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Legal environmental regulation and green technology innovation of energy enterprises: based on panel threshold regression

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Legal environmental regulation is not only an important tool for green technology innovation and energy efficiency improvement, but also a key measure for enterprise upgrading and high-quality economic development. Based on the panel data of China's listed energy companies from 2010 to 2020, this paper finds that legal environmental regulation has a significant positive impact on enterprise green technological innovation by using SYS-GMM. And the threshold regression model is used to examine the nonlinear impact of legal environmental regulation on green technology innovation in this paper. The results show that the positive impact of legal environmental regulation on green output of energy enterprises is more prominent than that of non-R&D investment. In addition, the impact of legal environmental regulation on green technology innovation of energy enterprises has a threshold effect. That is, the loose legal environmental regulation (LER ≤ 399.656) has a negative impact on the green output of energy enterprises, while the impact of strict legal environmental regulation (LER > 399.656) is the opposite. Meanwhile, the loose legal environmental regulation (LER ≤ 491.291) and strict legal environmental regulation (LER > 491.291) have a negative impact on the non-R&D investment of energy enterprises. Finally, there are huge differences in green technology innovation capabilities of energy enterprises.

KEYWORDS

legal environmental regulation, green technology innovation, energy enterprises, green output, non-R&D investment, panel threshold regression

1 Introduction

The contradiction between environmental pressure and economic growth has become increasingly prominent (Xu et al., 2019; Xia and Wang, 2021). Reasonable and orderly economic development is not only the inherent requirement of the ecological environment, but also an important support for strengthening environmental protection (Yildirim et al., 2018; Xu et al., 2019; Liu and Ding, 2020). And the environmental system is also closely related to the energy system. However, with the continuous expansion of the scope and scale of energy use, while promoting economic growth, the serious ecological and environmental problems would have been caused by the excessive development and utilization of various energy resources (Tiba and Omri, 2017). Environmental pollution and excessive greenhouse gas emissions caused by energy production and consumption have significant negative impact on human production and quality of life (Omri et al., 2022). In recent years, due to

the scarcity of energy resources, the frequent occurrence of energy security problems and the intensification of global climate change, the importance of energy issues has become more prominent. In order to actively respond to the extreme climate change caused by global environmental degradation, China has put forward the "double carbon" strategy, and the balance between environmental protection and economic development has been widely concerned (Guo et al., 2022). As an important measure to reduce carbon emissions, alleviate the frequent occurrence of extreme weather and promote green technology innovation, environmental regulation is not only the basic guarantee to achieve the "double carbon" goal, but also the key to achieve the "win-win" goal of healthy economic development and ecological environment protection (Huisingh et al., 2015; Tan and Xu, 2022). However, the research on the dynamic relationship between energy and economic and environmental systems has attracted the attention of scholars in many disciplines (Ahmad et al., 2020). Although there are a large number of research results in this field, the research conclusions have not reached a consensus, and the research on green technology innovation of energy enterprises is almost zero. Therefore, the impact of the implementation of legal environmental regulation policies on green technology innovation of energy enterprises is discussed in this paper.

Specially, with the continuous strengthening of environmental regulation, enterprises will inevitably reduce the additional cost of responding to environmental standards through technological innovation (Li and Zou, 2018; Jin et al., 2022). However, under the influence of market and economic policy uncertainties, there are significant differences in the level of green technology innovation of enterprises. In the short term, environmental regulations may squeeze the R&D investment of enterprises, reduce financial performance and inhibit green technology innovation (Berrone et al., 2013; Shao et al., 2020). In the long run, environmental regulation promotes enterprises to adjust production behavior and optimize industrial structure by implementing energy conservation and emission reduction constraints (Bu et al., 2020). The effect of "innovation compensation" exceeds the input cost required for green technology innovation, and increases the profits of enterprises in the process of realizing green production (Wang et al., 2021). Nevertheless, the existing research on environmental regulation mainly focuses on how to affect the transformation and upgrading of enterprises (Yuan and Chen, 2019), pollution control (Cui and Jiang, 2019), environmental protection investment (Liu et al., 2022), financial performance (Lee, 2020) and enterprise financial performance (Bao and Yu, 2022). In addition, some studies also discussed the impact of environmental regulations on green technology innovation of enterprises, which are mostly concentrated in manufacturing and heavily polluting enterprises (Yuan and Xiang, 2018; Cai et al., 2020). Few studies have analyzed the role of legal environmental regulation in green innovation of energy enterprises and provided operational policy recommendations for environmental governance in the energy industry. In this context, in order to verify the direct effect of legal environmental regulation on green technology innovation of energy enterprises, and avoid the inconsistency of parameter estimation caused by endogeneity, the SYS-GMM for regression test is chosen in this paper. Additionally, considering that there may be a nonlinear relationship between legal environmental regulation and green technology innovation of energy enterprises and the reliability of parameter estimation, the panel threshold model for verification is chosen in this paper. While from the perspective of the sustainable development of the energy industry and the effectiveness of legal environmental regulation, it provides policymakers with practical policy implications.

The main contributions of this paper are as follows: first, this paper focuses on the impact of legal environmental regulation on green technology innovation of energy enterprises, which is helpful to provide suggestions for the policymakers to adopt effective legal environmental regulation measures to promote green technology innovation of energy enterprises, and also further enrich the research literature in this field. Second, considering the heterogeneity of the impact of the change in the intensity of environmental regulation on the level of green technology innovation of enterprises, this paper discusses the differences in the impact of different intensity of legal environmental regulation on the level of green technology innovation of energy enterprises and the driving mechanism, which are helpful to provide suggestions for policymakers to formulate differentiated legal environmental regulation measures to improve the green technology innovation ability of energy enterprises. Third, in order to more accurately describe the impact of changes in the intensity of legal environmental regulation on green technology innovation of energy enterprises, and improve the endogenous problems of the model. The panel threshold regression analysis method is adopted, which is conducive to a more comprehensive and systematic study of the impact of legal environmental regulations on the level of green technology innovation of energy enterprises.

2 Literature review

Although the current environmental issues have attracted much attention (Zameer et al., 2021a), it has been regarded as a secondary issue of social development until Porter and van der Linde (1995) put forward the famous Porter Hypothesis at the end of the 20th century (Shao et al., 2020). In addition, the impact of energy consumption on economic growth has also continued to receive attention as environmental problems have become prominent (Yasmeen et al., 2019). Therefore, countries have introduced various environmental regulations to deal with environmental problems. Environmental regulation is a necessary constraint to achieve high-quality economic development (Jiang et al., 2023), which is regarded as a policy tool for internalizing the external costs of enterprises, and is the national control of high-polluting production (Jiang et al., 2021), such as collecting pollution taxes, formulating environmental regulations and using pollution charges (Sui and Wang, 2011). Meanwhile, environmental regulation plays a positive regulatory role in the impact of energy endowment on energy efficiency (Wang L. et al., 2022). From the perspective of environmental economics, environmental regulation will promote green technological innovation, industrial transformation and upgrading, improve productivity, and achieve high-quality economic development (Hojnik and Ruzzier, 2016). Furthermore, environmental regulation can be divided into mandatory environmental regulation represented by government (Jiang et al., 2021; Xu and Xu, 2022) and voluntary environmental regulation

represented by non-governmental organizations, enterprises and individuals (Nie et al., 2022; Zameer and Yasmeen, 2022; Zhou et al., 2022). As the definition and specific measures, legal environmental regulation can be Attributable to the mandatory environmental regulation, which focuses more on the governance of environmental problems at the government level.

Nevertheless, the conclusions that the impact of the legal environmental regulation on the green technology innovation of energy enterprise are dissimilar in different researches. Based on this, the current legal environmental regulation researches on green technology innovation are briefly sorted out.

2.1 The negative relationship between legal environmental regulation and green technology innovation

Neoclassical economics believes that policies and regulations on environmental regulation will lead to higher production costs for enterprises, weaken the competitive advantage of enterprises, and thus offset the positive effects of environmental protection on society (Gollop and Roberts, 1982). This point has been supported by some scholars who found that the implementation of environmental regulations has a "crowding-out effect" on the capital investment of green technological innovation. Anson and Turner (2009) pointed out that due to the pressure of environmental regulations, enterprises have to bear a lot of environmental protection costs, which will encourage enterprises to carry out green technology innovation. Therefore, enterprises must invest in environmental technology transformation, which will lead to the increase of enterprise costs (Pan et al., 2019). If green technology innovation is not compensated in the future, the enterprises income will fall sharply, which would squeeze other types of investment and reduce production. And due to the differences in regional resource endowments and financial levels, the economic development of backward regions will rely more on natural resources (Wang et al., 2019; Zameer et al., 2020), and environmental regulation will have a greater crowding-out effect on the green technology innovation of enterprises in this region. Moreover, the "Pollution Haven Hypothesis" holds that legal environmental regulation will promote the migration of pollutants (Liao, 2018). Generally, the intensity of environmental regulation in low-income areas is relatively low, which is more likely to become a pollution paradise (Zeng and Zhao, 2009).

At present, the legal environmental regulation has a great impact on the environmental cost control, enterprise profitability, environmental protection investment (Chen and Wu, 2021; Huang et al., 2023). The implementation of the legal environmental regulation has brought great pressure to the enterprises' environmental management, which has not only failed to promote the environmental investment of enterprises, but also hindered the total factor productivity of enterprises (Cui and Jiang, 2019; Cai and Ye, 2020). In sum up, environmental regulations would affect green technology innovation from the perspective of production costs. Due to the "cost crowding out effect," it would have different degrees of impact on enterprise innovation, investment and total factor productivity.

2.2 The positive relationship between legal environmental regulation and green technology innovation

The appropriate environmental regulation will promote green technological innovation of enterprises. Martínez-Zarzoso et al. (2019) used data from 14 OECD countries to test the Porter Hypothesis and found that environmental regulation has a positive impact on the innovation productivity of enterprises in the long run. Cai et al. (2020) used Poisson panel model to study the impact of environmental regulation on green technology innovation of listed heavy polluting enterprises in China, and found that environmental regulation plays an important role in promoting green technology innovation. Zhong and Peng (2022) analyzed the sample data of Shanghai and Shenzhen A-share listed companies from 2010 to 2019, and found that the environmental protection law significantly promoted the green technology innovation of heavily polluting enterprises, and compared with non-state-owned enterprises, the role of environmental protection law in promoting green technology innovation of state-owned enterprises is more significant. At the same time, with the deterioration of China's environmental problems and the improvement of public environmental awareness, although environmental regulatory enforcement has not yet played an active regulatory effects in the relationship between news media constraints, community residents constraints and green technology innovation, it has played an active regulatory role in the relationship between environmental NGO (non-governmental organization) constraints and green technology innovation (Zhao et al., 2022).

How does legal environmental regulation promote green technology innovation? Ambec and Barla (2002) believe that environmental regulation will force the green technological innovation ability of enterprises. In the early stage of the government's implementation of environmental regulation, the intensity of environmental regulation is weak. At this time, the fine payment in violation of environmental law and the cost of access to green technology is lower than the cost of green technology innovation and R&D, and the motivation of enterprises to develop green technology will be reduced (Acemoglu et al., 2014), which is the so-called "compliance cost" effect. With the strengthening of environmental regulation, the production cost of enterprises will be increased. In order to maximize profits, enterprises must digest the increase of production costs through technological innovation or change their product structure. When the benefits of green technology innovation exceed the cost of pollution, enterprises are more motivated to carry out green technology research and development, thus producing the "innovation compensation" effect (Li and Zou, 2018). In this case, environmental regulation provides opportunities for green technology innovation. And with the profit growth brought by technological innovation and the substantial improvement of production efficiency of energy enterprises, the overall energy production system has been further optimized (Zameer and Wang, 2018; Shahbaz et al., 2020). In general, environmental regulations would increase the environmental costs in the process of enterprise operation. However, the increase in profits brought about by technological innovation would offset the input costs and improve the operating conditions of enterprises.

2.3 Non-linear relationship between legal environmental regulation and green technology innovation

With the emphasis on ecological environment protection, the role of green technology innovation in environmental performance has been highlighted (Zameer et al., 2021b), so higher requirements have been put forward for environmental regulation. Most scholars believe that legal environmental regulation promotes green technology innovation, but few scholars hold that the relationship between legal environmental regulation and green technology innovation is not significant or nonlinear (Li and Ramanathan, 2018). Brunnermeier and Cohen (2003) studied how green technology innovation in U.S. manufacturing responded to the implementation of environmental regulations between 1983 and 1992, and found no additional innovation incentives resulting from existing regulations and enforcement activities. Wang et al. (2021) used the green patent data of listed companies in Shanghai and Shenzhen security markets from 2004 to 2015 as samples, and adopted the system-GMM method to examine the relationship between environmental regulation and green technology innovation, and found that it was U-shaped nonlinear.

The impact of environmental regulation on green technology innovation is heterogeneous in terms of enterprise characteristics, industry types, environmental supervision means, location and so on. For example, some enterprises that invest in pollutant emission reduction technologies or have a comparative advantage in environmental compliance are not affected by environmental regulations (Shao et al., 2020; Wang Y. et al., 2022). Newell et al. (1999) introduced environmental regulation theory into the product characteristic model, and found that the role of environmental management in green technology innovation is on specific products. In this process, the speed of green technology innovation is not related to environmental regulations. Meanwhile, the impact of command-and-control environmental regulations on green technology innovation has a single threshold effect, and the impact of market incentive environmental regulations on green technology innovation presents a double threshold effect (Yi et al., 2019). As far as the eastern, central and western regions of China are concerned, the impact of environmental regulation on green technology innovation is also different, Specifically, environmental regulation plays a positive role in promoting green technology innovation in resource-based cities in the central region, but has no significant role in promoting green technology innovation in non-resource-based cities in the east and west regions (Zhang et al., 2022).

Overall, with the increase of environmental regulation intensity, the green technology innovation of enterprises would be improved, which is in line with the Porter Hypothesis. However, it should be noted that this relationship will also be affected by other factors such as enterprise size, age and leverage. Meanwhile, the research on the impact of environmental regulation on enterprise green innovation is divided into two categories. One is the "cost crowding out effect" brought by environmental regulation, which reduces the enthusiasm of enterprise green innovation. The other is the "innovation compensation effect" brought by appropriate environmental regulation, so as to stimulate the enthusiasm of enterprises for green technology innovation. Moreover, most of the existing studies lack to measure the intensity of environmental regulation from the legal level (number of penalty cases), thus this conclusion cannot be applied to formulate legal environmental regulation policies. In addition, most of the existing research focuses on high-polluting enterprises, and lacks energy enterprises as the research object to investigate the impact of changes in the intensity of legal environmental regulation on green technology innovation.

3 Theoretical model

The internal mechanism of the impact of legal environmental regulation on green technology innovation of energy enterprises from the theoretical level is analyzed in this paper. As shown in Figure 1, with the increasingly prominent environmental problems brought about by economic activities, legal environmental regulation, represented by government issued laws and rules, have begun to affect corporate decision-making.

Firstly, legal environmental regulation will affect energy enterprises' environmental cost, which contains pollution hazard cost, environmental regulation cost, raw material and energy costs. The pollution hazard cost refers to the environmental pollution cost and environmental purification cost generated by energy enterprises in the process of product production, use and recycling. Environmental regulation cost means the related costs of environmental regulation department regulation policy, such as pollution tax and energy enterprise pollution control equipment update investment. Raw material and energy costs relates to the compensation for consumption of resources. Secondly, the environmental cost brought by legal environmental regulation will affect the green technology innovation decision of energy enterprises. And legal environmental regulation will have an impact on energy enterprises from the endogenous and exogenous power of green technology innovation. Specifically, endogenous power includes innovation risk, profit maximization and innovative consciousness. With the government's emphasis on the environment and the strengthening of environmental regulation policies, as well as the deepening of the research and application of environmental protection technology theories, it is conducive to accelerating the green technology innovation process of energy enterprises, shortening the lag period of green technology innovation income, increasing innovation income and reducing innovation risks. Meanwhile, in order to pursue profit maximization, the energy enterprises will urgently carry out green technology innovation to reduce the cost of resource elements and increase profits through innovation compensation. And when the environmental regulation is more and more strict, the environmental cost increases, the public demand for green products, only by strengthening innovation consciousness and developing new environmental protection technology can energy enterprises ensure their market position. At the same time, the external power contains market demand, market competition and government policy. With the popularization of the concept of sustainable development, the market's attention and demand for green products are getting more and more stronger. Driven by market demand, the enthusiasm of energy enterprises for green technology innovation would be stimulated. In addition, under the mature

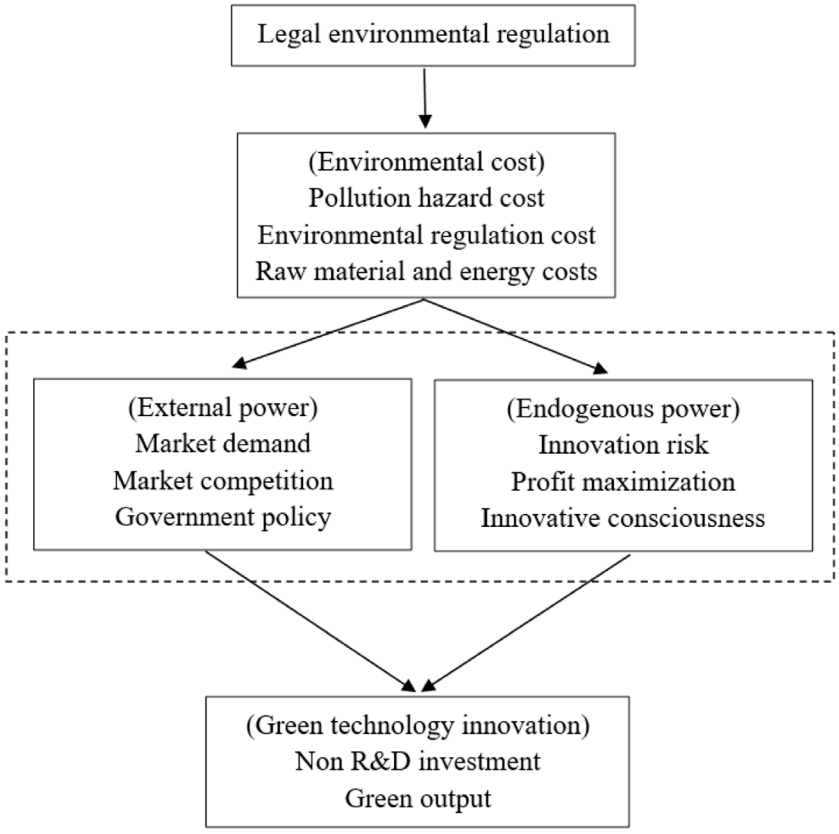

FIGURE 1
The transmission path of legal environmental regulation affecting green innovation of energy enterprises.

market mechanism, a good competitive environment is conducive to guiding the green innovation of energy enterprises. However, the simultaneous implementation of legal environmental regulation and other policies, inevitably makes conflicts between policies. And the government will coordinate various policies to coordinate the development of the policy system, which is conducive to the effectiveness of legal environmental regulation.

Finally, the results will be reflected in two aspects of green technology innovation, which means non-R&D investment and green output. On the one hand, the legal environmental regulation will directly influence the green technology innovation of energy enterprises through endogenous and exogenous power of green technology innovation. On the other hand, there is also a threshold effect between legal environmental regulation and green innovation of energy enterprises. According to Porter Hypothesis, strict and appropriate environmental regulation not only has positive externalities on social public welfare such as environmental performance, but also has positive externalities on enterprises themselves. And appropriate environmental regulation encourages enterprise technological innovation and improves enterprise productivity. The innovation compensation effect generated by technological innovation makes up for or even exceeds the compliance cost effect of environmental regulation, realizes Pareto improvement of environmental regulation and technological innovation, and finally achieves a 'win-win' state of economic performance and environmental performance. Moreover, with the gradual enhancement of the innovation compensation effect, the investment funds of energy enterprises are also relatively increased, so the R&D investment in green technology innovation of enterprises will be strengthened, and the promotion of green technology innovation of energy enterprises will be further increased.

4 Methodology

4.1 Data sources

Referring to the data selection methods of some scholars (Yang, et al., 2019; Tan et al., 2022) and the China Securities Regulatory Commission (2012 edition) industry classification, the panel data of 227 listed energy enterprises from 2010 to 2020 are selected in this paper, which have been screened by eliminating ST or PT enterprises, deleting a large number of samples with missing data and excluding the samples with abnormal data. The development status of energy enterprises and other data are obtained from Wind, CNRDS and CSMAR database, while the relevant information of legal environmental regulation from China Environmental Yearbook, China Environmental Statistics Yearbook and China Ecological Environment Bulletin.

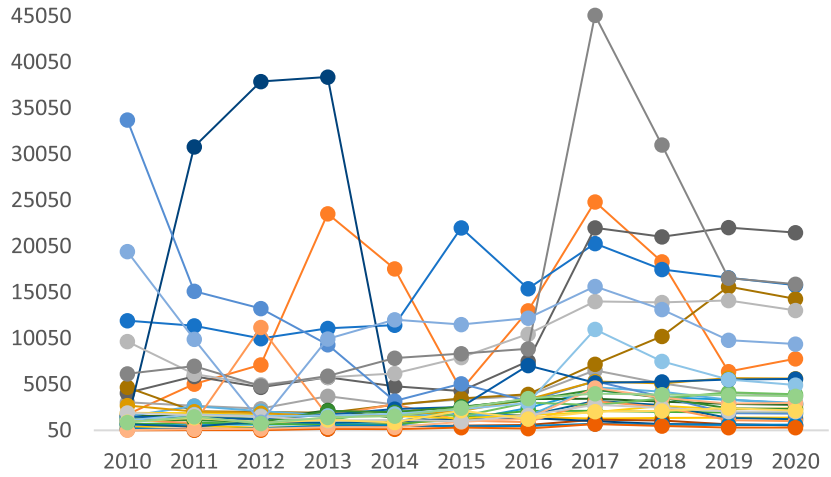

FIGURE 2
The total number of environmental punishment cases at end of year. (Data sources: China Statistics Yearbook on Environment, China Environmental Yearbook).

At the same time, the missing data would affect the regression results. This paper uses interpolation method to supplement (Saliba et al., 2021) for missing data, and 1,452 observations are finally obtained. Stata 16.0 is used for data analysis.

4.2 Variable definition

4.2.1 Dependent variable

In the existing research, green technological innovation of enterprises is mostly measured by R&D investment, green patent application and green patent authorization (Guo et al., 2022; Li, 2022). However, enterprise innovation activities are easily affected by external fluctuations, and there is a high degree of uncertainty. Only using R&D investment and the number of green patents cannot accurately reflect the index. Ju et al. (2013) proposed that intangible assets mainly include patents, non-patented technologies, trademark rights and copyrights. Therefore, the increase in intangible assets is the result of enterprise innovation investment and can be regarded as a comprehensive reflection of enterprise innovation activities. The green technological innovation of this paper is divided into two aspects: green output (measured by green patent application volume) and Non-R&D investment (using intangible assets to explain).

4.2.2 Independent variable

As an important indicator of environmental protection in the reaction area, environmental regulation can be expressed by the emissions of major pollutants, environmental taxes, sewage charges (Dong and Wang, 2019; Li and Xiao, 2020). According to different subjects, environmental regulation can be divided into economic environmental regulation, legal environmental regulation and supervised environmental regulation. With the continuous updating of environmental standards, the definition of environmental regulation has also been extended from government control to market-oriented regulation (Zhao et al., 2015). This paper focuses on the discussion of legal environmental regulation, that is, the government formulates strict industry environmental standards through legal means, regulates the production and operation activities of enterprises, and then bears corresponding environmental responsibilities. Once the enterprise is punished for violating the relevant regulations in the production and operation activities, it is recorded as an environmental punishment case and recorded in the total number. This paper uses the product of the total number of environmental punishment cases in each province at the end of the year and the market value of each enterprise to measure legal environmental regulation. Moreover, Figure 2 is drawn in this paper by using the total number of environmental punishment cases at end of year in Chinese province collected by "China Statistics Yearbook on Environment" and "China Environmental Yearbook". From Figure 2, it can be concluded that there are great differences in the number of environmental punishment cases at the end of the year in different provinces, that is, different energy enterprises are facing different degrees of legal environmental regulation. Therefore, the larger the index value, the stronger the environmental regulation faced by enterprises in this year.

4.2.3 Control variables

The control variables are divided into two levels in this paper. Firstly, Firm size, Firm age, ROE, leverage, Tobin Q are selected at the enterprise level. Secondly, the city level selects the annual GDP of each city. And all the control variables also have different degrees of influence on the green technological innovation activities of enterprises. All key variables are defined as Table 1.

According to Table 2, the average number of green patent applications of energy enterprises is 20.66, but the gap between the maximum value of 1,566 and the minimum value of 1 is wide, indicating that there is a huge difference in the internal innovation ability of energy enterprises. It may be due to the significant gap in the technological foundation conditions and the level of

TABLE 1 Variable definition.

Variables	Abbreviation	Measure	References
Explained Variables			
Intermediate outputs	lgpat	Ln (number of green patent applications of enterprises)	Ju et al. (2013); Li, (2022)
Non-research and development investment	lnia	Ln (enterprise annual intangible assets)	
Explanatory Variables			
Legal environmental regulation	ler	The product of the proportion of enterprise market value and the number of penalty cases for environment	Liu et al. (2018)
Control Variables			
Firm size	ts	Ln (total assets)	Liu et al. (2022); Guo et al. (2022)
Firm age	fa	Difference between sample year and firm listed year	
Return on equity	roe	$\frac{\text{Net profit}}{\text{Balance of shareholders' equity}}$	
Leverage	lev	Asset-liability ratio	
Tobin Q	tq	$\frac{\text{Total market value}}{\text{Assets}}$	
Gross domestic product	gdp	Ln (GDP of the cities where the enterprises are located)	

TABLE 2 Descriptive statistics.

Variables	N	Mean	p50	SD	Min	Max
lgpat	1,452	1.276	0.693	1.478	0.0	7.356
lnia	1,452	20.040	19.960	2.129	11.850	25.460
ler	1,452	1,085	385.800	2,737	0.885	45,140
ts	1,452	23.370	23.310	1.528	19.630	28.640
lev	1,452	0.521	0.539	0.188	0.013	1.034
roe	1,452	0.059	0.070	0.183	−3.340	0.729
tq	1,452	1.484	1.235	0.793	0.765	9.207
fa	1,452	2.916	2.944	0.331	1.099	3.611
gdp	1,452	6.202	6.319	1.316	2.188	8.261

infrastructure of energy enterprises, the lack of scientific, efficient, unified and coordinated decision-making and management mechanisms, and the need to improve the energy technology innovation system and mechanism.

Meanwhile, the correlation test results are shown in Table 3, which indicate that green technological innovation and legal environmental regulation of energy enterprises are significant at the 1% level. It can be seen that there is a strong correlation between them, which provides support for further regression analysis. The "Porter Hypothesis" suggests that appropriate environmental regulations will stimulate technological innovation. It can be seen that the ultimate goal of implementing environmental regulations is to force or motivate enterprises to increase research and development investment to improve pollution control capabilities and product technology content, thereby promoting green technology innovation.

4.3 Empirical model

Legal environmental regulation refers to the principle that the government or other regulatory agencies regulate the operation and behavior of specific industries or activities through formal legal documents such as laws and regulations to protect public interests, promote economic development, maintain social order and fair competition. The regulation is usually formulated and implemented by the government or other authoritative institutions, and the violation is regulated and restrained by punishment measures. At the same time, compared with other types of environmental regulation, legal environmental regulation is more mandatory, which could better reflect the Chinese government emphasis on ecological environment protection and provide new ideas for other developing countries to solve the contradiction between environmental problems and economic development. To discuss the impact of legal environmental regulation on green technological innovation activities of energy enterprises, the basic model as follows:

$$Lngpat_{it} = \alpha + \beta_1 LER_{it} + \beta_2 \sum X_{it} + \beta_3 Z_{it} + Year + \varepsilon_{it} \quad (1)$$

$$LnIA_{it} = \alpha + \beta_1 LER_{it} + \beta_2 \sum X_{it} + \beta_3 Z_{it} + Year + \varepsilon_{it} \quad (2)$$

Where i represents the enterprise, t represents the time; X_{it} represents a series of enterprise-level control variables; Z_{it} represents the control variables at the city level; $Year$ represents the year fixed effect; ε_{it} denotes random standard error.

Besides, because the impact of legal environmental regulation on enterprises is multidimensional, which may show different characteristics with the intensity of environmental regulation, that is, there may be a nonlinear relationship between variables. In order to test whether there is such a nonlinear relationship between variables, this paper uses the panel threshold regression model proposed by Hansen (1999) to test the nonlinear

TABLE 3 Correlation matrix of key variables.

Variables	lgpat	lnia	ler	ts	lev	roe	tq	fa	gdp
lgpat	1.000								
lnia	0.497***	1.000							
ler	0.216***	0.232***	1.000						
ts	0.676***	0.719***	0.283***	1.000					
lev	0.116***	0.166***	0.090***	0.351***	1.000				
roe	0.015	0.090***	0.014	0.075***	−0.212***	1.000			
tq	−0.247***	−0.272***	−0.131***	−0.482***	−0.358***	0.016	1.000		
fa	0.020	−0.043*	0.046*	0.043*	0.205***	−0.106***	−0.140***	1.000	
gdp	0.389***	0.140***	0.018	0.287***	−0.039	0.039	−0.168***	0.045*	1.000

relationship. The essence of threshold regression is to find threshold variables that reflect causality, in which the threshold value is estimated based on sample data, and to test whether there are significant differences in sample group parameters divided according to the threshold value (Che, 2013). Meanwhile, the reason for choosing the panel threshold model proposed by Hansen (1999) is that compared with the grouping test model, cross-term test model and threshold regression model are used in the existing threshold empirical researches, the panel threshold model could accurately estimate the threshold value and complete the significance test of the threshold effect, which makes up for the disadvantages of the above methods. For the econometric model of this paper, the panel threshold regression model is set as follows: $1(\cdot)$ represents the indicator function, when the expression in parentheses is false, the value is 0, otherwise the value is 1. According to whether the threshold variable environmental regulation is greater than the threshold value γ, it can be divided into two regimes.

$$Lngpat_{it} = \alpha_0 + \alpha_1 LER_{it} \cdot 1(LER_{it} \le \gamma) + \alpha_2 LER_{it} \cdot 1(LER_{it} \ge \gamma) + \alpha_3 \sum X_{it} + \alpha_4 Z_{it} + Year + \varepsilon_{it} \quad (3)$$

$$LnIA_{it} = \alpha_0 + \alpha_1 LER_{it} \cdot 1(LER_{it} \le \gamma) + \alpha_2 LER_{it} \cdot 1(LER_{it} \ge \gamma) + \alpha_3 \sum X_{it} + \alpha_4 Z_{it} + Year + \varepsilon_{it} \quad (4)$$

5 Empirical results

5.1 Baseline regression

Since the data used in this paper is unbalanced panel data, the Fisher Test is used to test the unit root of the data before the baseline regression. The results show that all variables pass the test at the 1% level, so the data is stable and the regression operation can be performed. This paper uses the Hausman test and finds that the test results strongly reject the null hypothesis, so the fixed effect model should be selected. Additionally, this paper considers the time effect in the fixed effect model, defines the annual dummy variable for this purpose, and tests the joint significance of all annual dummy variables. The test results show that the original hypothesis of 'no time effect' is strongly rejected, so the two-way fixed effect model is

TABLE 4 Baseline regression results.

Variables	Group 1		Group 2	
	lgpat	lnia	lgpat	lnia
ler	0.00009***	0.00010***	0.00001*	0.00002*
	(0.000)	(0.000)	(0.000)	(0.000)
ts			0.699***	1.168***
			(0.084)	(0.088)
lev			−0.943*	−0.152
			(0.494)	(0.541)
roe			−0.470***	0.270
			(0.157)	(0.214)
tq			0.219***	0.273***
			(0.072)	(0.092)
fa			−0.396*	−0.653
			(0.237)	(0.405)
gdp			0.163***	−0.158*
			(0.043)	(0.084)
			(0.212)	(0.300)
_cons	1.177***	19.877***	−15.284***	−5.275**
	(0.098)	(0.171)	(2.128)	(2.100)
N	1,452.000	1,452.000	1,452.000	1,452.000
Hansen	1.000	1.000	1.000	1.000
AR (1)	−6.260	0.340	−6.730	−2.030
AR (2)	−0.713	−0.367	−1.129	0.463

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE 5 The results of robust test.

Variables	Group 1		Group 2	
	lgpat	lnia	lgpat	lnia
ler	0.0001***	0.0001***	0.00003***	0.00002*
	(0.000)	(0.000)	(0.000)	(0.000)
ts			0.650***	1.147***
			(0.092)	(0.088)
lev			−0.644	−0.616
			(0.553)	(0.624)
roe			−0.344**	0.176
			(0.155)	(0.235)
tq			0.221**	0.157
			(0.087)	(0.108)
fa			−0.488*	−0.686
			(0.268)	(0.418)
gdp			0.213***	−0.164*
			(0.050)	(0.085)
	1.235***	20.016***	−13.482***	−3.561
_cons	(0.109)	(0.179)	(2.307)	(2.278)
	1,254.000	1,254.000	1,254.000	1,254.000
N	1.000	1.000	1.000	1.000
Hansen	−5.580	1.340	−6.270	−0.620
AR (1)	−1.305	−0.667	−1.129	0.288
AR (2)	0.0001***	0.0001***	0.00003***	0.00002*

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

used. At the same time, considering the impact of variable endogeneity on the effectiveness of regression results, this paper uses SYS-GMM to solve the endogeneity problem. And according to the characteristics of instrumental variables in the SYS-GMM model, the instrumental variables should be exogenous as far as possible. It should not directly affect the explained variable in theory, but indirectly affect the explained variable by affecting the instrumental variable. Therefore, some control variables are taken as instrumental variables in this paper. The results are described in group 1 of Table 4 reports the impact of legal environmental regulation on green innovation of energy enterprises without control variables, while group 2 adds corresponding control variables.

The regression results show that the AR (2) test does not have sufficient evidence to reject the null hypothesis that there is no second-order sequence correlation, which satisfies the assumptions of using system GMM. The *p*-value of Hansen test is significantly greater than 0.1, which accepts the null hypothesis that the instrumental variable is reasonable and effective. The regression results show that LER has a significant positive impact on both aspects of enterprise green technological innovation. This is consistent with the proposition of the "Porter Hypothesis", where legal environmental regulation can force energy companies to engage in green innovation, increase green investment, and achieve improved production efficiency while reducing pollution and emissions. For instance, as the result shows, the impact of LER on enterprise green output is particularly prominent. This result shows that appropriate environmental regulation will have a positive impact on green technological innovation of energy enterprises. In order to avoid the increase of pollution costs and uncertain moral hazard, energy enterprises would actively respond to environmental regulation policies and increase investment in innovative research and development. As the largest developing country, energy utilization and environmental protection have always been issues that cannot be ignored in economic development. The government's appropriate control of the environment to achieve effective incentives for enterprise innovation is the key to balancing economy and environmental protection. The existing policy proposes to accelerate the green transformation of development methods and promote the formation of green and low-carbon production methods. The most effective way is for energy enterprises to respond to environmental regulations by implementing environmental strategy and innovate green technology.

TABLE 6 Panel threshold value in Model (3).

Model	Threshold	Lower	Upper
Th-1	399.656	376.874	402.876

5.2 Robustness checks

Considering that the implementation of environmental regulation measures may have a time lag in the effect, the robustness of baseline regression is tested by lagging the explanatory variable in this paper. The internal mechanism is that enterprises adjust their internal production structure in response to environmental protection policies, which requires a certain amount of time to plan. At the same time, the measures implemented in the year may be highlighted in the next year. The results in Table 5 suggest that the coefficient of environmental regulation in green product is still positive and no significant change in value. In the long run, legal environmental regulation policies would gradually improve, guiding energy enterprises to engage in green technology innovation would greatly reduce the risks of green technology innovation, and the incentive effect on green technology innovation is greater than the crowding out effect. In sum up, this paper believes that legal environmental regulation could stimulate green technological innovation of energy enterprises.

5.3 Threshold effect analysis

Jaffe and Palmer (1997) have explored the Porter Hypothesis, and refined the original theory into Narrow-PH, Weak-PH and Strong-PH, which expanded the single environmental regulation to

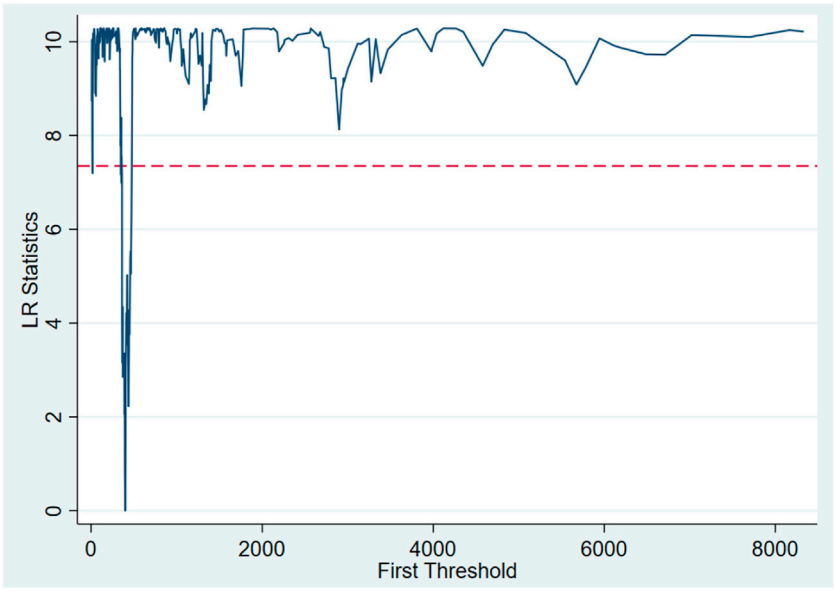

FIGURE 3
Panel threshold estimation results in Model (3).

TABLE 7 Panel threshold parameter estimation results in Model (3).

lgpat	Coef.	Std.Err.	t	$p > t$	[95% Conf.	Interval]
ts	0.507	0.094	5.370	0.000	0.322	0.692
lev	−0.854	0.395	−2.160	0.031	−1.630	−0.079
roa	−0.212	0.360	−0.590	0.556	−0.918	0.494
roe	0.053	0.074	0.710	0.477	−0.093	0.199
tq	0.797	0.253	3.140	0.002	0.299	1.294
fa	0.619	0.127	4.880	0.000	0.370	0.868
gdp	0.507	0.094	5.370	0.000	0.322	0.692
LERit≤γ	−0.001	0.000	−2.980	0.003	−0.001	−0.000
LERit≤γ	0.000	0.000	1.930	0.054	−0.000	0.000
cons	−16.172	1.931	−8.380	0.000	−19.963	−12.382
sigma_u	0.853					
sigma_e	0.761					
rho	0.556					

TABLE 8 Panel threshold value in Model (4).

Model	Threshold	Lower	Upper
Th-1	491.291	473.679	502.485

a multidimensional perspective. With the deepening of scholars' research on environmental regulation and green innovation, it is strongly proved that Weak-PH, that is, appropriate environmental regulation can stimulate innovation (Mi, et al., 2018). However, due to the great differences in the market conditions faced by different industries, it is necessary to discuss the impact of the intensity of environmental regulation on the green technology innovation of different types of enterprises. Therefore, the panel threshold regression model is used in this paper in order to further explore the impact of different legal environmental regulation intensity on green technological innovation of energy enterprises. According to the principle of the threshold regression model, the threshold variable can be either an explanatory variable in the model or other independent variables. When the LER reaches a certain level, the impact on the green technological innovation of energy enterprises will change. Considering the different operating conditions of energy enterprises, this paper selects the explanatory variable legal environmental regulation as the threshold variable for analysis.

5.3.1 Threshold effect of green output in green innovation

Table 6 shows that there is a threshold value is 399.656, and the corresponding likelihood ratio function is shown in Figure 3. The real threshold value corresponding to the lowest point of the LR statistic is represented by the dotted line as the critical value, which is obviously larger than the above threshold value. Therefore, the threshold value is effective in this paper.

The threshold regression result of green output stage in green technological innovation of energy enterprises is shown in Table 7. It can be seen that when LER is loose ($LER \leq 399.656$), the influence coefficient of LER on green technological innovation of energy enterprises is negative. While when LER is strict ($LER > 399.656$), the regression coefficient is positive, which shows that the green output of energy enterprises is increasing with the continuous enhancement of LER. The reason maybe is the fierce competition

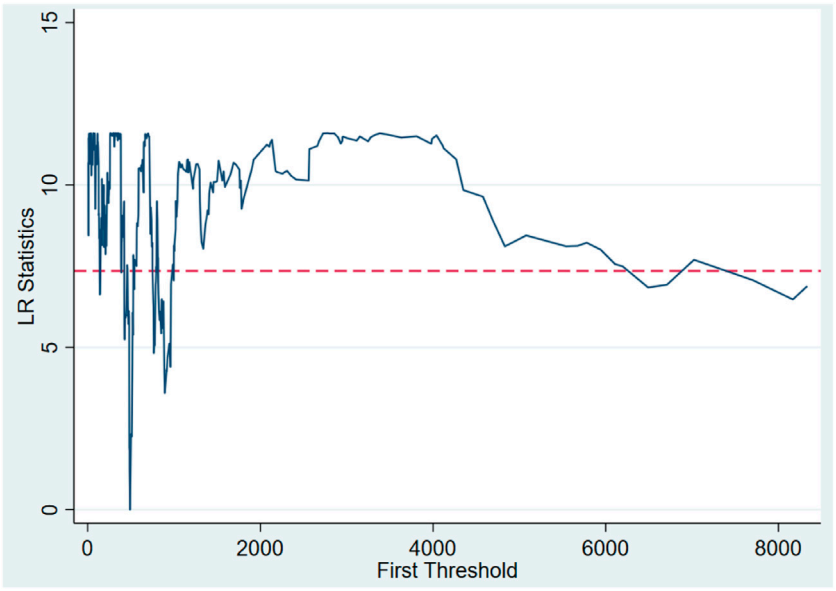

FIGURE 4
Panel threshold estimation results in Model (4).

TABLE 9 Panel threshold parameter estimation results in Model (4).

lnia	Coef.	Std.Err.	t	$p > t$	[95% Conf.	Interval]
ts	1.106	0.063	17.610	0.000	0.983	1.229
lev	0.040	0.262	0.150	0.880	−0.475	0.555
roa	−0.153	0.240	−0.640	0.524	−0.623	0.318
roe	0.182	0.050	3.680	0.000	0.085	0.279
tq	0.698	0.167	4.170	0.000	0.370	1.027
fa	−0.145	0.084	−1.720	0.086	−0.311	0.020
gdp	1.106	0.063	17.610	0.000	0.983	1.229
LERit≤γ	−0.001	0.000	−3.280	0.001	−0.001	−0.000
LERit≤γ	−0.000	0.000	−1.270	0.205	−0.000	0.000
cons	−7.100	1.288	−5.510	0.000	−9.628	−4.572
sigma_u	1.510					
sigma_e	0.507					
rho	0.899					

in the energy industry, and under the strict LER, enterprises would ensure their market position by improving innovation efficiency. With the continuous strengthening of legal environmental regulation, the proportion of environmental payment costs in the total cost of energy enterprises is gradually increasing. Some high energy consumption and high pollution energy enterprises may be eliminated, prompting energy enterprises to strengthen technological innovation and management system innovation, increase the output level of green technology innovation, and further improve the economic benefits and core competitiveness of enterprises. For example, implementing a pollution discharge permit management system in accordance with the law, strengthening supervision and inspection of enterprise pollution discharge behavior, these legal environmental regulations would have a significant positive policy effect on green technology innovation of energy enterprises, in line with the policy background of green production and service for enterprises in modern environmental governance system.

5.3.2 Threshold effect of intangible assets in green innovation

Moreover, another measure index of green technological innovation of energy enterprises is analyzed, which is intangible assets. The threshold value obtained by Table 8 is 491.291, and it can be seen from Figure 4 that the true threshold value corresponding to the lowest point of the LR statistic is significantly greater than the threshold value 491.291, thus the threshold value is effective in this paper.

Table 9 shows the regression results of the panel threshold. Firstly, when $LER \leq$ 491.291, the impact of LER on green technological innovation of energy enterprises is negative and significant at the 1% level. When $LER >$ 491.291, the regression coefficient is not significant. The reason for this result maybe is that non-R&D investment not only includes expenditures related to green technological innovation of enterprises, but also includes investment in enterprise costs in production and operation activities. With the increase of LER, the operating costs of enterprises rise, extruding funds for green technological innovation, thus having a negative impact on the results. Moreover, the reason why the regression results are not significant is that some energy enterprises maybe pay more attention to green technological innovation, and the investment

in fund and manpower is stable. Therefore, when the LER intensity reaches a certain level, the regression results are not significant. According to institutional theory, policy regulation is one of the main factors affecting corporate decision-making, behavior, and performance. Current policymakers should flexibly adjust the strength of environmental regulations, promote enterprises to coordinate different environmental strategies, help enterprises reduce operating costs, and improve the level of green technological innovation.

Therefore, when LER is loose, there is a certain negative impact on the green output stage of green technological innovation of energy enterprises and the non-R&D investment stage, but it would not continue, and would be improved with the increase of the strictness of LER. At present, China is in a critical stage of economic transformation from high-speed development to high-quality development. High quality development is a sustainable development with low input of production factors, high resource allocation efficiency, low resource and environmental costs, and good economic and social benefits. It takes improving the quality of economic development as the basic policy foothold, and pays attention to relevant policies such as talent, technological innovation, and ecological protection. Therefore, LER can be used as a forced mechanism to stimulate the green technological innovation enthusiasm of energy enterprises, and a catalyst to regulate the contradiction between economic development and environmental protection, following the goal of green and low-carbon transformation of the current economic development mode.

5.4 Summary of conclusion

In sum up, on the one hand, this paper focuses on the mechanism of legal environment regulation on green technological innovation of energy enterprises, which is different from most scholars who focus on the impact of environmental regulation on green innovation of heavily polluting enterprises (Cai et al., 2020; Zhong and Peng, 2022). On the other hand, the conclusion of this paper is that environmental regulation will have a positive impact in promoting green technological innovation of enterprises, which is contrary to the conclusion of Gollop and Roberts (1982) that environmental regulation has a negative impact on green innovation of enterprises. The reason for this difference maybe that environmental regulation is a multi-dimensional social regulation, not only including administrative punishment, but also related to laws and environmental protection measures (Li et al., 2021). Therefore, the indicator measurement methods are not uniform, leading to differences in research results. In addition, the conclusion of the threshold effect of legal environment regulation on the green output of green technological innovation of energy enterprises has been drawn in this paper, which is consistent with the conclusion that there is a nonlinear relationship between legal environmental regulation and green technological innovation proposed by Li and Ramanathan (2018).

5.5 Discussion

Based on the panel data of China's listed energy enterprises from 2010 to 2020, the impact of the legal environment regulation on the green technological innovation of energy enterprise is studied by the SYS-GMM model in this paper, including green output and non-R&D input of energy enterprises. Besides, the threshold regression model is used to explore the response of green technological innovation of energy enterprises to different levels of legal environment regulation, and the timing change of legal environment regulation threshold in the industry is clarified. The conclusion is that environmental regulation will have a positive impact in promoting green technological innovation of enterprises, and the threshold effect of legal environment regulation on the green output of green technological innovation of energy enterprises have been drawn in this paper.

Therefore, this study demonstrates that the relevant policies of the current environmental governance system have effective practical significance. Overly loose legal environmental regulation cannot achieve the goal of green production, and often have a restraining effect on green innovation of enterprises and economic development. Only moderate legal environmental regulation can have a "coercive effect". For example, improving the pricing and charging mechanism, strictly implementing the policy guidance of "whoever pollutes pays," and establishing and improving mechanisms such as "polluter pays and third-party governance". According to the principle of compensating for treatment costs and making reasonable profits, improve and implement the sewage and waste treatment fee policy. Strengthening legal environmental regulation for energy enterprises in a reasonable manner is in line with the current goal of low-carbon transformation of China's energy structure and innovation upgrading of the energy industry.

6 Conclusion and policy implications

6.1 Conclusion

This paper used panel data and panel threshold model to analyze the relationship between legal environmental regulation and green technology innovation of Chinese energy enterprises. The system GMM method is used to analyze the direct effect of legal environmental regulation on green technology innovation of Chinese energy enterprises, and the threshold effect between different intensity legal environmental regulation and green technology innovation of energy enterprises were empirically investigated. This paper draws the following conclusions: First, legal environmental regulation has a significant positive impact on the green output and non-R&D investment of green technology innovation of energy enterprises, which indicates that legal environmental regulation promotes the green technology innovation of energy enterprises to a certain extent. Second, the positive impact of legal environmental regulation on the level of green output is more prominent than that on non-R&D investment, indicating that legal environmental regulation would significantly promote the increase of green output of energy enterprises. More enterprises only pay attention to the quantity of green technology innovation and ignore its quality. In the future, energy enterprises should coordinate the coordinated development of innovation quantity and innovation quality, and promote the green transformation and upgrading of energy industry structure.

Third, legal environmental regulation has a threshold effect on green technological innovation of energy enterprises. The empirical results show that stricter legal environmental regulation will be more conducive to enterprises to improve green output efficiency, which shows that the stronger the intensity of environmental regulation, the more it can stimulate the innovation vitality of energy enterprises. Finally, there is a huge gap in the number of green patent applications among different energy enterprises, indicating that there is a huge difference in the internal innovation ability of energy enterprises.

6.2 Policy implications

Based on the above conclusions, the relevant policy recommendations on legal environment and green technology innovation are as follows: Firstly, in the future, the government maybe should pay attention to the potential of legal environment to drive green technology innovation of energy enterprises, give full play to the positive regulatory role of legal environment in green technology innovation of energy enterprises, and make legal environment become a catalyst for regulating the contradiction between economic development and environmental protection. Secondly, the country maybe should further strengthen the scientific design of legal environmental regulation tools, strengthen the monitoring of energy consumption and major pollutant emission reduction of energy enterprises by playing a 'baton' role to transmit environmental regulation signals and guide energy enterprises to carry out green innovation. Thirdly, when formulating legal environmental regulations, the government maybe should formulate appropriate regulatory intensity according to local conditions and optimize environmental regulatory governance, which would help improve the green technology innovation ability of Chinese energy enterprises. Moreover, the formulation of legal environmental regulation policies should consider the heterogeneity of industry types. Legal environmental regulation has different impacts on green technology innovation in different industries. The "one-size-fits-all" environmental regulation policy cannot reasonably reflect the environmental governance needs of different industries. Legal environmental regulations should be suitable for industry development, and benign competition of enterprises maybe should be formulated according to the particularity of the energy industry, so as to give full play to the reverse effect of environmental regulation on green innovation. Finally, the government also needs to increase the publicity of environmental protection, enhance the R&D support for green technology innovation, improve the compensation mechanism for green innovation of energy enterprises, and form a benign interaction between legal environmental regulation and green technology innovation. Because many enterprises lack the awareness of environmental protection, the level of green technology innovation in the whole energy industry is very different, which requires the government to strengthen publicity and education and improve the environmental awareness of enterprises. Enterprises could be required to disclose information on environmental protection, use the power of mass supervision and media public opinion, praise enterprises that vigorously carry out environmental protection work, and also severely punish enterprises that cause huge pollution to the environment.

6.3 Research limitations and prospects

The research limitations and prospects of this paper are as follows: First, due to the availability of data, this paper has only focused on energy enterprises in China, which maybe have a certain impact on the comprehensiveness and authenticity of empirical results. Future research could be extended to industries and enterprises worldwide or specifically to renewable energy enterprises for heterogeneity analysis. Second, the green technology innovation of enterprises has many influencing factors such as the innovation environment. This paper has only considered the input and output aspects of innovation, which may have a certain impact on the comprehensive evaluation value of green technology innovation of enterprises. Future research could explore this topic by building a more comprehensive indicator system, such as taking the innovation environment of enterprises into account. Third, this paper has only studied the impact of legal environmental regulation on green technology innovation in energy enterprises. In the future, other impacts of legal environmental regulation on enterprises could be studied, such as green economic growth and environmental management performance of enterprises. To put forward targeted and comprehensive policy implications for green technological innovation and sustainable development of energy enterprises.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://www.gtarsc.com/.

Author contributions

DX: conceptualization; project administration; resources; methodology. YC: investigation; data curation; resources. JW: formal analysis; project administration; review and editing. XH: investigation; data curation; software. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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