)
lnES	0.061*** (5.10)	0.297* (2.14)	0.072** (2.07)	0.160 (0.83)	0.057 (1.54)	1.257 (0.66)
lnEI	1.036*** (23.13)	1.280*** (7.09)	1.172*** (8.70)	1.249*** (8.92)	1.199*** (8.49)	1.257*** (8.02)
lnFOR	0.048 (0.73)	0.267 (0.79)	0.320 (1.47)	0.202 (0.63)	0.213 (1.08)	0.260 (0.69)
lnOP	-0.009 (-1.18)	0.011 (0.72)	0.002 (0.13)	-0.002 (-0.17)	-0.004 (-0.24)	0.004 (0.32)
Constants	0.405 (0.86)	3.995 (1.17)	-1.337 (-0.41)	0.561 (0.25)	-2.838 (-0.81)	0.241 (0.13)
Number of observations	255	255	255	255	255	255
R^2	0.987	0.899	0.924	0.896	0.928	0.895
Individual fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes

4.5 Analysis of the mechanism of action

Through the above analysis, it can be found that the carbon emission reduction effect of green technology innovation has some differences in regions with different degrees of economic development, different status of human resources in science and technology, and different investment in environmental management. In order to further examine the influence mechanism that produces the carbon emission reduction effect, this paper identifies it from the energy perspective.

Table 6, column (1) shows the emission reduction effect of green technology innovations, which can reduce CO_2 emissions. Further, the article examines how green technology innovations reduce emissions, using the share of clean energy (lnSCE) to test the mechanism of action. Table 6 (2) shows the effect of green technology innovation on the share of clean energy, and the results show that green technology innovation can increase the share of clean energy use by 31.1%. On the one hand, green technology innovation covers areas such as clean production and clean energy, mainly through optimizing production processes and improving technology to achieve cleaner production and thus reduce carbon emissions (Madaleno et al., 2022). On the other hand, the spread of the concept of green development has led to an increase in the environmental protection philosophy of consumers, and green product innovation has met the public's demand for green consumption. The public's green consumption preference stimulates healthy competition among enterprises to produce green products, further spreading the signal of cleaner production to achieve low carbon development (Liu et al., 2017).

Table 6: Test of mechanism

	lnCE	**lnSCE**
Variables	**(1)**	**(2)**
lnGP	-0.050* (-1.82)	0.311* (1.84)
lnGDPP	0.881*** (6.64)	-1.942*** (-3.01)
lnPOP	1.171*** (6.91)	-0.433 (-0.36)
lnIS	0.043 (0.37)	1.580*** (2.47)
lnES	0.055 (1.42)	-0.179 (-0.79)
lnEI	1.186*** (9.40)	-1.225*** (-3.08)
lnFOR	0.078 (0.63)	-0.608 (-0.54)
lnOP	0.016 (1.25)	0.079 (0.79)
Constants	-0.631 (-0.42)	1.363 (0.15)
Number of observations	510	510
R^2	0.895	0.586
Individual fixed effects	Yes	Yes
Time fixed effects	Yes	Yes

5. Conclusion

Based on data from 30 provincial-level regions in China from 2005 to 2021, this paper uses a fixed-effects model to study the CO_2 emission reduction effect of green technology innovation. We conduct a series of robustness tests, identify the differences in the emission reduction effect of green technology innovation in different regions and study the carbon reduction pathways of green technology innovation. Finally, we obtain the following conclusions:

(1) From the baseline regression results, green technology innovation has a significant carbon emission reduction effect, with each unit increase in green technology innovation achieving a 5% CO_2 reduction. This result remains robust after replacing the core explanatory variable measures, changing the sample interval and lagging the variables by one period.

(2) Heterogeneity analysis shows that the emission reduction effect of green technology innovation is economically heterogeneous, heterogeneous in terms of human resources in science and technology, and heterogeneous in terms of environmental management inputs. Specifically, the emission reduction effect of green technology innovation is significant in regions with developed economies, abundant human resources in science and technology and high investment in environmental management.

(3) The analysis of the mechanism of green technology innovation's effect on carbon emission reduction shows that green technology innovation achieves CO_2 emission reduction by improving the level of cleanliness.

Based on the above findings, we have some suggestions for investors. First, strengthen the macro policy guidelines for green technology innovation. The national level should accelerate the formulation of action plans for green technology development in the context of carbon peaking and carbon neutrality, and establish a phased and dynamically adjustable roadmap for green technology development. Green technology selection targets for different industries should be further clarified, and guidelines for green technology optimization based on total CO_2 emission and intensity control targets should be established. Second, increase financial support for green technology innovation. The deployment and implementation of national carbon neutral and carbon peaking key R&D programs should be accelerated. Set up a number of special funds in the field of green and low-carbon technologies. It should promote the cultivation of green and low-carbon technology leaders and use financial funds to nurture and support young scientists to carry out green technology research and development. Special funds should be set up for the transfer and transformation of green technology achievements by enterprises to support innovative enterprises in green and low-carbon fields to carry out green technology demonstrations on the ground. Third, reduce the regional imbalance in the development of green technologies. Combining the characteristics of regional development, increase support for the research, development and introduction of green technologies in less developed regions, and adopt financial subsidies and other multifaceted policy instruments to promote green technology innovation. It should deepen the exchange and cooperation of green technologies between regions and promote the targeted assistance of developed regions to less developed regions in green technology talent training. Cross-regional green technology trading should be explored and pilot demonstrations of green technology in key industries, enterprises and industrial parks should be strengthened.

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