PROBLEMY EKOROZWOJU – PROBLEMS OF SUSTAINABLE DEVELOPMENT
2021, 16(2), 147-157
DOI: 10.35784/pe.2021.2.15

The Effect of Green R&D Activities on China's SO_2 Emissions: Evidence from a Panel Threshold Model

Wpływ ekologicznych działań badawczo-rozwojowych na emisje SO_2 w Chinach – dane z panelowego modelu progowego

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Abstract

Previous studies on the effectiveness of improving sustainable development have acknowledged the importance of domestic research and development (R&D) activities. However, these studies remain general and ambiguous because they assume that all R&D activities are related to energy-saving and sustainable development. The corresponding empirical evidence is scabrous and ambiguous. In this paper, we focus on the effect of green innovation R&D activities on SO_2 emission which is an important greenhouse gas affect global climate change and eco-civilization. Considering that there is heterogeneity exists in the innovation activities, the R&D activities are divided into three performers with two purposes. The empirical results based on a Chinese inter-provincial dataset of 2000-2016 suggest that the green innovation R&D activities are crucial for the reduction of the SO_2 emission. However, the innovation R&D activities of different purposes and performers show statistically differentiated effects on SO_2 emission. The major positive effect of green innovation R&D activities on SO_2 emissions reduction is mainly from enterprises and utility-type of R&D activities. A further study based on the panel threshold also indicates that effects of green innovation R&D activities on SO_2 emissions are nonlinear, depending on the technology absorptive ability.

Key words: green innovation activities, SO_2 emissions, technology absorptive ability, sustainable development

Streszczenie

Dotychczasowe badania nad zrównoważonym rozwojem potwierdziły znaczenie krajowych działań badawczo-rozwojowych (B + R). Jednak badania te pozostają ogólne i niejednoznaczne, ponieważ zakładają, że wszystkie działania B + R są związane z energooszczędnością i zrównoważonym rozwojem. Odpowiednie dowody empiryczne są niejednoznaczne. W artykule skupiamy się na wpływie działań badawczo-rozwojowych związanych z zielonymi innowacjami na emisję SO_2, który jest ważnym gazem cieplarnianym, wpływającym na globalne zmiany klimatyczne. Biorąc pod uwagę, że istnieje heterogeniczność działań innowacyjnych, działalność B + R wskazano 3 aktorów z 2 celami. Wyniki empiryczne oparte na chińskim międzyprowincjalnym zbiorze danych z lat 2000-2016 sugerują, że działania badawczo-rozwojowe związane z zielonymi innowacjami są kluczowe dla redukcji emisji SO_2. Jednak innowacyjne działania o różnych celach i różnych wykonawcach wykazują statystycznie zróżnicowany wpływ na emisję SO_2. Główny pozytywny wpływ działań B + R w zakresie zielonych innowacji na redukcję emisji SO_2 wynika głównie z działalności przedsiębiorstw i działalności B + R o charakterze użytkowym. Dalsze badanie oparte na panelu wskazuje również, że wpływ działań badawczo-rozwojowych związanych z zielonymi innowacjami na emisje SO_2 jest nieliniowy, w zależności od zdolności absorpcyjnej technologii.

Słowa kluczowe: ekologiczne działania innowacyjne, emisje SO_2, zdolność absorpcji technologii, zrównoważony rozwój

1. Introduction

Over the past 40 years of reform and opening up, China's sustainable development is becoming increasingly severe that attracts worldwide attention. The area of acid rain has already accounted for 30% of the country's land. The economic loss caused by acid rain and SO_2 pollution is more than 100 billion yuan per year. China's SO_2 emissions rank first in the world and have exceeded 20 million tons for many years[1]. Sustainable development has always been a hot topic and the ultimate goal of global economic development. As the best embodiment of sustainable development, green energy-saving has been valued by governments of all countries, and China has taken green innovation and energy reduction as a long-term implementation of the whole society.

SO_2 emissions not only harms human health, but also forms acid rain, corrodes building materials, and damages the ecosystem, which are resulting in huge economic losses and it becomes one of the important factors of restricting the sustainable development of the environment and society. According to the report entitled with *Towards an environmentally sustainable future: the national environmental analysis of the People's Republic of China* jointly published by Asian Development Bank and Tsinghua University in 2013, among the 10 most polluted cities by SO_2 all over the world, China accounted for 70%. As an important factor of sustainable development, the SO_2 emissions have become an intractable problem that needs to be solved urgently. A series of reasons such as coal-based energy structure, immature desulfurization technology, and low pollutant discharge fees have caused serious SO_2 pollution facts which have affected the sustainable development of society and economy. Under this background, the analysis the driving forces of the change in SO_2 emissions has important implications in solving the contradiction between sustainable development and energy intensity. It is a possible way for China to join the management of climate change, and promote green transformation and development, as well as actively participating in new opportunities for global low-carbon development, and cultivating new motivation for sustainable development.

2. Literature review

Most scholars have investigated the driving forces of the change in SO_2 emissions, finding that the domestic R&D activities and structural change are important for SO_2 emission reduction. For instance, Voigt et al. (2014) used the World Input-Output Database to analyze energy intensity trends and drivers in 40 major economies around the world. They believe that technological advancement is the most important cause of the decline in energy intensity during the period 1995-2007. Yu (2012) used the spatial panel model to analyze the influencing factors of China's inter-provincial energy intensity from 1988 to 2007, whose research results show that the increase of R&D investment can significantly reduce China's energy intensity, while the heavy industry-based economic structure and coal-based energy consumption structure significantly hinders China's energy reduction. At the industry level, by employing the two-stage least square method, Shen and Lin (2020) report that the R&D inputs is positively associated with the energy intensity reduction for China's 27 manufacturing industrial sub-sectors over the period of 2001-2014.

Based on the literature above, it can be found that the increase in R&D activities helps to reduce SO_2, but these research results only consider the impact of overall R&D activities on SO_2, and do not distinguish between R&D activities related to green innovation and R&D not related to green innovation. In fact, not all R&D activities will affect environmental variables. Therefore, the research conclusions and policy recommendations obtained from the above studies are not scientific. In order to explore the impact of R&D activities on SO_2 more specific, it is necessary to focus on green R&D innovation activities.

Due to the importance of the SO_2 emissions, there have been a number of researchers who explored the driving factors behind China's SO_2 emission, and accordingly put forward policy guidance for the reduction of the SO_2 emission. Most of the existing researches focus on the effects of the entire technological innovation activities on CO_2, SO_2, etc. (Xu et al., 2019; Zheng et al., 2019; Li et al., 2012). In fact, only green innovation R&D activities can significantly affect CO_2 and the SO_2 emission (Zhang et al., 2015; Li et al., 2018; Cai et al., 2019; Teng et al., 2019). This also makes the relevant research conclusions and policy recommendations too scabrous and ambiguous, which make it is worth to be further discussed.

Second, significant heterogeneities exist within the green R&D activities. Different types of green R&D activities will result in differentiated ecological outcome. For example, there are different purposes of green R&D activities, which can be divided into untility-type activities and innovation-type activities. We can expect these two different types of activities have different effects on eco-civilization variables. Untility-type activities focus on practical value, which may have greater effect on SO_2 emissions. Although innovation-type activities show more attention to most advanced technology, they

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[1] Based on the air quality report from Ministry of Ecology and Environment of the People's Republic of China 2001-2017.

still too stick to theoretical value which may cause less efficient to reduce SO_2 emissions.

Furthermore, the effect of green R&D activities on sustainable development is closely related to technology absorption capacity. For instance, it is more likely for the enterprises with higher level of technology absorption to have a positive effect from the R&D activities. By contrast, the ones with low level of technology absorption capacity are likely to undergo a negative spillover effect. Unfortunately, the majority of the existing studies have not given sufficient attention to this issue, and only a few scholars have carried out relevant studies. For instance, based on the panel threshold model and a China's provincial dataset over the period of 2000-2016, Chen et al. (2019) reported that when the human capital stock is low, it is hard to the provinces to expect a positive energy intensity reduction effect from the domestic R&D activities.

Similar to Steinberger et al. (2010) and Shafiei et al. (2014), Mensah et al. (2019) using STIRPAT and IPAT models, found transportation-related technologies have been beneficial to green growth in the Oceania sub-region. OECD Asia's technologies for production and processing of goods have been beneficial to green growth. Climate change technologies in relation to generation and transmission of energy are detrimental to green growth in the OECD economies and its impact is evident in Asia and Europe sub-panels. Environmental related budget and taxes have been found worthwhile in the pursuit of green growth from the dominant negative coefficient values. Various studies employ the IPAT model (Dietz et al.,1997; York et al.,2003). Wen et al. (2019) used the IPAT model and included 16 indicators from 2001 to 2016 to determine and classify the influencing factors of CO_2 emission. Empirical results show that affluence, technology and energy have a significant positive impact on CO_2 emission at the national level.

With these gaps in mind, this study focuses on the green R&D activities. The fixed effects model are employed to explore the effect of green R&D activities on SO_2 emissions at first. Considering that the impact of green R&D activities on SO_2 emissions will undergo structural break when the technology absorptive ability is at different levels, the panel threshold model is further applied. In addition, considering that there is significant heterogeneity within the green R&D activities, we divided the green R&D activities according to their purposes and the effect of green R&D activities, and an independent analysis is also conducted.

The main contributions of the current research are threefold. First, to provide the valid policy implications of sustainable development for the governments, the total R&D activities is narrowed down to its green R&D activities. Second, the green R&D activities are also classified according to their different purposes, showing more details how green R&D activities influence the sustainable development. Third, the technology absorptive ability is also incorporated as an important factor influencing the effect of green R&D activities on reducing SO_2 emissions.

The structure of the current study is as follows. As highlighted in Section 2, the literature review based on factors that influence SO_2 emissions. Section 3 undertakes the methodology and data management. Empirical results from linear regression and thresholds model are introduced in section 4. The conclusions and discussion are given in Sections 5, together with the policy implications respectively.

3. Methodology and data management

3.1. The empirical model for SO_2

The STIPRAT model is the most widely used to employ environmental problems at home and abroad . Usually, logarithms are taken on both sides of the equation to reduce data fluctuation and heteroscedasticity when processing panel data. After taking the logarithm, the equation becomes:

$$lnI_{it} = \beta_0 + \beta_1 lnP_{it} + \beta_2 lnA_{it} + \beta_3 lnT_{it} + \varepsilon_{it} \quad (1)$$

In the above equation, i stands for different provinces, t stands for time, β_0 stands for a constant term, ε_{it} is the random interference term. βm $(m = 1, 2,3)$ are the parameters to be estimated, including the impact of population size, economic development level, and technological development level on SO_2 emissions.

In practical application, since the factors affecting SO_2 emissions are not limited to the independent variables above, but also related to other variables such as urbanization and environmental management, it is necessary to add in relevant variables appropriately according to the actual case of the research problem. In order to test whether there is an environmental Kuznets curve (EKC) between SO_2 emissions and economic development level, this paper further investigates the relationship between the SO_2 emissions and the GDP per capita of each province. By taking the GDP per capita and the square of GDP per capita as the independent variables, this paper follows the double logarithmic model proposed by Shafik and Bandy Opadhyay (1992), and expands the STIRPAT model as follows:

$$ln(PSO_{it}) = \beta_0 + \beta_1 ln\,(PGDP)_{it} + \beta_2\,(\,ln\,(\,PGDP\,))^2{}_{it} + \beta_3 ln\,X_{it} + \varepsilon_{it} \quad (2)$$

In the above formula, PSO represents SO_2 emissions, β_1 and β_2 represent the coefficients of provincial GDP per capita and GDP per capita square respectively; εit represents the disturbance terms. The footnotes i (I = 1,2, 3, ..., M, N) and t(t=1,2,3,... ,S,T) represent the province and year respectively. In addition to that, X are the control variables, including IND, UR, ENSTR and FDI_STR, denoting the proportion of secondary industry to GDP, urbanization, energy structure and foreign direct investment structure, respectively. The shape of the environmental Kuznets curve can be judged by analyzing the sign of the coefficients[2].

The follow-up research of this paper will base on the equations (2). Since there may be unobservable heterogeneity in the aspects of production methods, social values, etc. among different regions, if OLS regression is directly performed on equation (2), the parameter estimation could be biased. Generally, an individual fixed effect (FE) model is used to eliminate the time-independent individual effects.

3.2. Data source and management

Since the data of Tibet, Hong Kong, Macao, and Taiwan is unavailable (cause the data cannot be captured), a panel dataset that only include China's 30 provinces between 2000 and 2016 are included in our sample analysis.

The explained variable (i.e. SO_2 emissions) is represented by the ratio SO_2 consumption divided by population (unit: Ton/person). The data on population and the SO_2 emissions are respectively sourced from China Statistical Yearbooks (CSY) from year 2001 to 2017.

GDP per capita is denoted by the ratio of GDP divided by population. Before calculating the GDP per capita, the data on GDP should be adjusted in 2000 constant price.

The ratio of the added value in the secondary industry to GDP denotes the economic structure. The proportion of FDI in fixed asset investment means the FDI structure. The effect of urbanization on SO_2 emissions is obtained by percentage of City Resident Population to total population. The corresponding data is available in the China Statistical Yearbooks. The ratio of the carbon consumption to total energy consumption denotes the energy structure. The corresponding data is available in the China Energy Statistical Yearbooks.

Energy-saving technology innovation is denoted by the number of energy-saving patents, which are sourced from the database of Chinese Patents. We obtain the number of energy-saving patents using the standard application date. The number of invention patents and utility model patents denote the different purposes of energy-saving innovations activities. The invention patents primarily represent energy-saving technological proposals on new products, new materials, and so on. Although the utility patents are less technological than invention patents, they emphasize practical application value. Finally, because of the time lag effect between energy-saving technology and SO_2 emissions, we employ the lagged energy-saving patents rather than the current energy-saving patents, in our empirical model. Consequently, the number of energy-saving patents from 1999 to 2015 in our empirical analysis is applied. Table1 provides the definition and description of all variables.

Table 1. Definition and data description of the variables

Symbol	Definition	Proxy variables	Unit
PSO	SO_2 emissions	The ratio of the SO_2 emissions divided by population	%
PGDP	GDP per capita	The ratio of GDP divided by population	%
PGDP2	GDP per capita square	The square of GDP per capita	%
IND	Economic structure	The ratio of the secondary industry to GDP	%
ENSTR	Energy structure	The ratio of the carbon consumption to total energy consumption	%
FDI-STR	FDI structure	The ration of FDI in fixed asset investment	%
UR	Urbanization	City Resident Population rate	%
ZZL	Total patent	The total energy-saving innovation activities	pcs
SYZL	Utility-type patent	The utility-type of energy-saving activities	pcs
FMZL	Innovation-type patent	The innovation-type of energy-saving activities	pcs
QY	Enterprises patent	The energy-saving innovation activities carried by enterprises	pcs
GX	University patent	The energy-saving innovation activities carried by higher education institutions	pcs
GR	Individual patent	The energy-saving innovation activities carried by individuals	pcs
FWGL	Waste management	The green innovation R&D activities carried by waste management	pcs
XZGL	Administration management	The green innovation R&D activities carried by administration management	pcs
JNJS	Energy-saving technology	The green innovation R&D activities carried by energy-saving technology	pcs
YS	Transport	The green innovation R&D activities carried by transport	pcs

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[2] The relationship between the coefficients and the EKC curve is as follows: When β_1=β_2= 0, there is no stable correlation between environmental quality and economic growth. When $\beta_1 \neq 0$, $\beta_2 = 0$, there is a monotonous increasing (or decreasing) linear relationship between environmental quality and economic growth. When $\beta_1 > 0$, $\beta_2 < 0$, the relationship between environmental quality and economic growth presents as an inverted U curve.

4. Results and discussions

4.1. Results from the Linear Regression Analysis

In Table 2, models (1) - (4) adopt fixed-effect model based on equations (2) respectively to examine the linear impact of various sources of technological progress on China's SO_2 emissions.

The regression results show that the proportion of secondary industry has a significant positive effect on SO_2 emissions. It can be seen from Table 2 that the correlation between industrial structure and provincial SO_2 emissions has passed the 1% significance test and is significantly positive. This shows that the larger the proportion of the secondary industry is, the greater the SO_2 emissions are. The environmental effect of the industrial structure is obvious. Unreasonable industrial structure will increase environmental pollution. Many scholars have done research on the environmental effects of industrial structure. For example, Ding et al. (2012) and other scholars have carried out research based on panel data of 30 provinces in China and obtained similar results. At present, although the industrial structure of most provinces in China is developing in a more rationalized fashion, some provinces still rely too much on the secondary industry, and the problems of high resource and energy consumption and serious environmental pollution still exist undoubtedly. Adjusting and optimizing the industrial structure is still a crucial issue in China's current stage of economic development. In particular, reducing the proportion of the secondary industry and improving the efficiency of economic development are important ways to improve China's environmental quality.

It is shown that the structure of FDI has a negative impact on the intensity of industrial SO_2 emissions and is significant at the 10% level. From the perspective of the effect of FDI structure on SO_2 emissions, the regression coefficients are -0.044 and -0.042, indicating that the inflow of FDI actually helps to promote the industrial sector to improve desulfurization equipment and reduce SO_2 emissions. However, judging from the significant results, this effect is very weak. In general, FDI has not shown a trend of transferring pollutants to China on a large scale but has helped to adjust and optimize related industries. By analyzing the above phenomenon, this paper believes that it is mainly caused by the following reasons. Firstly, the scale of FDI in China is constantly expanding. The advanced environmental technologies owned by foreign companies can help to promote the reduction of SO_2 emissions in the industry, and their technological spillovers to domestic companies can also compel domestic companies to lower SO_2 emissions. Secondly, with the continuous increase of FDI in China, the domestic environmental management system has been therewith strengthened, and the environmental standards for foreign-invested enterprises have been significantly heightened accordingly, meanwhile, the restrictions on the *pollution transfer* has much increased compared to that in the initial period of the opening up. China 's positive environmental spill over is getting stronger in the long run.

Urbanization is an important factor in the continuous expansion of energy use. This study shows that urbanization has a negative and insignificant effect on SO_2 emissions. This judgment is mainly based on that urbanization is an evolutionary process, and that different stages of urban development will bring forth different industrial layouts and scales. Generally speaking, the industrial layout in the early stages of urban development is more focused on industries, and this stage is where pollutants increase rapidly. As the level of economic development improves, with more capital and technology, the ability of environmental governance and the environmental standards of the foreign-invested enterprises are enhanced. Meanwhile, some outdated production lines and industries with high pollution and high energy consumption will be phased out, and transferred to under-development regions and nations. Judging from the regression results, this kind of *pollution migration* has become more obvious. The *pollution refuge* has emerged among regions of different economic development levels, that is, pollutive industries move from areas with high population density to areas with low population density.

With regard to total patents, as expected, the coefficient (i.e. ln*ZZL*) is negative and significant, this suggests that total patents will have a positive role in reducing the SO_2 emissions. A 1% increase in total patents will lead to approximately 17.3% decrease in the SO_2 emissions.

4.1.1. The effect of green innovations with different purposes

When we consider the green innovations with different purposes (i.e. ln*FMZL* and ln*SYZL*), we still employ the FE estimators to re-estimate the model. The empirical results are shown in column 3 of Table 2. Although the utility-type activities are equipped with lower technology level compared to the invention activities, they are devoted to solving the practical problems and emphasize practicability. Utility patents is significantly negative to SO_2 emissions (-0.243), while invention patents are significantly positive (0.047), which implies that invention patents hinder environmental improvement as they are not meant for practical application. As shown, it is still surprising that there are great differences in terms of the coefficients on ln*FMZL* and ln*SYZL*. Between the two different purposes of green innovations, only the utility-type activities show a positive and significant role in decreasing the SO_2 emissions, implying the major positive reduction effect of the SO_2 emissions is from utility-type activities rather than the invention activities.

Table 2. The results based on fixed effect

	d1	d2	d3	d4
ln*PGDP*	0.389*** （-0.087）	0.353*** （-0.088）	0.516*** （-0.089）	0.511*** （-0.096）
ln*PGDP2*	-0.141*** （-0.029）	-0.126*** （-0.028）	-0.088*** （-0.029）	-0.137*** （-0.028）
ln*IND*	0.531*** （-0.104）	0.514*** （-0.101）	0.507*** （-0.101）	0.475*** （-0.104）
ln*ENSTR*	0.702*** （-0.085）	0.707*** （-0.083）	0.681*** （-0.083）	0.699*** （-0.084）
ln*FDI_STR*	-0.044* （-0.023）	-0.03 （-0.023）	-0.018 （-0.023）	-0.042* （-0.023）
ln*UR*	-0.107 （-0.195）	-0.072 （-0.192）	-0.002 （-0.188）	-0.005 （-0.196）
ln*ZZL*	-0.173*** （-0.03）			
ln*SYZL*		-0.243*** （-0.033）		
ln*FMZL*		0.047* （-0.028）		
ln*FWGL*			-0.129*** （-0.031）	
ln*XZGL*			-0.065*** （-0.019）	
ln*JNJS*			0.038 （-0.024）	
ln*YS*			-0.108*** （-0.029）	
ln*QY*				-0.072*** （-0.022）
ln*GX*				-0.083*** （-0.031）
ln*GR*				-0.085*** （-0.031）
_cons	-0.944 （-0.889）	-0.928 （-0.862）	-1.102 （-0.847）	-1.092 （-0.875）
Hausman(p)	32.72***	32.17***	32.77***	40.1***
Heteroscedasticity test	1174.05***	2735.51***	1210.46***	1143.8***
Autocorrelation test	75.389***	68.702***	75.595***	69.405***
CD	38.754***	38.792***	39.282***	38.554***
N	510	510	510	510

Notes: (a) ***, **, and * denote significance at the 1% level, 5% level, and 10% level respectively. (b) Values in ( ) denote the std. error for the coefficient. (c) The null hypothesis for heteroscedasticity test is that there is no heteroscedasticity. (d) The null hypothesis for autocorrelation test is that there is no first order autocorrelation. (e) The CD test checks cross-sectional dependence of residuals. In CD test, the null hypothesis is cross-section independent.

4.1.2. The effect of green innovations with different types

When we examine the green innovations with different types (i.e. ln*FWGL*, ln*XZGL*, ln*JNJS* and ln*YS*), we still employ the FE estimators to re-estimate the model. The empirical results are shown in column 4 of Table 2. Waste management, administrative management, and transportation is all significantly negative to the SO_2 emissions, suggesting that such green innovation R&D activities have positive effect on the reduction of the SO_2 emissions, while energy saving technology does opposite. As shown, it is still surprising that there are great differences in terms of the coefficients of ln*FWGL*, ln*XZGL*, ln*JNJS* and ln*YS*. Among the four different types of green innovations, only the energy-saving technology activities show a negative role in decreasing the SO_2 emissions emission, implying the major positive reduction effect of the SO_2 emissions is not from energy-saving technology rather than other three activities.

4.1.3. The effect of green innovations with different performers

Based on the above analysis, when discussing green innovations with different performers, we can expect a positive role from utility and invention patents. This implies that green innovations with different performers are very effective in reducing SO_2 emissions per capita. However, there are significant heterogeneities within the activities because different performers undertake them, when considering R&D activities from the perspective of different performers (i.e. ln*QY*, ln*GX*, and ln*GR*). The fourth column of Table 2 shows estimates of the roles of different performers in the SO_2 emissions based on FE estimator. To examine whether the activities of universities, enterprises and individuals are beneficial in reducing the SO_2 emissions, we also employ FE for the estimation. Column 5 shows the results. The purpose of the enterprises is clear, which is to maximize profit. Besides they are at the forefront of production and understand practical production problems. Notably, all the three performers have significant influence in reducing SO_2 emissions emission, implying positive effect from green innovations carried out by different performers in reducing the SO_2 emissions. Patents from enterprises, universities and individuals are all beneficial to the reduction of SO_2 emissions, but among which the effect of university patents (-0.063) is weaker than enterprise patens (-0.083) and individual patents (-0.095), suggesting that enterprises will actively adopt energy saving technology to survive in the market of full competition and thus lowering the SO_2 emissions.

4.2. Results from the threshold models

For the purpose of comprehensively revealing the manner in which the technology absorption capacity impacts various innovations that influences China's SO_2 emissions, the panel threshold model is employed. Before carrying out the nonlinear analysis, it is necessary to test the presence of a threshold impact between technology innovations and China's SO_2 emissions with the use of *bootstrap method* put forward by Hansen. Subsequent to the application of *bootstrap method* for testing if there is a threshold effect, the number of thresholds requires estimation as follows.

$$\ln pso_{i,t} = \theta_1 X_{it}(q_{it} \le r) + \theta_2 X_{it}(q_{it} > r) + \mu_i + e_{it}\,, \quad (3)$$

where subscripts *i* and *t* represents the region and time, respectively; X corresponds to the independent variables, namely green R&D activities, economic structure, energy mix, FDI, and export; Θ_i (I = 1, 2) denotes the vectors of the coefficients on X on either side of the threshold; r represents the selected threshold value; and q denotes the threshold. The specification of model (3) could be extended to the multiple threshold case.

As indicated in Huang et al., Lai et al., and Cohen and Levinthal, human capital stock (HCS) and full-time equivalent of R&D personnel（FEP）are capable of not just serving as a key driver for accelerating the technological progress, but also improving the technology absorption capacity as well. Accordingly, HCS and FEP are typically considered to be a tool to measure technology absorption capacity. We use the number of years of education per capita to indicate HCS and number of R&D staff recruited in accordance with their duty hours to indicate FEP[3].

Table 3 and 4 provides the nonlinear estimation findings through the application of the panel threshold model when HCS is at varied levels. When selecting total patents (ln*ZZL*), utility-type patents (ln*SYZL*), invention patents (ln*FMZL*),enterprise patents (ln*QY*), university patents (ln*GX*) , individual patents (ln*GR*), together with green innovation R&D activities as the variables we are concerned about, the rejection of non-existent thresholds for the total patents (ln*ZZL*), utility-type patents (ln*SYZL*) and green innovation R&D activities generated by waste management (ln*FWGL*), administrative management (ln*XZGL*), and transportation (ln*YS*) reached significance at the 1% level. In summary, the test results in Table3 and Table 4 show that the impact of technological innovations generated by various channels on the SO_2 emissions of China has a significant threshold effect, which will change with the intensity of HCS input and is very sensitive. Table 3 and Table 4 give the specific estimation results using the threshold panel model.

As shown in Table 3, row 6 shows HCS as the threshold variable. The impact of technological innovations generated by the invention patent (ln*FMZL*) channel on the SO_2 emissions varies as the degree of HCS input changes. When the HCS entry level is less than the first threshold (i.e. 8.2146), the technological innovation effect of the invention patent channel can significantly increase SO_2 emissions. Once the HCS exceeds the first threshold but is less than the second threshold value (i.e. 9.4226), the technological spillover generated by *FMZL* chan-

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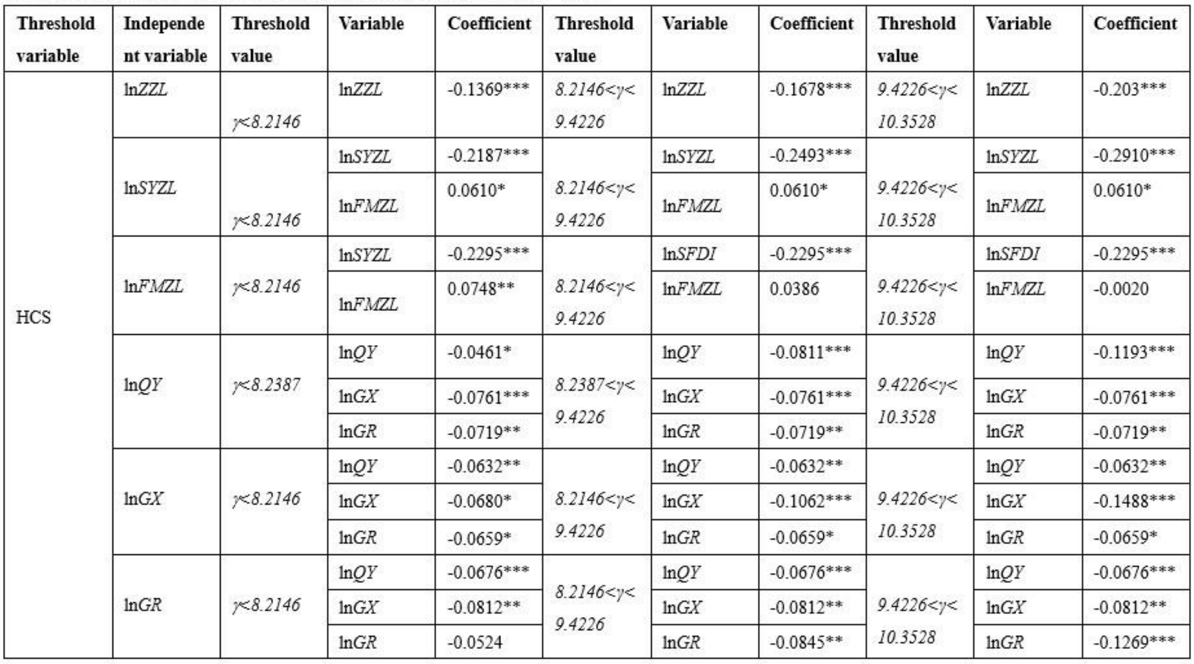
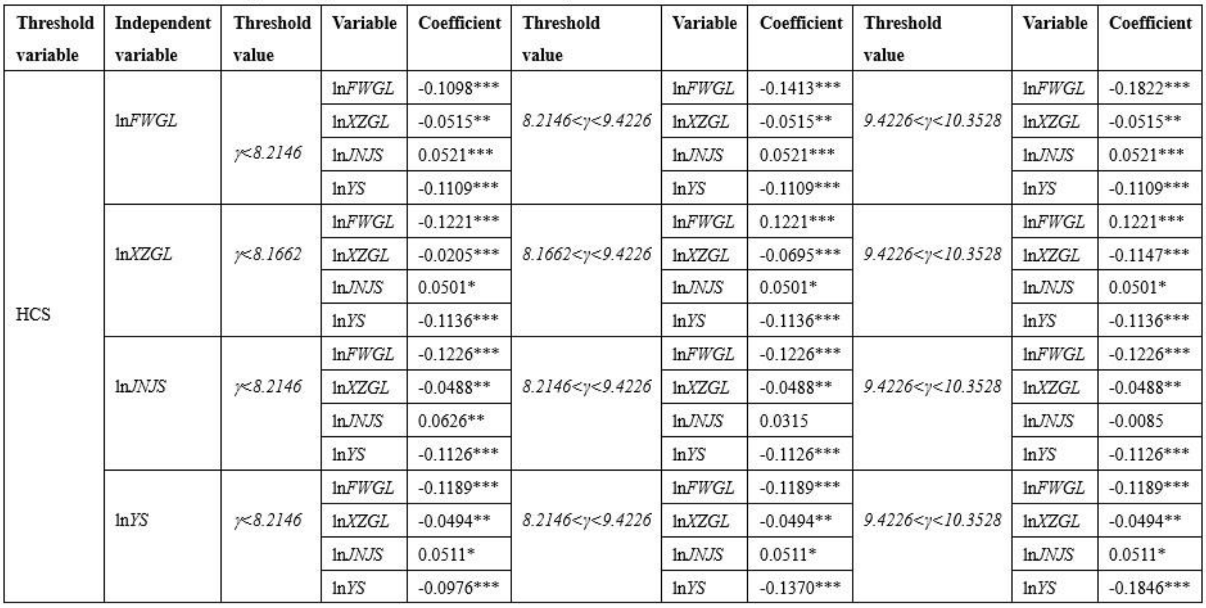
[3] when FEP or HCS is selected as another threshold variable, the test findings still clearly reject the linear structure of the model. The above empirical evidence reveals that various innovations manifest high sensitivity towards changes in HCS or FEP (paper is limited, one can ask the author for results).

Table 3. Test of threshold effects by selecting HCS as the threshold variable – part 1



Threshold variable	Independent variable	Threshold value	Variable	Coefficient	Threshold value	Variable	Coefficient	Threshold value	Variable	Coefficient
HCS	ln*ZZL*	$\gamma<8.2146$	ln*ZZL*	-0.1369***	$8.2146<\gamma<9.4226$	ln*ZZL*	-0.1678***	$9.4226<\gamma<10.3528$	ln*ZZL*	-0.203***
	ln*SYZL*	$\gamma<8.2146$	ln*SYZL*	-0.2187***	$8.2146<\gamma<9.4226$	ln*SYZL*	-0.2493***	$9.4226<\gamma<10.3528$	ln*SYZL*	-0.2910***
			ln*FMZL*	0.0610*		ln*FMZL*	0.0610*		ln*FMZL*	0.0610*
	ln*FMZL*	$\gamma<8.2146$	ln*SYZL*	-0.2295***	$8.2146<\gamma<9.4226$	ln*SFDI*	-0.2295***	$9.4226<\gamma<10.3528$	ln*SFDI*	-0.2295***
			ln*FMZL*	0.0748**		ln*FMZL*	0.0386		ln*FMZL*	-0.0020
	ln*QY*	$\gamma<8.2387$	ln*QY*	-0.0461*	$8.2387<\gamma<9.4226$	ln*QY*	-0.0811***	$9.4226<\gamma<10.3528$	ln*QY*	-0.1193***
			ln*GX*	-0.0761***		ln*GX*	-0.0761***		ln*GX*	-0.0761***
			ln*GR*	-0.0719**		ln*GR*	-0.0719**		ln*GR*	-0.0719**
	ln*GX*	$\gamma<8.2146$	ln*QY*	-0.0632**	$8.2146<\gamma<9.4226$	ln*QY*	-0.0632**	$9.4226<\gamma<10.3528$	ln*QY*	-0.0632**
			ln*GX*	-0.0680*		ln*GX*	-0.1062***		ln*GX*	-0.1488***
			ln*GR*	-0.0659*		ln*GR*	-0.0659*		ln*GR*	-0.0659*
	ln*GR*	$\gamma<8.2146$	ln*QY*	-0.0676***	$8.2146<\gamma<9.4226$	ln*QY*	-0.0676***	$9.4226<\gamma<10.3528$	ln*QY*	-0.0676***
			ln*GX*	-0.0812**		ln*GX*	-0.0812**		ln*GX*	-0.0812**
			ln*GR*	-0.0524		ln*GR*	-0.0845**		ln*GR*	-0.1269***

Table 4. Test of threshold effects by selecting HCS as the threshold variable – part 2

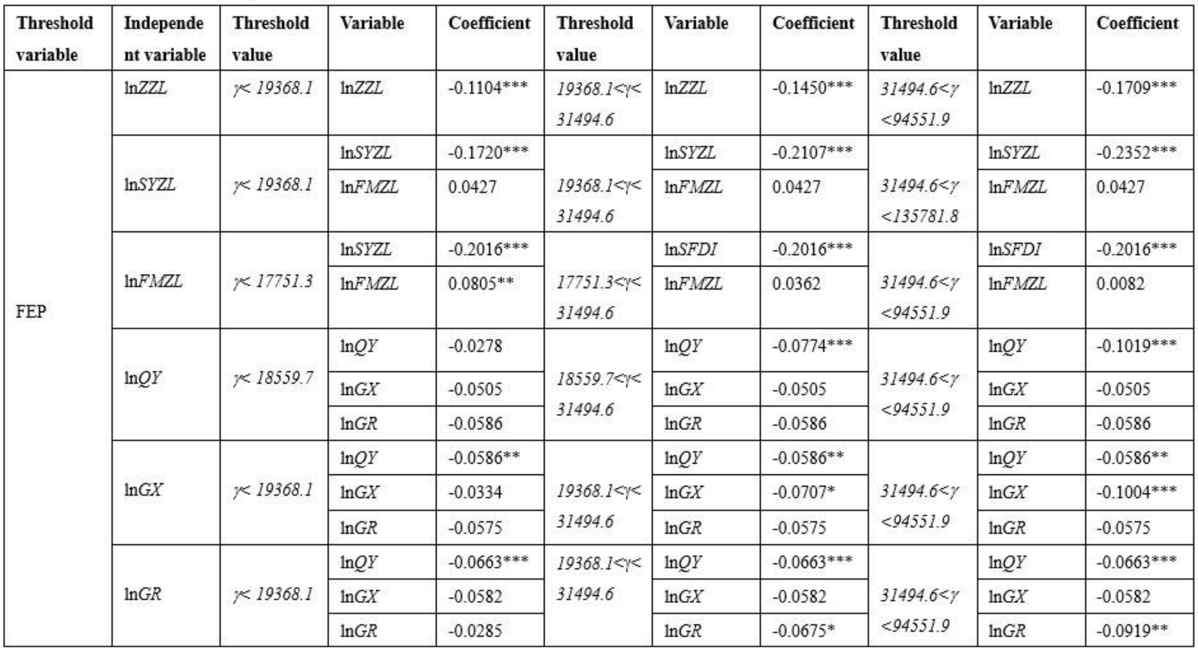


Threshold variable	Independent variable	Threshold value	Variable	Coefficient	Threshold value	Variable	Coefficient	Threshold value	Variable	Coefficient
HCS	ln*FWGL*	$\gamma<8.2146$	ln*FWGL*	-0.1098***	$8.2146<\gamma<9.4226$	ln*FWGL*	-0.1413***	$9.4226<\gamma<10.3528$	ln*FWGL*	-0.1822***
			ln*XZGL*	-0.0515**		ln*XZGL*	-0.0515**		ln*XZGL*	-0.0515**
			ln*JNJS*	0.0521***		ln*JNJS*	0.0521***		ln*JNJS*	0.0521***
			ln*YS*	-0.1109***		ln*YS*	-0.1109***		ln*YS*	-0.1109***
	ln*XZGL*	$\gamma<8.1662$	ln*FWGL*	-0.1221***	$8.1662<\gamma<9.4226$	ln*FWGL*	0.1221***	$9.4226<\gamma<10.3528$	ln*FWGL*	0.1221***
			ln*XZGL*	-0.0205***		ln*XZGL*	-0.0695***		ln*XZGL*	-0.1147***
			ln*JNJS*	0.0501*		ln*JNJS*	0.0501*		ln*JNJS*	0.0501*
			ln*YS*	-0.1136***		ln*YS*	-0.1136***		ln*YS*	-0.1136***
	ln*JNJS*	$\gamma<8.2146$	ln*FWGL*	-0.1226***	$8.2146<\gamma<9.4226$	ln*FWGL*	-0.1226***	$9.4226<\gamma<10.3528$	ln*FWGL*	-0.1226***
			ln*XZGL*	-0.0488**		ln*XZGL*	-0.0488**		ln*XZGL*	-0.0488**
			ln*JNJS*	0.0626**		ln*JNJS*	0.0315		ln*JNJS*	-0.0085
			ln*YS*	-0.1126***		ln*YS*	-0.1126***		ln*YS*	-0.1126***
	ln*YS*	$\gamma<8.2146$	ln*FWGL*	-0.1189***	$8.2146<\gamma<9.4226$	ln*FWGL*	-0.1189***	$9.4226<\gamma<10.3528$	ln*FWGL*	-0.1189***
			ln*XZGL*	-0.0494**		ln*XZGL*	-0.0494**		ln*XZGL*	-0.0494**
			ln*JNJS*	0.0511*		ln*JNJS*	0.0511*		ln*JNJS*	0.0511*
			ln*YS*	-0.0976***		ln*YS*	-0.1370***		ln*YS*	-0.1846***

nel has no significant effect on SO_2. When HCS further increases, i.e. $9.4226<\gamma<10.3528$, technological innovation in FMZL channel will reduce the SO_2 emissions. This shows that the increase in HCS has changed the negative effect of *FMZL* on the SO_2 emissions.

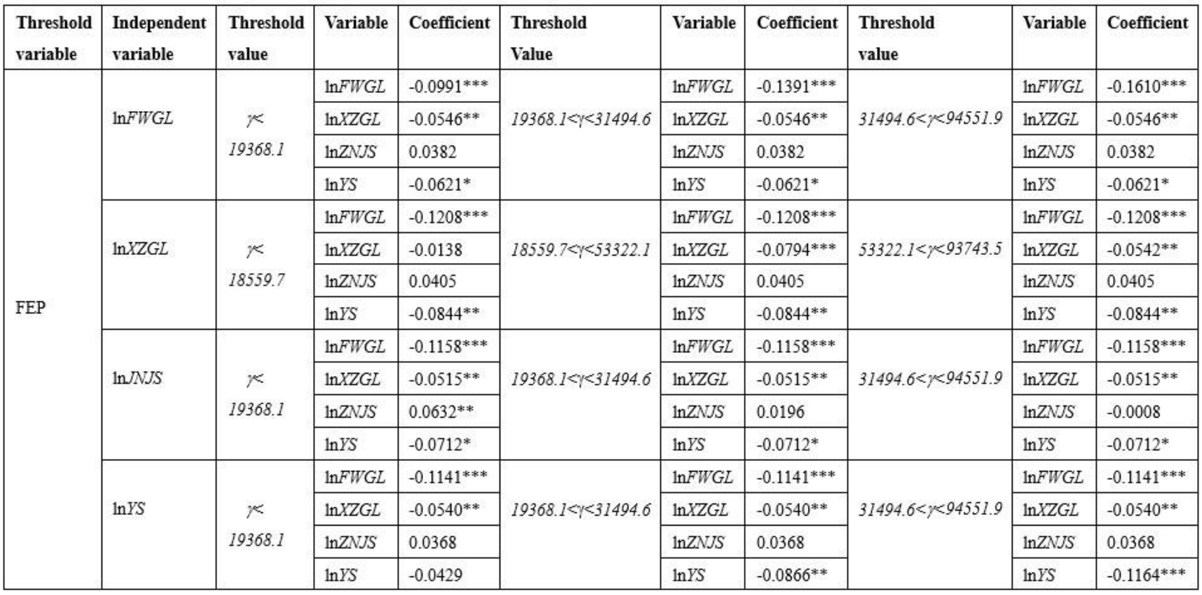
As above, the empirical results of selecting HCS as a threshold variable show that the increase in HCS can enhance the positive spillover effect of green innovation R&D activities on reducing the SO_2 emissions. The increase in HCS can make the impact of utility patents on SO_2 reduction more significant, because the enterprises in production will actively digest and absorb the SO_2 emissions reduction knowledge and technology, which will help various channels to form a positive spillover effect on reducing the SO_2 emissions. In theory, human capital can not only directly create knowledge and improve economic efficiency, but at the same time improve the performers' ability to digest and absorb advanced knowledge and technology and promote technological innovation in various channels. The empirical results show that the purpose of HCS investment by Chinese enterprises and universities is clear and can directly reduce the SO_2 emissions. This conclusion is similar to Zheng et al. (2011) who studied the nonlinear effect of independent innovation on the export channel of China 's industrial energy intensity.

Table 5. Test of threshold effects by selecting FEP as the threshold variable – part 1



Threshold variable	Independent variable	Threshold value	Variable	Coefficient	Threshold value	Variable	Coefficient	Threshold value	Variable	Coefficient
FEP	ln*ZZL*	$\gamma< 19368.1$	ln*ZZL*	-0.1104***	$19368.1<\gamma< 31494.6$	ln*ZZL*	-0.1450***	$31494.6<\gamma <94551.9$	ln*ZZL*	-0.1709***
	ln*SYZL*	$\gamma< 19368.1$	ln*SYZL*	-0.1720***	$19368.1<\gamma< 31494.6$	ln*SYZL*	-0.2107***	$31494.6<\gamma <135781.8$	ln*SYZL*	-0.2352***
			ln*FMZL*	0.0427		ln*FMZL*	0.0427		ln*FMZL*	0.0427
	ln*FMZL*	$\gamma< 17751.3$	ln*SYZL*	-0.2016***	$17751.3<\gamma< 31494.6$	ln*SFDI*	-0.2016***	$31494.6<\gamma <94551.9$	ln*SFDI*	-0.2016***
			ln*FMZL*	0.0805**		ln*FMZL*	0.0362		ln*FMZL*	0.0082
	ln*QY*	$\gamma< 18559.7$	ln*QY*	-0.0278	$18559.7<\gamma< 31494.6$	ln*QY*	-0.0774***	$31494.6<\gamma <94551.9$	ln*QY*	-0.1019***
			ln*GX*	-0.0505		ln*GX*	-0.0505		ln*GX*	-0.0505
			ln*GR*	-0.0586		ln*GR*	-0.0586		ln*GR*	-0.0586
	ln*GX*	$\gamma< 19368.1$	ln*QY*	-0.0586**	$19368.1<\gamma< 31494.6$	ln*QY*	-0.0586**	$31494.6<\gamma <94551.9$	ln*QY*	-0.0586**
			ln*GX*	-0.0334		ln*GX*	-0.0707*		ln*GX*	-0.1004***
			ln*GR*	-0.0575		ln*GR*	-0.0575		ln*GR*	-0.0575
	ln*GR*	$\gamma< 19368.1$	ln*QY*	-0.0663***	$19368.1<\gamma< 31494.6$	ln*QY*	-0.0663***	$31494.6<\gamma <94551.9$	ln*QY*	-0.0663***
			ln*GX*	-0.0582		ln*GX*	-0.0582		ln*GX*	-0.0582
			ln*GR*	-0.0285		ln*GR*	-0.0675*		ln*GR*	-0.0919**

Table 6. Test of threshold effects by selecting FEP as the threshold variable – part 2



Threshold variable	Independent variable	Threshold value	Variable	Coefficient	Threshold Value	Variable	Coefficient	Threshold value	Variable	Coefficient
FEP	ln*FWGL*	$\gamma< 19368.1$	ln*FWGL*	-0.0991***	$19368.1<\gamma<31494.6$	ln*FWGL*	-0.1391***	$31494.6<\gamma<94551.9$	ln*FWGL*	-0.1610***
			ln*XZGL*	-0.0546**		ln*XZGL*	-0.0546**		ln*XZGL*	-0.0546**
			ln*ZNJS*	0.0382		ln*ZNJS*	0.0382		ln*ZNJS*	0.0382
			ln*YS*	-0.0621*		ln*YS*	-0.0621*		ln*YS*	-0.0621*
	ln*XZGL*	$\gamma< 18559.7$	ln*FWGL*	-0.1208***	$18559.7<\gamma<53322.1$	ln*FWGL*	-0.1208***	$53322.1<\gamma<93743.5$	ln*FWGL*	-0.1208***
			ln*XZGL*	-0.0138		ln*XZGL*	-0.0794***		ln*XZGL*	-0.0542**
			ln*ZNJS*	0.0405		ln*ZNJS*	0.0405		ln*ZNJS*	0.0405
			ln*YS*	-0.0844**		ln*YS*	-0.0844**		ln*YS*	-0.0844**
	ln*JNJS*	$\gamma< 19368.1$	ln*FWGL*	-0.1158***	$19368.1<\gamma<31494.6$	ln*FWGL*	-0.1158***	$31494.6<\gamma<94551.9$	ln*FWGL*	-0.1158***
			ln*XZGL*	-0.0515**		ln*XZGL*	-0.0515**		ln*XZGL*	-0.0515**
			ln*ZNJS*	0.0632**		ln*ZNJS*	0.0196		ln*ZNJS*	-0.0008
			ln*YS*	-0.0712*		ln*YS*	-0.0712*		ln*YS*	-0.0712*
	ln*YS*	$\gamma< 19368.1$	ln*FWGL*	-0.1141***	$19368.1<\gamma<31494.6$	ln*FWGL*	-0.1141***	$31494.6<\gamma<94551.9$	ln*FWGL*	-0.1141***
			ln*XZGL*	-0.0540**		ln*XZGL*	-0.0540**		ln*XZGL*	-0.0540**
			ln*ZNJS*	0.0368		ln*ZNJS*	0.0368		ln*ZNJS*	0.0368
			ln*YS*	-0.0429		ln*YS*	-0.0866**		ln*YS*	-0.1164***

It is easy to see from table 5 and table 6 that when FEP is the threshold variable, the impact of technological innovations generated by different innovations varies with the changes in FEP. Regardless of the range of FEP, the technological innovations generated by the above channels can all play a role in reducing SO_2 emissions, which is similar to the results in table 3 and 4.

5. Conclusion and policy implications

This paper establishes a unified analysis framework that includes the technological progress formed by green innovations, and analyzes the impact of various technological progresses on the SO_2 emissions using China's inter-provincial panel data from 2000 to 2016. Firstly, this paper applies a fixed effect model to analyze and compare the impact of various sources of technological progress on the SO_2 emissions. Secondly, given that the obvious differences in technology absorption capacity may lead to differentiated effects of various technological innovations on the SO_2 emissions, this paper also applies the threshold panel model to analyze the characteristics of the impact of HCS and FEP on the SO_2 emissions through various technological innovations channels. The main research conclusions and policy recommendations of sustainable development are as follows.

The regression results based on the linear model show that: among various sources of technological progress, enterprises play a vital role in reducing the SO_2 emissions per capita in China, and their impact is far greater than the technological innovation produced by universities and individuals. Secondly, utility-type patents can reduce the SO_2 emissions, while the technological innovations formed by invention patents have instead increased the SO_2 emissions in China. Finally, among the impacts of technological innovations formed by green innovation on the SO_2 emissions, channels including waste management, administrative management and transportation are all able to reduce the SO_2 emissions. However, technological innovations formed by energy-saving technologies have instead increased the SO_2 emissions in China.

Provinces have the opportunity of increasing the production efficiency and lowering the manufacturing costs through the absorption, digestion, and application of external knowledge. The technology absorption capacity is one of the pivotal factors for the determination of the emission of SO_2. The empirical research based on the threshold panel model shows that the impact of technological innovations formed by various channels on the SO_2 emissions has a non-linear effect, which is closely related to factors such as HCS and FEP. When the level of HCS is low, the technological innovations generated by enterprises, universities, and individuals can reduce the SO_2 emissions, but the effect is not significant. With the increase of HCS, the technological innovations formed by enterprises, universities, and individuals on the SO_2 emissions will be significantly enhanced. Similar to the impact of invention patents on the SO_2 emissions, the effect of technology innovations generated by energy-saving technologies will also vary from positive to negative as the level of HCS increases. This shows that invention patents and energy-saving technologies need more upfront investment to finally form a positive effect, which is conducive to the reduction of China's SO_2 emissions and also to the sustainable development.

The empirical model also shows that the effect of technological innovation formed by enterprises, universities, individuals, administrative management and transportation on the SO_2 emissions will increase with the increase in FEP. However, invention patents cannot increase the effect on the reduction of the SO_2 emissions, instead, it suppresses it.

The results above show that in order to reduce the SO_2 emissions and achieve the final goal of sustainable development, China should continue to adhere to the development path of green innovation and regard green innovation as an important tool. Technological innovations from various channels are important factors affecting the SO_2 emissions, particularly utility-type patents and waste management. In order to promote the positive spillover effect of energy-saving technologies and invention patents on the reduction of SO_2 emissions, despite the introduction of policies on patent protection, China should also combine technological innovation policies with sustainable economic development strategies. The non-linear effects of various technological innovations on the SO_2 emissions indicate that policymakers should fully consider the characteristics of the impact of various sources of technological progress on SO_2 when formulating corresponding policies. In order to maximize the positive spillover effect of various technological innovations, the level of HCS should be appropriately increased, with the emphasis on strengthening enterprises' innovation. In addition, the government should improve the energy structure and industrial structure, meanwhile promote the decline in the proportion of secondary industries and reduce the proportion of high energy consumption industries.

Although the empirical research conclusions of this paper are helpful to reveal the impact mechanism of various technological innovations on China's SO_2 emissions, due to the data limitations (e.g. some patents data is 0), the constructed indicators cannot fully and accurately reflect the characteristics of technological absorption capacity of green innovations affecting the SO_2 emissions per capita in China and the sustainable development should be more considered in the future policy.

References

1. CAI H.X, FAN R.G., 2019, Regional Total Factor Energy Efficiency Evaluation of China: The Perspective of Social Welfare, *Sustainability*,11(15): 4093.
2. DIETZ T., ROSA E.A., 1997, Effects of population and affluence on CO_2 emissions, *Proceedings of the National Academy of Sciences*, 94(1):175-179.
3. HUANG J.B., DU D., HAO Y., 2017, The driving forces of the change in China's energy intensity: An empirical research using DEA-Malmquist and spatial panel estimations, *Econ. Model.*, 65, 41-50.
4. LI L. B., HU J. L., 2012, Ecological total-factor energy efficiency of regions in China, *Energy Policy*, 46(2): 216-224.
5. LI Y., CHIU Y. H., LU L., 2018, Regional energy, CO_2, and economic and air quality index performances in China: a meta-frontier approach, *Energies*, 11(8).
6. MENSAH C.N., LONG X., DAUDA L. et al., 2019, Technological innovation and green growth in the Organization for Economic Cooperation and Development economies, *Journal of Cleaner Production*, 240.
7. SHAFIEI S., SALIM R.A., 2014, Non-renewable and renewable energy consumption and CO_2 emissions in OECD countries: A comparative analysis, *Energy Policy*, 66: 547-556.
8. SHUXING Ch., XIANGYANG D., JUNBING H., CHENG Ch., 2019, The Impact of Foreign and Indigenous Innovations on the Energy Intensity of Chinas Industries, *Sustainability*, 11(4): 1107.

9. STEINBERGER J. K., ROBERTS J. T., 2010, From constraint to sufficiency: The decoupling of energy and carbon from human needs, 1975-2005, *Ecological Economics*, 70(2): 425-433.
10. SHI-CHUN, X., YI-WEN L., YONG-MEI et al., 2019, Regional differences in nonlinear impacts of economic growth, export and fdi on air pollutants in China based on provincial panel data, *Journal of Cleaner Production*, 228: 455-466.
11. TENG X., LU L.C., CHIU Y.H., 2019, Energy and emission reduction efficiency of China's industry sector: a non-radial directional distance function analysis, *Carbon Management*, 10(4): 333-347.
12. VOIGHT S., DE C. E., SCHYMURA M., VERDOLINI E., 2014, Energy intensity developments in 40 major economies: structural change or technology improvement? *Energy Economics*, 41: 47-62.
13. WEN L., LI Z.K., 2019, Driving forces of national and regional CO_2 emissions in China combined IPAT-E and PLS-SEM model, *Science of the Total Environment*, 690: 237-247.
14. YORK R., ROSA E. A., DIETZ T., 2003, STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts, *Ecological Economics*, 46(3): 351-365.
15. YU H.Y., 2012, The influential factors of China's regional energy intensity and its spatial linkages: 1988-2007, *Energy Policy*, 45: 583-593.
16. ZHANG N., KONG F., YU Y., 2015, Measuring ecological total-factor energy efficiency incorporating regional heterogeneities in China, *Ecological indicators*, 51: 65-172.
17. ZHENG Y.M., QI J.H., CHEN X.L., 2011, The effect of increasing exports on industrial energy intensity in China, *Energy Policy*, 39: 2688-2698.
18. ZHENG-XIN, WANG DE-JUN Y., HONG-HAO et al., 2019, The influence of market reform on the CO_2 emission efficiency of China, *Journal of Cleaner Production*, 225: 236-247.