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Research article

The impact of heterogeneous environmental regulations on the technology innovation of urban green energy: a study based on the panel threshold model

Xueying Xu[1], Peng Hou[1,*] and Yue Liu[2]

[1] School of Economics and Management, Beijing Forestry University, Beijing 100083, China
[2] Business School, Hunan Institute of Technology, Hengyang 421002, China

* **Correspondence:** Email: houpeng9@bjfu.edu.cn; Tel:+8601062338410.

Abstract: Since the Porter hypothesis was proposed, environmental regulation has been recognized as a critical factor influencing technology innovation. However, there is no unified conclusion on whether the relationship between the two is linear or non-linear, and environmental regulation is always examined from single angles. Therefore, according to the difference of environmental regulation implementation subjects, this paper divides environmental regulation into formal regulation and informal regulation. Utilizing the panel data of 281 prefecture-level and above cities in China from 2011–2019, the non-linear effects of heterogeneous environmental regulations on green energy technology innovation are analyzed based on the panel threshold model, and the non-linear relationship between the two under the difference in urban economic development level is further considered. The results indicate that: (1) The threshold effect of the environmental regulations on China's green energy technology innovation is significant, and there is heterogeneity in the effects of different environmental regulations. (2) At present, positive relationship are observed between the informal environmental regulation and green energy technology innovation in China, while the formal environmental regulation exerts a significant inhibitory effect on green energy technology innovation. (3) The level of regional economic development plays a significantly positive role in moderating the relationship between environmental regulation and green energy innovation. However, there exists a certain heterogeneity in the moderating role between the formal regulation-innovation link and informal regulation-innovation relationship. This study provides a reference for further clarifying the relationship between heterogeneous environmental regulations and green energy technology innovation.

Keywords: formal environmental regulation (formal regulation); informal environmental regulation (informal regulation); green energy technology innovation; panel threshold model

JEL Codes: J23, P18

1. Introduction

To address the global climate change challenge, in 2015, the Paris Climate Agreement proposed that "holding the increase in the global average temperature to well below 2 ℃ above pre-industrial levels, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century". By November 2020, the UN Secretary-General noted that "despite pledges by many governments to be carbon neutral by 2050, the world is still far from achieving this goal"[1]. According to the report entitled "Net Zero by 2050, A Roadmap for the Global Energy Sector"[2] released by the International Energy Agency in 2021, energy consumption accounts for three-quarters of all greenhouse gas emissions. Therefore, it is particularly important to accelerate the energy transformation and promote the development of green energy. As the best solution to accelerate the development of green energy, technology innovation deserves our attention (Vona et al., 2012). Since the Porter hypothesis was proposed, environmental regulation has been considered the key factor affecting technology innovation (Johnstone et al., 2010; Nesta et al., 2014; Kim et al., 2017). Due to the spillover of knowledge, technological innovation has "positive externality" characteristics (Glaeser et al., 1992), while the public nature of the environmental issues gives it characteristics of "negative externality". Green energy technology innovation incorporates both "environmental protection" and "technology innovation", so it has the characteristics of "dual externalities" (Long et al., 2017). In this sense, it is of great importance to identify the impact of environmental regulation on green energy innovation (Yan et al., 2020).

According to the difference of implementation subjects, environmental regulation can be divided into formal regulation and informal regulation. Formal environmental regulations are formulated by the government and guaranteed by public power (Zhou & Wang, 2016). Meanwhile, with the continuous improvement of social informatization, the public attention to environmental problems has gradually formed a public opinion pressure, which has evolved into a kind of "informal environmental regulation" different from the mandatory government and participated by the public. Moreover, informal environmental regulation is generally considered as a solid supplement for formal environmental regulation, especially in developing countries where formal environmental regulation is generally weak (Blackman, 2010). As the world's largest developing country as well as the world's largest energy producer and consumer, China has actively responded to the UN deployment and issued a series of related environmental policies and measures to reduce environmental pollution and improve environmental quality. At the same time, the public in China has also actively participated in environmental governance through various ways and achieved good results. In this context, what role do formal and informal environmental regulations play in China's green energy technology innovation? Is there any heterogeneity in the effects of the two environmental regulations? These are the two main issues concerned in this paper.

[1]https://news.un.org/en/story/2020/11/1077202

[2]https://www.iea.org/reports/net-zero-by-2050

In theory, there are mainly two mechanisms for environmental regulation to affect technology innovation. The approach of “compliance cost” of environmental regulation will increase the cost of enterprises, reduce the research and development (R&D) investments, and inhibit technology innovation. By taking the “innovation compensation” approach, enterprises will increase their income and promote technology innovation. The effects of these two approaches are pretty opposite, and the intensity of action depends on the intensity of environmental regulation. Therefore, the effect of environmental regulation on technology innovation may not be linear but vary with the change of environmental regulation intensity. Further, as the role that the government and public played in environmental issues may differ, the non-linear effect of formal and informal environmental regulation on green energy technology should also be different.

In terms of empirical research, the relationship between environmental regulation and technology innovation has always been a hot research topic in academia. Most of the existing studies have focused on the linear role of formal environmental regulation on green technology innovation, and the research conclusions can be roughly divided into “positive” (Pelin et al., 2011, Lin et al., 2014), “negative” (Wagner, 2007), and unrelated (Walz et al., 2011). With the deepening understanding of the concept of environmental regulation, the reseaech focus of environmental regulation is not only limited to the single aspect of the government as the implementation subject, but gradually includes the public and non-governmental environmental organizations. However, there is no unified research conclusion on the effect of different types of environmental regulations on green technology innovation (Zhou & Wang, 2016; Feng & Chen, 2018, Luo et al., 2021). Some studies also explore the non-linear relationship between the two by introducing the square term of environmental regulation in the linear econometric model or using the panel threshold model (Zhang et al., 2016; Liu et al., 2018; Guo et al., 2018; Liu & Gong, 2018; Yi et al., 2019), but obtaining different conclusions. To the best of our knowledge, it is rare to study the non-linear relationship between heterogeneous environmental regulations and green energy technology innovation in the existing literature, and most of the relevant studies are based on the data of national or industrial level, lacking targeted research at the urban level.

There are huge differences in economic development levels among Chinese cities (Song et al., 2019), which often leads to the heterogeneity of the effect of environmental regulation on green energy technology innovation. Existing research generally focuses on exploring the similarities and differences of the impact of environmental regulation on technology innovation under different economic conditions by grouping the research objects according to their economic development levels. Although this method can reflect the impact of economic level on the relationship between green energy innovation and environmental regulation to a certain extent, it can not accurately investigate the role of economic level in moderating the environmental regulation-green energy innovation relationship. This issue can be addressed by panel threshold model which automatically identifies endogenous characteristics of the data to effectively identify the accurate relationship intervals (Zheng et al., 2020). Therefore, we further consider studying the moderating role of economic development level through the panel threshold model and explore whether there exists heterogeneity under the formal and informal environmental regulations.

Based on the above analysis, this paper uses the panel data of prefecture-level and above cities in China from 2011 to 2019 to investigate the threshold effect of heterogeneous environmental regulations on green energy technology innovation and further explore the impact of economic differences on the relationship between the two. The main contributions of this research are twofold. First, this paper examines the non-linear relationship between environmental regulation and China’s urban green energy innovation, incorporating both formal and informal environmental regulations, which provides a new perspective of exploring the green energy technology innovation effect of heterogeneous environmental regulations. Second, this paper takes the level of economic development as a threshold variable and explores the moderating role of economic development in the impact of heterogeneous environmental regulations on green energy technology innovation, and it is conducive to a better understanding of the dynamic relationship between regional economic development level, environmental regulation, and green energy technology innovation.

The rest of this paper is arranged as follows. Section 2 puts forward research hypotheses. Section 3 introduces the econometric models, variables and data. Section 4 presents the empirical results and analysis of the threshold effects of formal and informal environmental regulations on green energy technology innovation. Section 5 focuses on the empirical results and analysis of the moderating effect of economic development level in the impacts of formal and informal environmental regulations on green energy technology innovation. Section 6 draws the conclusions and puts forward some policy implications.

2. Relevant literature and research hypotheses

2.1. Formal and informal environmental regulation and green energy technology innovation

As mentioned above, there are two main impact mechanisms of environmental regulation on green energy technology innovation, namely "compliance cost" effect and "innovation compensation" effect.

On the one hand, the "compliance cost" effect can be subdivided into "capital crowding out effect", "investment crowding out effect", and "resource allocation distortion effect", all of which have inhibitory effects on green energy technology innovation. When enterprises face the pressure of environmental regulations, they have to spend money dealing with environmental pollution issues such as pollutant discharge, which will increase production costs. Firstly, in order to reduce costs, enterprises often respond by reducing R&D investment, which drains part of the funds that should be used for green technological innovation, which is called the "capital crowding out effect" of environmental regulations. Secondly, according to the theory of new classical economics, the increase in production cost will weaken the enterprises' competitiveness in the market, forcing part of polluting enterprises to transfer their businesses to other regions with weak environmental regulations, reducing the share of innovation investment in the original areas. This is called the "investment crowding out effect" of environmental regulation, which is also not conducive to local technological innovation. Finally, due to the existence of the "distortion effect of resource allocation", enterprises gain economic output by increasing the input of production factors to offset the rise of production costs, which eventually leads to the increase of pollution emissions, resulting in a vicious circle of pollution-treatment-re-pollution, making it difficult for enterprises to truly improve their technological innovation capacity.

On the other hand, according to Porter's innovation compensation theory, the pressure brought by the increase of production cost can provide a direct driving force for enterprise innovation (Porter & Linde, 1995). By conducting green technology innovation activities, enterprises can optimize resource allocation, further improve production efficiency, save production costs, and bring innovation benefits, which will gradually offset the cost of enterprises caused by the rise of environmental regulation, resulting in an "innovation compensation effect". That is to say, the "innovation compensation effect" of environmental regulation lags behind the negative effect of "compliance cost". Only when environmental regulation reaches a certain intensity, its positive "compensation effect" on technological innovation of enterprises will play a major role. Therefore, the impact of environmental regulation on innovation should be non-linear, depending on the intensity of environmental regulation itself.

As noted already, formal and informal environmental regulation have different characteristics. In theory, the implementation subject of formal environmental regulation is the government, so it should be mandatory, sustainable, and holistic. In contrast, informal environmental regulation is less mandatory and sustainable, and usually not holistic. This means that although informal environmental regulation has less impact on environmental pollution control than formal environmental regulation, enterprises must implement corresponding measures quickly to deal with the environmental issue when they face the informal environmental regulation. Otherwise they will face serious problems of social reputation and image damage, affecting their survival and development. Therefore, in some areas, the positive contribution of informal environmental regulation to the environment protection is more significant. Although there exists differences between formal and informal environmental regulation, their effects on green energy technology innovation also follow the above-mentioned "compliance cost " and "innovation compensation" mechanisms. Whereas, the overall effect of formal and informal environmental regulation on green energy innovation may be different due to their different characteristics.

Based on the above analysis, this paper proposes the following hypothesis:

H1. There is a non-linear relationship between environmental regulation and green energy technology innovation, and the effect of formal and informal environmental regulations on green energy technology innovation is different.

2.2. Formal and informal environmental regulation and green energy technology innovation under different levels of economic development

Economic development level plays a moderating role in the relationship between environmental regulation and green energy innovation. Generally speaking, regions with higher levels of economic development have favorable technological innovation environment and abundant innovation resources, and their market mechanism is more sound, and intellectual property protection system is more sophisticated, which is more conducive to the incentive effect of environmental regulation on green energy technology innovation (Hudson & Minea, 2013; Wang et al., 2016). However, in areas with low economic development levels, technological innovation environment and resources are relatively poor, the enterprises are always hard to cope with the rising costs caused by environmental regulations, and the "crowding out effect" is noticeable, which is often not conducive to green energy technology innovation. At the same time, in areas with low economic development levels, government officials generally face the pressure of GDP assessment. Considering their own career promotion, they often implement loose policies in environmental law enforcement to achieve the purpose of rapid economic development (Li et al., 2021; Zhang, 2014). In this case, the relatively loose environmental regulation policy can not play its "reverse forcing mechanism" to green energy technology innovation, so the promotion effect of environmental regulation on green energy technology innovation should be smaller in the regions with low level of economic development.

From the perspective of two kinds of environmental regulation, the moderating role of economic development level in the impacts of formal and informal environmental regulations on green energy innovation may be different. First, as mentioned above, formal environmental regulations are mandatory, normative, and unified environmental policies formulated by government functional departments. However, differences in economic development levels will lead to different intensities of formal environmental regulations in different regions. Second, when faced with formal environmental regulations, the enterprises in the areas with higher levels of economic development can easily cope with corresponding issues, compared with areas with low levels of economic development. Therefore, in the areas with low economic development levels, strengthening formal environmental regulation often trigger the "compliance cost" mechanism of environmental regulation on green energy technology innovation, which is not conducive to technological innovation. However, the informal environmental regulation level in a region is often directly linked to its economic development level; that is, in areas with a low level of economic development, the public's awareness of environmental protection is generally relatively weak, leading to a weak intensity of informal environmental regulation and a small promotion effect on green energy technology innovation.

Based on the above analysis, this paper puts forward the following hypothesis:

H2. The level of economic development plays a positive role in moderating the impact of environmental regulation on green energy technology innovation, and the moderating effects on formal and informal environmental regulations are different.

3. Empirical Research

3.1. Model specification

This paper aims to study the non-linear relationship between environmental regulation and green energy technology innovation by using the panel data from 281 the prefecture-level and above cities in China from 2011 to 2019. For studying a non-linear relationship between the two, standard processing methods include adding square or higher terms of environmental regulation in the linear econometric model, or directly selecting the threshold effect model. In order to avoid possible colinearity problems by introducing the square terms in the linear econometric model, this paper refers to Hansen (1999), Lian & Cheng (2006), selects the panel threshold effect model for the empirical study, and sets the benchmark measurement model in Equation (1) as follows:

$$\begin{aligned} lnGEP_{it} &= \alpha + \beta_1 lnER_{it} I(thr_{it} \le r_1) + \beta_2 lnER_{it} I(r_1 < thr_{it} \le r_2) \\ &+ \beta_3 lnER_{it} I(thr_{it} > r_3) + \gamma_{it} X_{it} + \varepsilon \end{aligned} \tag{1}$$

where GEP is the number of green energy patents of each city to measure the region green energy innovation capacity; ER represents environmental regulation intensity, including formal environmental regulation (OER) and informal environmental regulation (IER); vector X includes a series of control variables: human resources level (REL), openness (DO), economic development level (RGDP), and government support (GS); i=1,..., 281 represents 281 prefecture-level and above cities in China; t=2003,..., 2016 represents the year; ε is the random error term.

In addition, this paper provides a new perspective on the relationship among environmental regulation, economic development level, and green energy technology innovation. Taking the urban economic development level as the threshold variable, this paper studies the moderating role of economic development level in the relationship between environmental regulation and green energy technology innovation. The econometric model is set as shown in Equation (2):

$$\begin{aligned} lnGEP_{it} &= \alpha + \beta_1 lnER_{it} I(RGDP_{it} \le r_1) + \beta_2 lnER_{it} I(r_1 < RGDP_{it} \le r_2) \\ &+ \beta_3 lnER_{it} I(RGDP_{it} > r_3) + \gamma_{it} X_{it} + \varepsilon \end{aligned} \tag{2}$$

3.2. Variable selection and data source

3.2.1. Variable selection

Explained variable

The explained variable in this study is the Green Energy Technology Innovation level (GEP). Existing research has used the following three indicators to measure regional general innovation ability: the first is R&D input, which is measured by the amount of R&D investment; the second is innovation output, which is measured by the quantitative index of patent application or grant; the third is to combine R&D input with innovation output and measure it by DEA and other methods. However, because it is difficult to obtain the investment information in the technological field of R&D expenditure, and patents have detailed classification numbers in the technological field, the measurement of green energy innovation in this paper is basically based on patent indicators. Referring to Ardito et al. (2016) and Liu et al. (2020), according to the International Patent Classification (IPC) number in the "IPC Green Inventory" issued by the World Intellectual Property Organization (WIPO), the categories of "alternative energy production" and "energy conservation" patents are combined into energy green patents, and the urban green energy innovation capacity is measured by the sum of the number of patents of the two categories. In addition, due to the differences between Chinese patent classification number and IPC number, this paper follows Liu et al. (2020) and obtains the application numbers of green energy patents in various cities in China by connecting the IPC number and the China patent classification number of green energy patents according to the Patent Star website of China National Intellectual Property Administration[3]. Both patent applications and patent grants are widely used to measure regional innovation capabilities (Guo et al., 2019; Li et al., 2019; Yi et al., 2019; Li et al., 2020). However, given that patent applications contain information about patent grants, and it takes a certain period of time from patent application to authorization (Pan et al., 2019; Liu et al., 2020), this paper holds that green energy patent applications can better reflect the current green energy innovation level of a city.

Explanatory variables

The first explanatory variable in this study is formal environmental regulation intensity (OER). At present, the academic measurement of formal environmental regulation can be roughly divided into the following three types. The first is the investment in environmental pollution control, such as investment in environmental pollution control and sewage charges. The second is the pollutant removal rate, and the third is the number of environmental administrative regulations or environmental punishment cases. In order to overcome the possible bias of a single index in measuring environmental regulation, combined with the availability of prefecture-level and above data in China, based on the research of Chao & Lian (2020) and Li & Du (2021), this paper selects four indicators, including comprehensive utilization rate of industrial solid waste, treatment rate of domestic sewage, the green coverage rate of built-up area, and harmless treatment rate of garbage, to synthesize a comprehensive index using the entropy method to investigate the intensity of environmental regulation in prefecture-level and above cities comprehensively. This paper refers to Wang et al. (2013) and constructs the index by following three steps: first, the original data of 4 indicators are standardized; second, the entropy weight is calculated

[3]https://cprs.patentstar.com.cn/.

using the entropy method; finally, the environmental regulation intensity index of each city is calculated based on the standardized indexes and weights.

The second explanatory variable is informal environmental regulation intensity (IER). Similarly, the academic measures on informal environmental regulation can be roughly divided into two types. One is the degree of public participation, which is usually measured by media exposure of pollution events and environmental pollution concern value of search engines; the other is the comprehensive index, which usually selects indicators such as income level, education level, population density, and age structure to build a comprehensive index as an alternative index. This paper holds that informal environmental regulation refers to the degree of public participation in environmental protection, which is a kind of environmental pressure derived from public opinion. Indicators such as income level, population density, and age structure can not directly reflect the public environmental awareness, while Baidu and Google index websites scientifically analyze and calculate the weighted sum of search frequency of each keyword in a network search based on the search volume of their network users and taking keywords as the statistical object, so the relevant indicators can well reflect the public attention (Zheng et al., 2012; Du et al., 2019). Therefore, referring to Xu (2014) and Peng et al. (2021), this paper selects the public attention to environmental issues on the Internet to measure the informal environmental regulation. The specific steps are: first, choose Baidu index website to search with "environmental pollution" as the keyword, and regional classification is carried out to get the average daily search volume of "environmental pollution" in each city; second, in order to make it comparable, the intensity of informal environmental regulation in 281 cities is obtained by comparing with the average daily search volume of "environmental pollution" in Beijing.

Control variables

By referring to some existing relevant studies (Li and Du, 2021; Vona et al., 2012; Luo et al., 2021; Guo et al., 2018; Feng et al., 2019), this paper selects the degree of opening up (DO), level of economic development (RGDP), human resources level (REL), and government support (GS) as the control variables.

The variables involved in the empirical analysis and their definitions are shown in Table 1.

Table 1. Variable definitions.

Variable type	Variable symbol	Variable descriptions
explained variable	GEP	Green energy patent applications
explanatory variable	OER	Formal environmental regulation: synthesis of four indicators by the entropy method
	IER	Informal environmental regulation: Baidu Index search volume of "Environmental Pollution" (based on Beijing City data)
control variable	DO	Degree of openness: total imports and exports/GDP
	RGDP	GDP per capita (taking 2011 as the base year)
	REL	Number of college students per ten thousand
	GS	Government science and technology investment expenditure/government expenditure

3.2.2. Sample selection and data source

Considering the consistency and comparability of indicators data, this paper determines the time interval as 2011–2019. Tongren and Bijie were newly established prefecture-level cities in Guizhou Province in 2011, Sansha was newly established in Hainan Province in 2012, and Haidong area of Qinghai Province was changed to Haidong city in 2013, while data of Laiwu, Longnan, Zhongwei, Pu'er, and Lhasa are seriously missing, the number of sample cities is reduced from 290 to 281.

The data of green energy patents are from the Patent Star Website of China National Intellectual Property Administration. The data of informal environmental regulation are from the Baidu Index website, and the data of other variables are from China Urban Statistical Yearbook, China Statistical Yearbook, and the CSMAR database.

Table 2 shows the descriptive statistical analysis results of each variable.

Table 2. Descriptive statistics of variables.

VarName	Obs	Mean	SD	Min	Median	Max
lnGEP	2529	3.91	1.651	0	3.73767	8.907071
lnOER	2529	−0.34	0.242	−1.892756	−0.258203	−0.0544024
lnIER	2529	−2.30	1.107	−5.099866	−2.271333	0
DO	2529	0.27	1.023	0	0.0830938	28.23327
lnRGDP	2529	10.74	0.582	8.841593	10.71086	12.54422
REL	2529	217.78	260.978	0.9315925	130.6097	1597.56
GS	2529	0.02	0.017	0.0005981	0.0115497	0.2068348

4. Threshold effects of formal and informal environmental regulation on green energy technology innovation

4.1. Formal environmental regulation

This subsection uses the panel data of 281 cities in China from 2011 to 2019 to investigate the threshold effect of formal environmental regulation on green energy technology innovation with the help of the panel threshold model. First, we test whether there exits a significant threshold effect of the formal environmental regulation on green energy innovation, and the results are reported in Table 3.

Table 3. Threshold effect test of formal environmental regulation on green energy innovation

Threshold variable	No. of thresholds	1%	5%	10%	F value	P value	threshold value	95% confidence interval
lnOER	Single	9.178	5.769	4.280	5.277*	0.062	−0.224	(−0.847, −0.094)
	Double	9.177	6.581	4.742	11.109***	0.002	−0.247 −0.224	(−0.671, −0.247) (−0.224, −0.220)
	Triple	−0.185	−2.385	−4.654	−6.511	0.158		

Note: (1) *p*-Values and critical values are the result of bootstrap simulations 500 times; (2) ***, **, and * are significant at the level of 1%, 5%, and 10%, respectively.

It can be seen from Table 3, first, the P value of single threshold effect was 0.062, thus rejecting the null hypothesis that the single threshold effect did not exist, and the threshold value $\gamma = -0.224$. Then, we test the second threshold effect on the basis of determining the existence of a single threshold effect. According to the P value (0.002), we find that the double threshold effect exists with threshold values of −0.224 and −0.247, and the corresponding 95% confidence interval is (−0.224, −0.220) and (−0.671, −0.247), respectively. Finally, the P value of triple threshold effect (0.158) indicates that the null hypothesis that the triple threshold effect did not exist can not be rejected, i.e., there is no triple threshold effect. Therefore, the impact of formal environmental regulation on green energy technology innovation will be analyzed below based on the panel threshold model with double thresholds.

Second, to better understand the above threshold estimation results, the likelihood ratio function diagrams of the double threshold value are drawn in Figure 1. The estimated value of the threshold parameter refers to the value of γ when the likelihood ratio (LR) test statistic is 0, which are −0.247 (see the left of Figure 1) and −0.224 (see the right of Figure 1) in the panel threshold model with double thresholds. The 95% confidence interval of each threshold estimate is the interval composed of the critical value γ when all LR values are below the 5% significance level (corresponding to the dotted line in the figure). It can be seen that the threshold estimates of −0.247 and −0.224 for the double threshold are statistically significant.

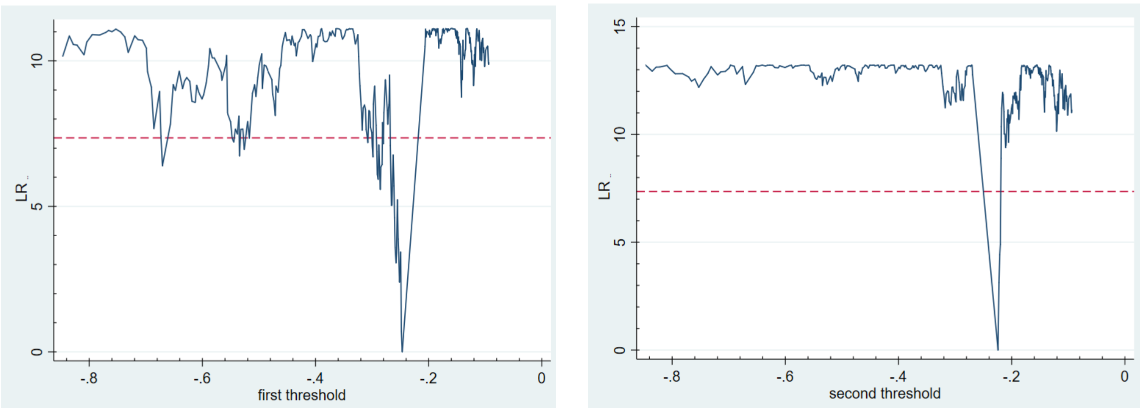

Figure 1. Estimates and confidence intervals for the first threshold and the second threshold (from left to right).

Table 4 further presents the results of the threshold effect of formal environmental regulation on green energy technology innovation under the panel threshold model with double thresholds. Clearly, in the first interval, when the intensity of formal environmental regulation is less than −0.247, its impact on green energy technology innovation is not statistically significant. When the intensity of formal environmental regulation is between −0.247 and −0.224, which is in the second interval, the negative impact on green energy technology innovation increases with the increase of the intensity of formal environmental regulation, and it is significant at the level of 1%, with a coefficient of −1.297. When the intensity of formal environmental regulation is greater than −0.224, the coefficient of environmental regulation is 0.138, but this positive effect is insignificant. It can be seen that the negative effect of the formal environmental regulation on green energy technology innovation is apparent, whereas the positive effect is implicit.

Table 4. Panel threshold estimation result of formal environmental regulation on green energy innovation.

lnGEP	lnOER	double
Threshold variable	lnOER<−0.247	−0.0595
		(−0.63)
	−0.247<lnOER<−0.224	−1.297***
		(−3.10)
	lnOER>−0.224	0.138
		(0.39)
Control variable	DO	0.156***
		(7.28)
	lnRGDP	0.962***
		(19.89)
	REL	0.002***
		(19.00)
	GS	23.462***
		(15.04)
	cons	−7.357***
		(−14.54)
	N	2529
	R^2	0.479

Note: ***, **, and * indicates significance at the 1%, 5%, and 10% level, respectively.

The above empirical results may be explained as follows. First, when the formal environmental regulation is in the first interval, its effect on green energy technology innovation is not significant. For this kind of environmental regulation intensity, enterprises tend to choose an "end treatment" approach, that is, simply increasing the cost of sewage treatment, which will squeeze out part of the funds originally used for R&D investment but will not have a significant impact on their innovation, indicating that the formal environmental regulation intensity is not enough to trigger technological innovation of enterprises. Moreover, the crowding-out effect is not enough to significantly inhibit technological innovation. Second, when the intensity of formal environmental regulation is further improved, which is within the interval of (−0.247, −0.224), enterprises face increasing formal environmental regulation pressure. They raise the investment of environmental pollution control, thus enhancing the crowding-out effect on technological innovation, further suppressing the improvement of green energy technology innovation capacity. At this time, only relying on "end treatment" is not enough to cope with the improvement of environmental regulation intensity, and enterprises begin to seek the source of environmental pollution control. Third, when the formal environmental regulation intensity is greater than −0.224, the "end treatment" approach for enterprises to deal with environmental regulation fails, and they have to carry out green energy technology innovation to reduce the emission of pollutants from the source. At this time, formal environmental rules have generated sufficient innovation power for enterprises, and the "reverse forcing mechanism" of environmental regulation has initially taken shape, but the output of innovation results takes a certain time, so it has a positive but insignificant impact on green energy technology innovation.

As for the control variables, they all have significant and positive impacts on green energy technology innovation. Among them, the impact coefficient of government support is the largest, reaching 23.46. This means that the government support increases by one unit, the green energy technology innovation capacity increases by 23.46 units. It is not difficult to understand that government support, as a direct financial subsidy, can reduce enterprises' R&D cost, reduce the innovation risk of enterprises, and provide a strong driving force for enterprises to carry out green energy technology innovation. In addition, the impact coefficient of economic development level on green energy technology innovation is 0.962, which is significant at the level of 1%; that is, the higher the regional economic development level, the stronger the green energy technology innovation ability. This will be analyzed in detail in the subsequent sections. In addition, the degree of opening to the outside world and the level of human resources also have positive impacts on green energy technology innovation.

4.2. Informal environmental regulation

For the informal environmental regulation, the existence of the threshold effect is firstly tested in this subsection. As can be seen from Table 5, similarly, according to the P value of single threshold effect (0.002) and double threshold effect (0.004), we can find that the double threshold effect exists with threshold values of −0.995 and −2.797, and the corresponding 95% confidence interval is (−2.094, −0.738) and (−2.964, −0.418), respectively. Finally, the P value of triple threshold effect is 1, indicating that there is no triple threshold effect.

Table 5. Threshold effect test of informal environmental regulation on green energy innovation.

Threshold variable	No. of thresholds	1%	5%	10%	F value	P value	Threshold value	95% confidence interval
lnIER	Single	14.185	7.444	6.018	18.692***	0.002	−0.995	(−1.030, −0.962)
	Double	7.679	4.329	3.270	9.807***	0.004	−2.797 −0.995	(−2.964, −0.418) (−2.094, −0.738)
	Triple	0	0	0	0	1		

Note: (1) *p*-Values and critical values are the result of bootstrap simulations 500 times; (2) ***, **, and * are significant at the level of 1%, 5%, and 10%, respectively.

Based on the above results, the LR function diagrams are shown in Figure 2. When the estimated value of the threshold parameter is −2.797 (the left of Figure 2) or −0.995 (the right of Figure 2), the value of LR statistic is 0, confirming the existence of double threshold effect. Therefore, the impact of informal environmental regulation on green energy technology innovation will be analyzed based on the panel threshold model with double thresholds.

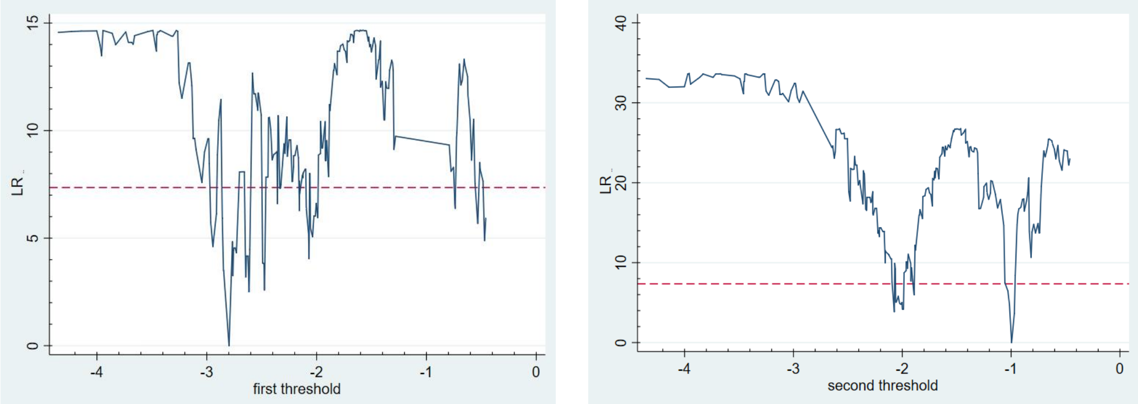

Figure 2. Estimates and confidence intervals for the first threshold and the second threshold (from left to right).

Table 6 presents the the results of the threshold effect of informal environmental regulation on green energy technology innovation. Clearly, in the first interval, that is, when the intensity of informal environmental regulation is less than −2.797, it has a significant positive impact on green energy technology innovation, and the coefficient is 0.374. With the increase of informal environmental regulation intensity, when the intensity is between −2.797 and −0.995, it still has a significant positive impact on green energy technology innovation, and the impact coefficient increases to 0.438. When the intensity of informal environmental regulation is greater than −0.995, its impact on green energy technology innovation changes from significant to insignificant. From the above analysis, it can be seen that the impact of informal environmental regulation on green energy technology innovation is non-linear, but the effect is different from that of formal environmental regulation. Therefore, Hypothesis 1 is proved.

Compared with formal environmental regulation, informal environmental regulation has the opposite effect on green energy technology innovation. This paper believes that there are two main reasons. First of all, the implementation subject of informal environmental regulation is the public, which is less inclusive of environmental pollution. For this kind of environmental regulation, it is not enough for enterprises to carry out "end treatment" only to deal with it. The environmental pressure from the society is gradually increasing, forcing enterprises to trace back to the source of environmental pollution, update and upgrade their original production technology, and fundamentally solve the problem of environmental pollution. Therefore, when the threshold value is less than −0.995, informal environmental regulation plays a prominent role in promoting green energy technology innovation, and the promotion effect increases with the increase of its intensity. Secondly, since informal environmental regulation originates from the public and is a voluntary behavior of the public, it lacks organization and strategy, resulting in its intensity can not be well controlled, which often brings too much environmental pressure to enterprises. In particular, for some small and medium-sized enterprises, when facing strong pressure of informal environmental regulation, they lack sufficient resources to respond flexibly, and they cannot bear the risks that may be brought by technological innovation, and they may even fall into business difficulties, at this time, informal environmental regulation is not conducive to the innovation of green energy technology. In view of the situation that the threshold value of informal environmental regulation intensity is greater than −0.995, the negative effect of informal environmental regulation on green energy technology innovation appears initially, but because it is not mandatory, the inhibitory effect is not significant. From the above analysis, it can be seen that due to the differences in the characteristics of informal environmental regulation and formal environmental regulation, they have different or even completely opposite effects on green energy technology innovation in specific intensity intervals.

Table 6. Panel threshold estimation result of informal environmental regulation on green energy innovation.

LnGEP	lnIER	double
Threshold variable	lnIER < −2.797	0.374**
		(13.37)
	−2.797 < lnIER<−0.995	0.438***
		(10.31)
	lnIER > −0.995	−0.159
		(−1.14)
Control variable	DO	0.143***
		(7.10)
	lnRGDP	0.933***
		(20.44)
	REL	0.002***
		(13.26)
	GS	18.591***
		(12.46)
	_cons	−5.922***
		(−11.96)
	N	2529
	R^2	0.539

Note: ***, **, and * indicates significance at the 1%, 5%, and 10% level, respectively.

5. Threshold effects of formal and informal environmental regulation on green energy technology innovation under the differences of economic development level

In order to further explore whether the effect of environmental regulation on green energy technology innovation is related to the regional economic development level, this paper continues to estimate the panel threshold model shown in Equation (2) based on the data of China's 281 cities.

5.1. Formal environmental regulation

Firstly, we treat the level of economic development as the threshold variables and examine whether there is a significant threshold effect of formal environmental regulation on green energy innovation. As shown in Table 7 and Figure 3, the P value of triple threshold effect (0.28) is larger than 10%, while the P values of single and double threshold effect are both 0.00. This means that the double threshold effect exists. Meanwhile, the threshold values are 11.153 and 11.886, with the corresponding 95% confidence intervals being (9.649,11.278) and (11.807,11.989), respectively. Therefore, the impact of formal environmental regulation on green energy technology innovation under economic differences will be analyzed using the panel threshold model with double thresholds.

Table 7. Threshold effect test of formal environmental regulation on green energy innovation under the differences of economic development level.

Threshold variable	No. of thresholds	1%	5%	10%	F value	P value	Threshold value	95% confidence interval
lnRGDP	Single	8.910	6.205	4.342	34.736***	0.000	11.125	(11.005, 11.260)
	Double	12.761	6.534	4.322	28.733***	0.000	11.886 11.153	(11.807, 11.989) (9.649, 11.278)
	Triple	0	0	0	0.00	0.280		

Note: (1) *p*-Values and critical values are the result of bootstrap simulations 500 times; (2) ***, **, and * are significant at the level of 1%, 5%, and 10%, respectively.

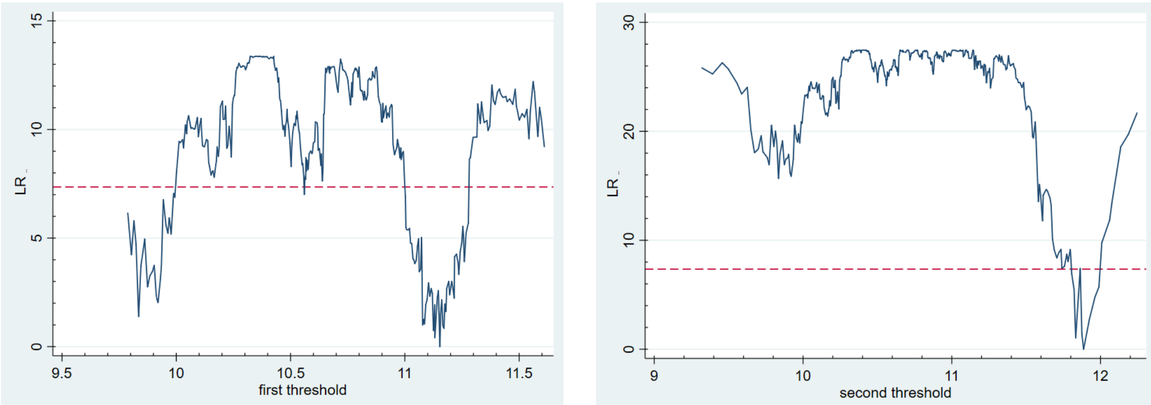

Figure 3. Estimates and confidence intervals for the first threshold and the second threshold (from left to right).

The estimation results in Table 8 show that, when the economic development level (lnRGDP) is under 11.153, the formal environmental regulation has an significant inhibitory effect on green energy innovation, with a coefficient of −0.25. When the level of economic development increases and lnRGDP rises to the range of (11.153, 11.886), the effect of formal environmental regulation on green energy technology innovation is changed to be significantly positive, with a coefficient of 0.199. When lnRGDP is greater than 11.886, the effect of formal environmental regulation on green energy technology innovation is significantly positive, with an impact coefficient of 1.700. This means that when per capita GDP increases by 1 percentage, formal environmental regulation will promote the green energy technology innovation level to increase by 1.7 percentage. In general, with the improvement of economic development level, the impact of formal environmental regulation on green energy innovation presents a U-shaped effect of "inhibition first and then promotion".

The regional innovation ability are always closely related to regional economic development level. Generally speaking, cities with a higher level of economic development have a good technological innovation environment, rich innovation resources, a more sound market mechanism, and a more sophisticated intellectual property protection system. Therefore, in the face of strict formal environmental regulations, enterprises in developed regions can enjoy more abundant innovation funds and innovative talents, and are more willing to conduct technological innovation to achieve the lowest marginal pollution cost; On the contrary, cities with low economic development levels are lack of innovation resources, having relatively poor market mechanism and imperfect intellectual property protection system. In the face of the improvement of formal environmental regulation, enterprises tend to conserve costs, choose fast and effective “end treatment” approaches and increase investment in environmental pollution control, which leads to tighter R&D funds, thus inhibiting the improvement of the level of green energy technology innovation.

Table 8. Panel threshold estimation result of formal environmental regulation on green energy innovation under the differences of economic development level.

LnGEP	lnOER	double
Threshold variable	lnRGDP < 11.153	−0.250***
		(−2.98)
	11.153 < lnRGDP < 11.886	0.199*
		(1.69)
	lnRGDP > 11.886	1.700***
		(5.72)
Control variable	DO	0.146***
		(6.82)
	lnRGDP	1.093***
		(20.77)
	REL	0.002***
		(18.65)
	GS	23.945***
		(15.43)
	_cons	−8.777***
		(−15.86)
	N	2529
	R^2	0.486

Note: ***, **, and * indicates significance at the 1%, 5%, and 10% level, respectively.

5.2. Informal environmental regulation

We further treat the level of economic development as the threshold variables and examine whether there is a significant threshold effect of informal environmental regulation on green energy innovation. According to the results shown in Table 9 and Figure 4, the existence of both the single threshold effect and double threshold effect can be verified at the significance level of 10%. The threshold values are 11.278 and 11.501, with the corresponding 95% confidence intervals being (10.948,11.706) and (11.268,11.706), respectively. However, according to the P value of triple threshold effect (0.302), we can find that there is no triple threshold effect. Therefore, the impact of informal environmental regulation on green energy technology innovation under the different economic development level will be analyzed below based on the panel threshold model with double thresholds.

Table 9. Threshold effect test of informal environmental regulation on green energy innovation under the differences of economic development level.

Threshold variable	No. of thresholds	1%	5%	10%	F value	P value	Threshold value	95% confidence interval
lnRGDP	Single	12.277	6.977	4.782	48.647***	0.000	10.156	(10.145, 10.241)
	Double	−16.466	−26.701	−31.971	45.485***	0.000	11.501	(11.268, 11.706)
							11.278	(10.948, 11.706)
	Triple	0	0	0	0.00	0.302		

Note: (1) *p*-Values and critical values are the result of bootstrap simulations 500 times; (2) ***, **, and * are significant at the level of 1%, 5%, and 10%, respectively.

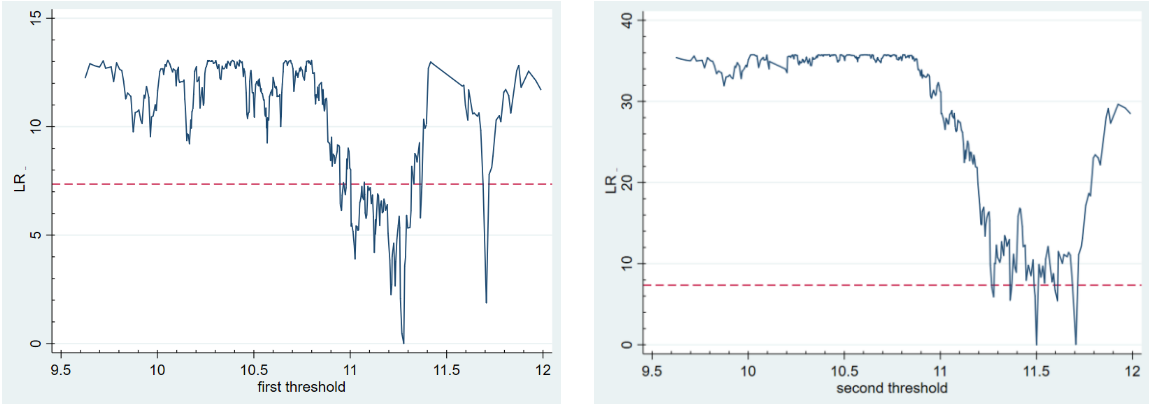

Figure 4. Estimates and confidence intervals for the first threshold and the second threshold (from left to right).

As can be seen from Table 10, the higher the level of economic development, the stronger the promotion effect of informal environmental regulation on the level of green energy technology innovation. Specifically, when the lnRGDP is less than 11.278, the effect of informal environmental regulation on green energy technology innovation is significantly positive, with a coefficient of 0.341. When the level of economic development increases and lnRGDP rises to the range of (11.278, 11.501), the effect of informal environmental regulation on green energy technology innovation is still significantly positive, and the coefficient increases to 0.451. When lnRGDP is greater than 11.501, the effect of informal environmental regulation on green energy technology innovation continues to improve, with an impact coefficient of 0.645, which remains significant at the 1% level. In conclusion, the moderating effect of economic development level on the relationship between informal environmental regulation and green energy technology innovation is non-linear. Meanwhile, when economic development level is selected as the threshold variable, the impact of informal environmental on green innovation shows a trend of gradually increasing, which is different from the "U" shaped relationship between formal environmental regulation and green energy innovation. Therefore, hypothesis 2 is proved.

Specifically, when lnRGDP is less than 11.153, formal environmental regulation inhibits green energy technology innovation, while informal environmental regulation promotes green energy innovation. Due to the fact that the enterprises in the regions with low economic development levels always lack capital, technology, and equipment, they often choose simple "end treatment" means to meet the requirements of environmental regulations stipulated by the government. In addition, the local governments of these regions will even sacrifice the environment and attract polluting industries to stimulate economic growth. At this point, formal environmental regulation fails to promote green energy technology innovation. The informal environmental regulation with the public as the main subjective can just fill this gap. The public's favor for environmental protection products will gradually drive the polluting products out of the market, and enterprises have to make technological improvement for their own interests, thus promoting the regional green energy innovation capacity.

Table 10. Panel threshold estimation result of informal environmental regulation on green energy innovation under the differences of economic development level.

LnGEP	lnIER	double
Threshold variable	lnRGDP<11.278	0.341***
		(14.17)
	11.278<lnRGDP<11.501	0.451***
		(12.25)
	lnRGDP>11.501	0.645***
		(14.58)
Control variable	DO	0.143***
		(7.08)
	lnRGDP	1.112***
		(20.91)
	REL	0.002***
		(16.03)
	GS	17.883***
		(11.95)
	_cons	−7.921***
		(−13.92)
	N	2529
	R^2	0.540

Note: ***, **, and * indicates significance at the 1%, 5%, and 10% level, respectively.

6. Conclusions and policy implications

Using the panel data of 281 prefecture-level and above cities in China from 2011 to 2019, this paper first investigates the non-linear impact of heterogeneous environmental regulations on green energy technology innovation through the panel threshold model, and then compares the moderating effect of economic development level in the relationship between heterogeneous environmental regulations and green energy technology innovation. The conclusions are summarized as follows.

Overall, the threshold effect of the environmental regulations on green energy technology innovation is significant, and there is heterogeneity in the effects of different environmental regulations. Specifically, the formal environmental regulation exerts a significant inhibitory effect on green energy technology innovation when the formal environmental regulation intensity is between −0.247 and −0.224. The informal environmental regulation significantly promotes green energy technology innovation when the informal environmental regulation intensity does not exceed −2.797. The informal environmental regulation exerts a significant but bigger promotional effect on green energy technology innovation when the informal environmental regulation intensity is between −2.797 and −0.995. Therefore, (−2.797,−0.995) is the optimal interval in terms of the impact of the informal environmental regulation on green energy technology innovation.

The level of economic development has a significant positive moderating effect in the relationship between environmental regulation and green energy technology innovation, that is, the higher the level of economic development, the stronger the promotion effect of environmental regulation on green energy technology innovation. However, there is a certain heterogeneity in the moderating role between the formal regulation-innovation link and informal regulation-innovation relationship. Specifically, for the formal environmental regulation, the improvement of economic development level can weaken its inhibition effect on green energy technology innovation, and the promotion effect of formal environmental regulation on green energy technology innovation can be significantly enhanced after crossing the threshold value. As for informal environmental regulation, the improvement of economic development level can significantly enhance its promotion effect on green energy technology innovation, and can offset its inhibition effect on green energy technology innovation due to its excessive intensity.

These results not only provide new insights into the relationship between heterogeneous environmental regulations and green energy innovation in China but also have obvious policy implications. On the one hand, the sample median of formal environmental regulation in this paper is −0.258, while the first threshold value is −0.247. The empirical results show that the formal environmental regulation in most regions of China does not cross the first threshold and does not significantly promote green energy technology innovation. Therefore, the local government in these regions needs to adjust the existing environmental regulations to stimulate green energy technology innovation. The median sample of informal environmental regulation is −2.271, which is far less than the second threshold of −0.995, indicating that informal environmental regulation in most regions has played a significant role in promoting green energy innovation at the current stage, but the government should strengthen the guidance of informal environmental regulation to avoid the inhibitory effect of green energy technology innovation caused by too strong informal environmental regulation. On the other hand, the level of economic development can well enhance the stimulating effect of environmental regulation on green energy technology innovation. Therefore, the local governments should actively promote economic transformation and upgrading, give consideration to environmental governance, and timely adjust environmental policies according to the local economic development level, so as to alleviate the negative economic effects brought by environmental regulation and realize the joint development and progress of economy, environment, and green energy innovation.

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Conflicts of interest

The authors declare no conflict of interest.

References

Ardito L, Petruzzelli AM, Albino V (2016) Investigating the antecedents of general purpose technologies: A patent perspective in the green energy field. *J Eng Technol Manage* 39: 81–100. https://doi.org/10.1016/j.jengtecman.2016.02.002

Blackman A (2010) Alternative pollution control policies in developing countries. *Rev Environ Econ Policy* 4: 234–253. https://doi.org/10.1093/reep/req005

Chao X, Lian Y (2020) Win-win Strategy for China's Environmental Regulation and Economic Development. https://doi.org/10.36689/uhk/hed/2020-01-029

Du WJ, Li MJ (2016) Nonlinear impact of environmental regulations on product innovation. *Stud Sci Sci* 34: 462–470. https://doi.org/10.16192/j.cnki.1003-2053.2016.03.017.

Du Y, Li Z, Du J, et al. (2019) Public environmental appeal and innovation of heavy-polluting enterprises. *J Cleaner Prod* 222: 1009–1022. https://doi.org/10.1016/j.jclepro.2019.03.035

Feng Z, Chen W (2018) Environmental regulation, green innovation, and industrial green development: An empirical analysis based on the Spatial Durbin model. *Sustainability* 10: 223. https://doi.org/10.3390/su10010223

Glaeser EL, Kallal HD, Scheinkman JA, et al. (1992) Growth in cities. *J Political Economy* 100: 1126–1152. https://doi.org/10.1086/261856

Guo Q, Zhou M, Liu N, et al. (2019) Spatial effects of environmental regulation and green credits on green technology innovation under low-carbon economy background conditions. *Int J Environ Res Public Health* 16: 3027. https://doi.org/10.3390/ijerph16173027

Guo Y, Xia X, Zhang S, et al. (2018) Environmental regulation, government R&D funding and green technology innovation: evidence from China provincial data. *Sustainability* 10: 940. https://doi.org/10.3390/su10040940

Hansen BE (2019) Threshold effects in non-dynamic panels: Estimation, testing, and inference. *J Econometrics* 93: 345–368. https://doi.org/10.1016/S0304-4076(99)00025-1

Hudson J, Minea A (2013) Innovation, intellectual property rights, and economic development: a unified empirical investigation. *World Dev* 46: 66–78. https://doi.org/10.1016/j.worlddev.2013.01.023

Jiang FX, Wang ZJ, Bai JH (2013) The Dual Effect of Environmental Regulations' Impact on Innovation—An Empirical Study Based on Dynamic Panel Data of Jiangsu Manufacturing. *China Ind Econ* 07: 44–55. https://doi.org/10.19581/j.cnki.ciejournal.2013.07.004.

Johnstone N, Haščič I, Popp D (2010) Renewable energy policies and technological innovation: evidence based on patent counts. *Environ Resour Econ* 45: 133–155. https://doi.org/10.1007/s10640-009-9309-1

Kim K, Heo E, Kim Y (2017) Dynamic policy impacts on a technological-change system of renewable energy: an empirical analysis. *Environ Resour Econ* 66: 205–236. https://doi.org/10.1007/s10640-015-9946-5

Li G, Guo F, Di D (2021) Regional competition, environmental decentralization, and target selection of local governments. *Sci Total Environ* 755: 142536. https://doi.org/10.1016/j.scitotenv.2020.142536

Li J, Du YX (2021) Spatial effect of environmental regulation on green innovation efficiency: Evidence from prefectural-level cities in China. *J Cleaner Prod* 286: 125032. https://doi.org/10.1016/j.jclepro.2020.125032

Li W, Gu Y, Liu F, et al. (2019) The effect of command-and-control regulation on environmental technological innovation in China: a spatial econometric approach. *Environ Sci Pollut Res* 26: 34789–34800. https://doi.org/10.1007/s11356-018-3678-3

Li W, Sun H, Tran D K, et al. (2020) The impact of environmental regulation on technological innovation of resource-based industries. *Sustainability* 12: 6837. https://doi.org/10.3390/su12176837

Lian YJ, Cheng J (2006) Relationship between Capital Structure and Performance with Different Growth Opportunities. *Modern Econ Sci* 02: 97–103+128.

Lin H, Zeng SX, Ma HY, et al. (2014) Can political capital drive corporate green innovation? Lessons from China. *J Cleaner Prod* 64: 63–72. https://doi.org/10.1016/j.jclepro.2013.07.046

Liu SM, Hou P, Gao YK, et al. (2020) Innovation and green total factor productivity in China: a linear and nonlinear investigation. *Environ Sci Pollut Res* 1–22. https://doi.org/10.1007/s11356-020-11436-1

Liu Y, Liu SM, Xu XY, et al. (2020) Does energy price induce China's green energy innovation? *Energies* 13: 4034. https://doi.org/10.3390/en13154034

Liu Z, Gong Y (2018) The threshold effect of environmental regulation on green technology innovation capability: An empirical test of chinese manufacturing industries. *Ekoloji* 27: 503–516.

Long X, Chen Y, Du J, et al. (2017) The effect of environmental innovation behavior on economic and environmental performance of 182 Chinese firms. *J Cleaner Prod* 166: 1274–1282. https://doi.org/10.1016/j.jclepro.2017.08.070

Luo Y, Salman M, Lu Z (2021) Heterogeneous impacts of environmental regulations and foreign direct investment on green innovation across different regions in China. *Sci Total Environ* 759: 143744. https://doi.org/10.1016/j.scitotenv.2020.143744

Nesta L, Vona F, Nicolli (2014) Environmental policies, competition and innovation in renewable energy. *J Environ Econ Manage* 67: 396–411. https://doi.org/10.1016/j.jeem.2014.01.001

Pan XF, Ai BW, Li CY, et al. (2019) Dynamic relationship among environmental regulation, technological innovation and energy efficiency based on large scale provincial panel data in China. *Technol Forecast Soc Chang* 144: 428–435. https://doi.org/10.1016/j.techfore.2017.12.012

Demirel P, Kesidou E (2011) Stimulating different types of eco-innovation in the UK: Government policies and firm motivations. *Ecol Econ* 8: 1564–1557. https://doi.org/10.1016/j.ecolecon.2011.03.019

Peng J, Song Y, Tu G, et al. (2021) A study of the dual-target corporate environmental behavior (DTCEB) of heavily polluting enterprises under different environment regulations: Green innovation vs. pollutant emissions. *J Cleaner Prod* 297: 126602. https://doi.org/10.1016/j.jclepro.2021.126602

Porter ME, Van der Linde C (1995) Toward a new conception of the environment-competitiveness relationship. *J Econ Perspect* 9: 97–118. https://doi.org/10.1257/jep.9.4.97

Song Y, Yang T Zhang M (2019) Research on the impact of environmental regulation on enterprise technology innovation—an empirical analysis based on Chinese provincial panel data. *Environ Sci Pollut Res* 26: 21835–21848. https://doi.org/10.1007/s11356-019-05532-0

Su X, Zhou SS (2019) Dual Environmental Regulation, Government Subsidy and Enterprise Innovation Output. *China Popul Resour Environ* 29: 31–39.

Tong J, Liu W, Xue J (2016) Environmental regulation, Factor Input Structure and Industrial Transformation. *Econ Res J* 51: 43–57.

Vona F, Nicolli F, Nesta L (2012) Determinants of Renewable Energy Innovation: environmental policies vs. market regulation. *Documents de Travail de l'OFCE* 5.

Wagner M (2007) On the relationship between environmental management, environmental innovation and patenting: evidence from German manufacturing firms. *Res Policy* 10: 1587–1602. https://doi.org/10.1016/j.respol.2007.08.004

Walz R, Marscheider-Weidemann F (2011) Technology-specific absorptive capacities for green technologies in Newly Industrialising Countries. *Int J Technol Glob* 5: 212–229. https://doi.org/10.1504/ijtg.2011.039765

Wang FX, Mao AH, Li HL, et al. (2013) Quality Measurement and Regional Difference of Urbanization in Shandong Province Based on the Entropy Method. *Sci Geogr Sinica* 33: 1323–1329. https://doi.org/10.13249/j.cnki.sgs.2013.11.006.

Wang S, Fan J, Zhao D, et al. (2016) Regional innovation environment and innovation efficiency: the Chinese case. *Technol Anal Strat Manage* 28: 396–410. https://doi.org/10.1080/09537325.2015.1095291

Wu J, Deng Y, Huang J, et al. (2013) Incentives and outcomes: China's environmental policy. *Natl Bureau Econ Res*. https://doi.org/10.3386/w18754

Xu. Y (2014) Whether Informal Environmental Regulation from Social Pressure Constraints on China's Industrial Pollution? *Financ Trade Res* 25: 7–15. https://doi.org/10.19337/j.cnki.34-1093/f.2014.02.002.

Yan Z, Zou B, Du K, et al. (2020) Do renewable energy technology innovations promote China's green productivity growth? Fresh evidence from partially linear functional-coefficient models. *Energy Econ* 90: 104842. https://doi.org/10.1016/j.eneco.2020.104842

Yi M, Fang X, Wen L, et al. (2019) The heterogeneous effects of different environmental policy instruments on green technology innovation. *Int J Environ Res Public Health* 16: 4660. https://doi.org/10.3390/ijerph16234660

Zhang H (2014) The Green Paradox Puzzle: Interpretation from the Perspective of Local Government Competition. *J Financ Econ* 40:114–127. https://doi.org/10.16538/j.cnki.jfe.2014.12.001.

Zhang P, Zhang PP, Cai GQ (2016) Comparative Study on Impacts of Different Types of Environmental Regulation on Enterprise Technological Innovation. *China Popul Resour Environ* 26: 8–13.

Zheng Y, Peng J, Xiao J, et al. (2020) Industrial structure transformation and provincial heterogeneity characteristics evolution of air pollution: Evidence of a threshold effect from China. *Atmos Pollut Res* 11: 598–609. https://doi.org/10.1016/j.apr.2019.12.011

Zheng S, Wu J, Kahn ME, et al. (2012) The nascent market for "green" real estate in Beijing. *Eur Econ Rev* 56: 974–984. https://doi.org/10.1016/j.euroecorev.2012.02.012

Zhou HH, Wang SL (2016) Study on the Influential Mechanism of Formal and Informal Environmental Regulations on Green Innovation. *Soft Sci* 30: 47–51. https://doi.org/10.13956/j.ss.1001-8409.2016.08.11.