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Does environmental regulation develop a greener energy efficiency for environmental sustainability in the post-COVID-19 era: Role of technological innovation

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Improving green energy efficiency (GEE) and promoting green economic transformation are important goals for China to achieve sustainable economic development in the post-COVID-19 era. Based on panel data of 27 manufacturing industries in China, this paper uses GMM model and threshold model to study the impact of environmental regulation and technological innovation on green energy efficiency. Our findings show that technological innovation promotes green energy efficiency in both pollution-intensive and clean industries, and its promotion effect is more pronounced in pollution-intensive industries. Environmental regulation not only directly improves the green energy efficiency of polluting industries and clean industries, but also plays a positive intermediary role between technology and green energy efficiency. The impact of technological innovation on GEE has a threshold effect of environmental regulation. When environmental regulation did not cross the threshold, technological innovation does not significantly promote GEE. The promotion effect of technological innovation on GEE will increase with the strengthening of environmental supervision. Therefore, the government should formulate reasonable environmental regulations according to the industry heterogeneity to vigorously promote the green energy efficiency of the manufacturing industry.

KEYWORDS

environmental regulation, technological innovation, green energy efficiency, China, environmental sustainability

1 Introduction

Since the 21st century, environmental problems such as environmental pollution, energy shortage and greenhouse effect have not only hindered the sustainable development of the world economy, but also run counter to the public's demands for healthy living conditions (Ahmad et al., 2021a; Akram et al., 2021; Rehman et al., 2021).

The excessive exploitation and wanton destruction of natural resources by human beings have exceeded the carrying capacity of the earth, making the economy and society face severe resource and environmental bottleneck constraints (Rees, 2017; Irfan et al., 2021; Khan et al., 2021). To solve the irreversible negative externalities caused by human economic activities to the environment, the 178 parties in world signed the "Paris Agreement" that pledged to limit the rise in average global temperatures to less than 2°C (Ari and Sari, 2017; Vandyck et al., 2018). However, the 26th United Nations Climate Change Conference (COP26) stated that even if current carbon reduction commitments are fully realized, global temperatures could rise by 2.2°C by the end of the century. How to transform from the traditional development model to green development and achieve a win-win situation between economic development and environmental protection has become an important problem that countries around the world need to solve urgently (Ahmad et al., 2021b; Isik et al., 2021). How to transform from the traditional development model to green development and achieve carbon peaking and carbon neutrality goals has become an important action that countries around the world urgently need to solve in the post-COVID-19 era (Zhou et al., 2022).

Manufacturing is the foundation of economic development and the backbone of industrialization (Fu et al., 2021). However, the economic growth mode that relies on energy input has brought a serious "ecological deficit" to China, which has caused China to face great constraints on resources and the environment (Wang A. et al., 2021; Yang et al., 2021b). The development of manufacturing is the main source of environmental pollution and resource consumption. Authoritative data show the ratio of manufacturing energy consumption to China's total energy consumption is 70%, while the industrial added value accounted for only 31.9%% of the national GDP. Therefore, the manufacturing industry needs to transform from extensive development to green and intensive development with low energy consumption and high green energy efficiency (Liu et al., 2018).

Technological innovation reduces environmental pollution, and realizes the recycling of raw materials and wastes (Chen and Lei, 2018; Ren et al., 2021; Ulucak, 2021). In particular, green technology is expected to be a dominant factor that can theoretically contribute to over 60% of targeted carbon emission reduction (IEA, 2013). Green technology innovation not only improves enterprises' productivity and competitiveness, but also benefits environmental protection (Wang M. et al., 2021); Cao et al., 2021). Existing studies have shown that environmental regulation is an important driving force for technological innovation (Cai et al., 2020; Shao et al., 2020; Mbanyele and Wang, 2022). Moreover, environmental regulation is an effective way to improve energy efficiency and actively develop renewable energy. To achieve pollution control and ecological protection, China has promulgated many environmental protection laws since 1979, including the "Energy Conservation Law", "Air Pollution Prevention and Control Law" and "Environmental Protection Law". It can directly affect the configuration of factors in the production process, and affect energy efficiency by affecting the production cost of enterprises (Georg et al., 1992). However, there are different research views on whether environmental regulation can effectively improve green energy efficiency. On the one hand, environmental regulation can force enterprises to upgrade sewage equipment and improve energy efficiency by raising the entry threshold for polluting industries and levying high pollution taxes (Li et al., 2020). Moreover, environmental regulation accelerates factor flow of resources from low-productivity firms to high-productivity firms, which is conducive to promote industrial transformation and the efficiency of economic growth (Ouyang et al., 2020). On the other hand, some scholars oppose the government's environmental policy, and suggest that strict environmental regulation can promote technological research and development, but the cost of regulation far exceeds the effect of innovation (Lanoie et al., 2011). Controlling pollution emissions may crowd out corporate technology research and development funds, which means that the positive relationship between environmental regulation and technology research and development does not hold (Chintrakarn, 2008). Because these two effects work in opposite directions, which effect is dominant will determine the final impact of environmental regulation on GEE (Wang A. et al., 2021). However, due to the difficulty in designing statistical indicators, few studies have examined the correlation between technological innovation and GEE from the perspective of environmental regulation.

To identify heterogeneous effects of environmental regulation on energy efficiency. Our research divides manufacturing into pollution-intensive and clean industries, and studys the impact of environmental regulation on green energy efficiency different industries. Furthermore, we discuss the role of technological innovation between environmental regulation and GEE, and calculate the optimal range of environmental regulation intensity for mobilizing the enthusiasm of enterprises to innovate. Compared with existing research, the main contributions of our study are as follows. First, the relationship between technological innovation and GEE is rarely covered by previous literature. Therefore, we incorporate the three into the same model to discuss the impact of corporate n technological innovation on GEE heterogeneity from the perspective of environmental regulation. Second, from the research methods, the systematic GMM method is applied to perform benchmark model regression in order to effectively overcome the endogeneity problem caused by the existence of bidirectional causal relationships between variables. Besides, with environmental regulation as the threshold variable, we construct a threshold model to investigate the threshold effect and influence mechanism of environmental constraints in the impact of technological innovation on GEE. Third, although the assumption of homogeneous industries has been frequently emphasized in previous studies, there are significant differences in resource consumption and pollution emissions among different industries. It means that the implementation of unified regulatory policies may adversely affect the development of the industry. Therefore, in our study, manufacturing is divided into pollution-intensive industries and cleaning industries. Our research findings can provide important references for governments to formulate differentiated regulatory policies.

The rest of the article is organized as follows: Section 2 reviews the relevant literature. Section 3 is the model and data. Section 4 is mainly about empirical results and discussion. The conclusion is in the final section.

2 Literature review

2.1 Environmental regulation and technological innovation

Environmental regulation refers to the environmental management and control measures introduced by the government to reduce pollution emissions (Tietenberg, 1990). Generally, its main regulatory tools roughly include executive order regulation, market regulation and voluntary regulation (Wu et al., 2020). Command-type market regulation mainly uses direct administrative means to prevent and control corporate emissions, including pollutant discharge standards and restrictions on pollutant discharge concentrations (Zhang and Ke, 2015). Market-based regulation mainly motivates enterprises to increase pollution discharge equipment and green technology research and development through collection of pollution discharge fees, subsidies for environmental protection technology innovation, and issuance of pollution discharge licenses (Fowlie et al., 2016). The measurement methods of environmental regulation can be roughly divided into four types: 1) cost indicators. It includes environmental taxes and sewage charges (Kim, 2010). 2) Input indicators: fiscal expenditure on environmental protection, investment in pollution control (Naso et al., 2017). 3) Performance indicators. It indirectly reflects the results of environmental regulation through the effectiveness of environmental governance, including carbon emissions per unit of industrial output, pollution emissions, and the number of pollution inspections published by the media (Alpay et al., 2010). 4) Comprehensive indicators. It usually covers multiple environmental indicators and is widely used by scholars (Walter and Ugelow, 1979). In the face of unprecedented difficulties in global environmental governance, many scholars have done some research on the relationship between environmental regulation and technological innovation, but the conclusions are inconsistent and divergent. First, traditional economic theories suggest that the contradiction between ecological protection and economic growth is insurmountable. Therefore, the strict environmental laws introduced by the government improve the quality of the ecological environment, but bring adverse effects on enterprises (Millimet and Roy, 2016). Environmental regulation increases the cost of pollution control compliance for enterprises. Enterprises usually reduce the investment in research and development to purchase green sewage equipment. The "crowding-out effect" caused by environmental regulation not only reduces the productivity of enterprises but also reduces the technological innovation of enterprises. In addition, many scholars have pointed out that environmental regulation may adversely affect the development of enterprises in the short term, but in the long run, environmental regulation will bring "innovation compensation effect" to enterprises (Li et al., 2021). Appropriate environmental regulation can motivate enterprises to optimize resource allocation and stimulate the innovation compensation effect of enterprises (Shapiro and Walker, 2018). In addition, some scholars have conducted a comprehensive study of the above two viewpoints, arguing that the impact of environmental regulation on technological innovation is uncertain. It depends on the strength of the two effects of "compliance cost" and "innovation compensation" (Shen et al., 2019).

2.2 Technological innovation and energy efficiency

With the increasingly serious problem of energy shortage, the government and scholars pay more and more attention to the research of energy efficiency, and derived various energy efficiency measurement methods. Single factor energy efficiency is generally measured by energy intensity (Cheng et al., 2020; Wang and Ma, 2022). It is usually measured by energy consumption per unit of output (Zhang et al., 2011). Based on the theory of total factor productivity, green total factor energy efficiency considers the substitution effect between energy and production factors, which is more in line with the actual production process (Lee and Lee, 2022). Green energy efficiency can be measured by parametric method (Stochastic Frontier Method (SFA)) and nonparametric method (Data Envelope Method (DEA)) (Yao et al., 2021). Compared with SAF, DEA method is widely used because it does not require more subjective assumptions (Liu and Xin, 2019). Moreover, it can measure the factor utilization efficiency of multiple inputs and multiple outputs (Xie et al., 2021). With the global extreme climate change and ecological destruction, scholars have begun to consider environmental effects in calculating energy efficiency, that is, green energy efficiency (Ren et al., 2022). Technological innovation is the main source of technological progress, and it affects energy efficiency by promoting technological progress. Whether technological innovation can significantly promote the improvement of energy efficiency depends on the bias of technological progress. In the research of technological innovation, Solow (1957) constructed an exogenous economic growth model with technological progress as an exogenous variable. It is found that technological progress can promote the increase of per capita output. Once the economy reaches a steady state, the rate of technological progress is the only factor that determines the growth of per capita output. Arrow (1971) studied the technology spillover effect from the perspective of externality, and believed that due to the existence of learning effect, low-tech enterprises can obtain the technology spillover of those R&D enterprises with advanced technology through imitation and learning. Romer (1986) suggests that technology is not an exogenous variable, but an endogenous one. In the long-term growth model, technology is considered as the same input factor as labor and capital, and the marginal productivity of technology is increasing. Therefore, technological progress can promote the increase of productivity. Whether technological innovation can significantly promote the improvement of energy efficiency depends on the technological progress bias (Chen and Liu, 2021). Therefore, if technological innovation promotes energy-biased technological progress, it can effectively reduce energy consumption and significantly improve energy efficiency when output and non-energy factors remain unchanged (Liao and Ren, 2020). However, if technological innovation promotes energy-consuming technological progress, it will reduce the relative marginal productivity of the energy factor. Further, it may cause the substitution of energy factors for non-energy factors and increase the input share of energy factors, which may lead to a decrease in energy efficiency.

3 Methodology and data

3.1 Econometric models

3.1.1 Basic model

To investigate the effect of environmental regulation (ER) on GEE, the base panel econometric model is conducted as follows:

$$GEE_{it} = \alpha_0 + \alpha_1 ER_{it} + \alpha_k X_{it} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{1}$$

GEE_{it} is the green energy efficiency of manufacturing; ER_{it} is the environmental regulation. X represents a series of control variables, including capital structure, sales value, energy consumption structure, import size, export competitiveness. α_0 is the constant term. α_1 is the main parameter to be estimated. μ_i and υ_t are the industry and year fixed effects. ε_{it} is the random disturbance term. For the heteroscedasticity and collinearity of the control model, all metrics are logarithmic.

As economic theory and reality show, green energy efficiency is cumulative and dynamic. That is, current green energy efficiency may be affected by previous efficiency changes. Therefore, we include a lagged one-period term of green energy efficiency (GEE_{it-1}) in the model to eliminate the path dependence of the variables. The dynamic panel model is set as follows.

$$GEE_{it} = \alpha_0 + \alpha_1 GEE_{it-1} + \alpha_2 ER_{it} + \alpha_3 X_{it} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{2}$$

3.1.2 Mediation effect model

The mediating effect model can study the process and mechanism of the influence of independent variables on dependent variables. Compared with studies that only examine the influence of independent variables on dependent variables, the study of mediation variables can not only explain the mechanism behind the relationship, but also integrate existing theories, which has significant theoretical and practical significance. To verify the transmission mechanisms of ER impacts on energy efficiency, the mediation effect model is constructed according to the stepwise regression method proposed by Baron and Kenny (1986).

$$TI_{it} = \beta_0 + \beta_1 ER_{i,t-1} + \beta_k X_{it} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{3}$$

$$GEE_{it} = \gamma_0 + \gamma_1 GEE_{i,t-1} + \gamma_2 TI_{it} + \gamma_3 ER_{it} + \gamma_k X_{it} + \mu_i + \upsilon_t + \varepsilon_{it} \tag{4}$$

The Eq. 3 estimates the impact of ER on the mediation variable (*technological innovation*). Eq. 4 is used to further examine the impact of technological innovation and ER on the green energy efficiency. The meanings of the relevant variables and parameters are consistent with Eqs 1, 2.

3.1.3 Threshold panel model

The effect of technological innovation on energy efficiency may be affected by the intensity of environmental regulation. That is, differences in the intensity of ER may lead to a threshold effect on the impact of technological innovation on GEE. To further test the non-linear relationship between ER, technological innovation and GEE, the dynamic threshold model is used to study the threshold mechanism.

$$GEE_{it} = \beta_0 + \beta_1 TI_{it} \bullet I(q_{it} \le \gamma) + \beta_2 TI_{it} \bullet I(q_{it} > \gamma) + \beta_3 X_{it} + \lambda_i + \varepsilon_{it} \tag{5}$$

Among them, q_{it} is the threshold variable (environmental regulation). γ is the threshold value.

3.2 Variables selected

1) Environmental Regulation. Existing studies often measure environmental regulation by the ratio of the sum of waste gas and wastewater treatment costs to the main business income. However, it cannot truly reflect the pollution burden at

current pollution levels. Therefore, referring to the method of Wang A. et al. (2021), the indicators constructed in this article are as follows:

$$pcc = \sum_{i=1}^{2} \frac{\cos_i}{emi_i} \frac{fac_i}{fac_1 + fac_2}$$

Among them, cos_1 and cos_2 represent the industry wastewater treatment costs and waste gas treatment costs, and respectively. emi_1 and emi_2 represent waste water discharge and exhaust gas discharge. fac_1 and fac_2 are wastewater treatment facilities and waste gas treatment facilities.

2) Technological innovation. Previous studies have frequently used patent grants to measure technological innovation. However, patent licensing can be influenced by political factors. Also, patents are often applied to production processes before they are officially granted. Therefore, the patent applications are stable and timely than the number of patent grants, and can better reflect the real level of innovation. Referring to the research of Liu et al. (2020), we use the number of industrial invention patent applications to measure technological innovation.
3) Green energy efficiency. Accurately measuring the GEE is an important basis for the following empirical research (Yang et al., 2021a). The "data envelopment analysis" (DEA) can evaluate the efficiency of multiple decision-making units with multiple inputs and multiple outputs. However, in actual production process, inputting production factors (labor, capital, and energy) produce industrial products, as well as undesired outputs. Compared with the traditional DEA, the EBM-DDF model is a developed method with the advantages of combining radial and non-radial, which can capture green energy efficiency information more accurately. Hence, to effectively avoid the shortcomings of the CCR model and the SBM model, the directional distance function (DDF) is defined based on the EBM model proposed by Tone and Tsutsui (2010). Suppose there are n decision-making units (j = 1, ···, n) with m kinds of inputs and s kinds of outputs, the EBM model is constructed as follows:

$$\gamma^* = min\theta - \epsilon_x \sum_{i=1}^{m} \frac{W_i S_i}{X_{i0}}$$

$$s.t. \begin{cases} \theta_{X_0} - X\lambda - s = 0 \\ \lambda Y \geq 0 \\ \lambda \geq 0 \\ 0 \leq \gamma^* \leq 1 \\ s \geq 0 \end{cases}$$

In the model, γ^* is the optimal efficiency value, which satisfies $0 \leq \gamma^* \leq 1$, W_i is the weight of the input element i and satisfies $\sum_{i=1}^{m} W_i = 1$ ($W_i \geq 0$), θ is the radial efficiency value, and S_i is the slack variable of the input element i, ϵ_x is a parameter of composite radial θ and non-radial slack variables, and λ is the relative importance of the reference decision-making unit. $X = \{x_{ij}\} \in R^{m\times n}$ is the input vector, $Y = \{x_{ij}\} \in R^{s\times n}$ is the output vector, and X > 0, Y > 0. We introduce the GML index based on the EBM model to measure the GEE. The expression of GML index is:

$$GML^G(X^t, Y^t, B^t, X^{t+1}, Y^{t+1}, B^{t+1}) = \frac{1 + \vec{D}_{EBM}^G(X^t, Y^t, B^t)}{1 + \vec{D}_{EBM}^G(X^{t+1}, Y^{t+1}, B^{t+1})}$$

Where, B^t and B^{t+1} represent the undesired output of the decision-making unit in period t and t + 1, respectively. We define the global production possibility set (PPS) as: $PPS_D^G = conv\{PPS_D^1, PPS_D^2, \ldots, PPS_D^T\}$, and the directional distance function. $\vec{D}_{EBM}^G(X^t, Y^t, B^t) = max\{\beta: (Y^t + \beta Y^t, B - \beta B) \in PPS_D^G\}$

The input variables include capital stock (k), labor (L) and energy consumption (E); desirable outputs variable is industrial sales output value; undesirable output variables include chemical oxygen demand (COD), SO_2 emissions, CO_2 emissions, solid waste emissions. The variable measurement method is shown in Table 1.

4) Control variables. Some control variables were introduced into the model to reduce the error in the results. The capital structure is expressed by the ratio of foreign investment in various industries to paid-in capital (Wang et al., 2018). The energy consumption structure is expressed by the ratio of coal consumption to total energy consumption. We use manufacturing sales output value to measure the operation of enterprises. The level of imports is expressed as the ratio of the value of sub-industry imports to the value of industrial sales. The trade export is expressed by the ratio of the industry's total export value to the industry's total output value. We reclassify the manufacturing industry according to the National Economic Industry Classification (2011) promulgated by the National Bureau of Statistics. Since the statistical caliber is different from the past, in order to maintain the authenticity of the data as much as possible, we have consolidated the sub-categories of some manufacturing sectors. Specifically, we merged the rubber and plastic products industry prior to 2012 into the rubber and plastic products industry. After 2012, the automobile industry and transportation equipment such as railways and ships are merged into the transportation equipment manufacturing industry. Considering the availability of data, we excluded the metal products industry and equipment repair industry, and the comprehensive utilization of waste resources. Finally, we sorted out 27 two-digit coding manufacturing industries (GB/T4754-2011). The statistical results of all variables are shown in Table 2.

4 Results and analysis

4.1 Benchmark model

OLS, FE and RE regression equations were adopted to examine the impact of technological innovation and green

TABLE 1 China's green total factor energy efficiency.

Attribute layer	First-class index level	Method and data source
Input variable	Capital stock (K)	The perpetual inventory method
	labor (L)	The annual average number of employees in industrial firms above designated size
	Energy consumption (E)	The total energy consumption of industrial firms above designated size
Desirable outputs	Industrial sales output value	Considering the availability of data, industrial sales output value is used as a substitute variable for expected output
Undesirable output	Chemical oxygen demand (COD)	—
	SO_2 emissions (SO_2)	—
	Carbon emission (CO_2)	Carbon emissions are estimated using 8 commonly used energy consumption and their carbon emission coefficients, carbon oxidation factors and calorific value
	Solid waste emissions	—

TABLE 2 The statistical description of variables.

Variable	Definition	Obs	Mean	Std. Dev.	Min	Max
GEE	Green energy efficiency	351	0.8741	0.2577	0.4011	2.0264
ER	Environmental regulation	351	15.5953	19.5905	0.2159	113.3026
CS	Capital Structure	351	0.2863	0.1529	0.0005	0.7638
ECS	Energy consumption structure	351	0.4576	0.2215	0.0672	0.8566
TI	Technological innovation	351	212.4502	137.9494	22.7476	774.1671
IM	Trade import	351	0.1286	0.2516	0.0009	1.9850
EX	Trade export	351	0.2387	0.3193	0.0046	1.6387
SS	Sales scale	351	19263.01	18112.45	1079.377	86308.14

energy efficiency. Besides, considering the variable endogeneity, we also introduce the hysteresis of green technology innovation, and adopt the GMM method to estimate Eq. 1. The *p*-values of AR 2) and Hansen report that the second-order serial correlation of the model does not hold, and instrumental variables are appropriate. Table 3 reflects that technological innovation can increase GEE, and this result is consistent with the findings of Sun et al. (2021). The development of green energy is an inevitable choice for energy transformation. It plays an important role in reducing the pressure of energy shortage, effectively solving environmental problems and improving energy consumption structure. Particularly, promoting technological innovation in energy conservation and emission reduction is an important way to achieve clean and low-carbon development of energy (Hanley et al., 2009). In the long run, technological innovation can not only continuously improve the competitiveness and economic benefits of energy production, but also promote the transformation and upgrading of enterprises to a certain extent, which provides new momentum for the improvement of energy ecological efficiency. Technological innovation improves energy efficiency from three aspects. First, from the perspective of energy production structure, with the continuous breakthrough of energy exploration and exploitation and equipment technology, the backward production capacity of coal power will be gradually eliminated, and the production of clean energy will continue to increase. Second, technological innovation can directly improve energy efficiency. Technological innovation investment (R&D funding and scientific research personnel) accelerates technology diffusion and improves energy efficiency. Finally, technological innovation can improve the level of industrialization, adjust the industrial structure and optimize the energy structure (Wang L. et al., 2021). Specifically, in the process of energy production, enterprises improve overall energy efficiency by introducing advanced technologies and high-efficiency equipment in the energy industry to reduce energy consumption in the production process and reduce energy intensity. In addition, technological innovation improves energy efficiency by optimizing the industrial structure and changing the structure of energy production and consumption. Our research also found that compared to the cleaning industry, the impact of technological innovation on energy efficiency is greater in highly polluting industries.

TABLE 3 Basic results.

Variables	RE	FE	GMM	Cleaning industry	Polluting industry
LNGI	0.0755***	0.0736***	0.0407***	0.0450***	0.1763**
	(3.40)	(3.01)	(6.70)	(6.57)	(2.36)
LNSV	−0.1406***	−0.1026***	−0.1070***	−0.1417***	−0.3689***
	(−8.69)	(−3.87)	(−15.01)	(−5.79)	(−4.17)
LNES	0.0907***	0.1283***	−0.2175***	−0.0594***	0.2301
	(3.14)	(4.14)	(−11.06)	(−2.69)	(1.43)
LNEXP	0.0426	0.1146***	−0.1290***	−0.1058***	0.1972***
	(1.64)	(3.05)	(−7.24)	(−2.97)	(3.45)
LNIMP	−0.0565***	−0.0574***	0.0246**	0.0088	0.0613
	(−3.12)	(−2.60)	(1.98)	(0.72)	(1.27)
LNSS	0.0152	0.0098	0.0151	0.0197	0.0333
	(0.61)	(0.32)	(0.95)	(0.42)	(0.40)
L.GEE			0.7430***	0.3834***	
			(32.83)	(3.34)	
_CONS	1.8358***	1.6689***	0.6240***	1.3953***	4.0073***
	(9.68)	(7.16)	(8.33)	(4.95)	(4.36)
R^2	0.4597	0.4668		0.4363	0.5908
AR(2)/p-value			1.20/[0.229]		
Hansen test/p-value			25.27/[0.613]		
F/Wald test			6343.40***		
N	351	351	351	234	117

Note: $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$; t or z statistics in (); p value in [].

4.2 Environmental regulation and GEE

Table 4 presents the estimated results of the impact of environmental regulation (ER) on energy efficiency. Columns (1) and (2) are the results of the OLS and FE econometric models, respectively. We find that the estimated coefficient of the direct impact of ER on green energy efficiency is significantly negative at the 1% level, indicating that ER can improve energy efficiency and play an innovative compensation effect. This result is consistent with Lin and Xu (2017), and Mandal (2010), but different from the research findings of Wu et al. (2020), who proposed there is a "U" relationship between environmental regulation and energy efficiency. To deal with the path dependence of energy efficiency, we employ the system generalized method of moments (SYS-GMM) to estimate a dynamic panel metering model. According to the SYS-GMM regression results in column (3), the coefficient of the lag term in the first period is significantly positive at the level of 1%, reflecting that energy efficiency is affected by the previous period. The results of Hansen's test and AR (2) test accept the null hypothesis at the 10% significance level, indicating that all instrumental variables used in this paper are valid and that the second-order serial correlation is not satisfied in the error term. The estimated coefficient of ER on energy efficiency is 0.0135, which is statistically significant at the 1% level. It is consistent with the results of static panel regression. The impact of ER on green energy efficiency is also a hot topic in academic discussions. From the perspective of the long-term dynamic process, appropriate environmental regulation can encourage enterprises to carry out technological innovation, improve the production technology and production methods of polluting enterprises, and thus improve the technical level and production efficiency. Although the cost of technological improvement and pollution control has increased in the process of environmental control, the lagging "innovation compensation effect" can offset the "compliance cost" of enterprises. Therefore, environmental regulation can achieve the purpose of improving environmental quality, increasing output and improving energy efficiency through efficiency improvement and technological progress.

4.3 Mediation effect results

The above regression results show that the positive impact of environmental regulation (ER) on energy efficiency has been demonstrated, but its indirect impact mechanism needs further examination. According to the constructed mediation effect model, we study the transmission mechanism of ER on green

TABLE 4 Basic results.

Variables	OLS	FE	GMM	Cleaning industry	Polluting industry
LNER	0.0373***	0.0394***	0.0103***	0.0013	−0.0646**
	(4.21)	(3.93)	(5.61)	(0.54)	(−2.14)
LNSV	−0.1718***	−0.1707***	−0.0759***	−0.0788***	−0.2276**
	(−16.81)	(−12.72)	(−13.60)	(−3.69)	(−2.56)
LNES	−0.1365***	-0.1421***	−0.1479***	-0.0967***	0.4714***
	(−5.62)	(−5.66)	(−7.40)	(−5.30)	(2.82)
LNEXP	−0.0742***	−0.0737***	−0.0927***	−0.03667	0.2017***
	(−5.78)	(−5.56)	(-8.76)	(−1.37)	(3.21)
LNIMP	−0.0185*	−0.0194*	0.01782*	−0.03557***	−0.00287
	(−1.75)	(−1.71)	(1.79)	(−4.95)	(−0.06)
LNSS	0.0488***	0.0478***	0.0260***	0.0423*	0.2517***
	(3.71)	(3.53)	(2.86)	(1.90)	(3.39)
_CONS	2.1447***	2.1074***	0.6308***	0.8179***	−37.3463
	(20.78)	(17.01)	(8.96)	(3.13)	(−1.53)
L.GEE			0.7704***	0.6221***	
			21.37	5.58	
R^2	0.4920	0.4983			0.8889
AR(2)/p-value			0.96/[0.336]		
Hansen test/p-value			23.48/[1.000]		
F/Wald test			1642.61***	11545.51***	
N	351	351	351	234	117

Note: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$; t or z statistics in ().

energy efficiency from the perspective of technological innovation. The results are reported in Table 6. Columns (1) and (2) in Table 5 report the estimated results of technological innovation as a mediating variable. The results in column (1) show that ER can significantly improve energy efficiency (0.010). The estimation results in column (2) show that the estimated effect of ER on technological innovation is positive and statistically significant (0.076), and column (3) reports the estimated effect of ER and technological innovation on energy efficiency. We found that technological innovation still had a positive impact on energy efficiency at the 1% level. Therefore, it can be concluded that ER can increase green energy efficiency, and its increased benefit can be attributed to the improvement of technological innovation capacity. The mediating effect of technology level is mainly manifested in three aspects. 1) Improving the intensity of environmental regulation will increase the production cost of enterprises in a short period of time. Environmental regulation forces enterprises to purchase more advanced sewage equipment and machines and introduce foreign green production processes, which is conducive to the improvement of energy efficiency. 2) The government's strict environmental regulation will accelerate the technological innovation of enterprises, improve the efficiency of resource allocation, and improve the internal structure of enterprises. It reduces the amount of pollutants and promotes the improvement of productivity and energy efficiency. 3) With the gradual advancement of technology, industrial enterprises can use energy more efficiently and reduce energy demand. Further, the decline in energy demand will also reduce energy prices, which encourages energy companies to carry out a new round of technological innovation. Therefore, the promotion effect of environmental regulation on energy efficiency is mainly realized by improving the technical level.

4.4 Threshold effect

Previous studies have shown China has a huge regional and regional dimension in environmental governance. Therefore, the increase effect of the environmental regulation on energy efficiency may show a nonlinear relationship. To verify the potential nonlinear effects between technological innovation and energy efficiency, this paper extends the procedure of Hansen (1999) and uses Wald's test for self-sampling (Bootstrap) to detect threshold effects. According to the existence test of threshold effect, different levels of ER are used as threshold variables for self-sampling. After 300 self-sampling results, the impact of environmental regulation presents nonlinear threshold characteristics.

TABLE 5 Mediation effect results.

Variables	GEE	GI	GEE
L.DEP	0.770***	0.532***	0.886***
	(21.375)	(79.938)	(27.029)
GI			0.065***
			(12.382)
LNER	0.010***	0.076***	−0.008***
	(5.613)	(9.256)	(−2.700)
LNSV	−0.076***	0.008	−0.044***
	(−13.605)	(0.438)	(−5.629)
LNES	−0.148***	−0.181***	−0.068***
	(−7.402)	(−7.021)	(−6.419)
LNEXP	−0.093***	−0.183***	−0.066***
	(−8.763)	(−3.776)	(−4.931)
LNIMP	0.018*	0.174***	−0.001
	(1.790)	(7.273)	(−0.143)
LNSS	0.026***	−0.021	0.024**
	(2.856)	(−0.662)	(2.299)
_CONS	0.631***	2.061***	−0.005
	(8.962)	(10.979)	(−0.049)
AR(2)/p-value	0.96/[0.336]	−1.91/[0.056]	1.24/[0.216]
Hansen test/p-value	23.48/[1.000]	26.90/[0.415]	25.14/[0.865]
F/Wald test	1642.61***	60227.47***	67566.13***
N	351	351	351

Note: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$; t or z statistics in ().

Further, we employ a robust standard deviation test to estimate a panel threshold model to overcome the undesired effect of heteroskedasticity. The corresponding estimation results are shown in Table 6. Based on the estimation results of model (1), it is found that the coefficients of each interval of technological innovation variables under the threshold model are significantly negative, indicating that there is a significant dynamic nonlinear relationship between technological innovation and green energy efficiency. From the threshold test results, when the ER value is lower than 3.465, the estimated coefficient of green finance is 0.1324, but not significant, indicating that it is necessary to show that the government appropriately strengthens environmental regulation. If the regulatory intensity is relatively relaxed, it will not be enough to form effective incentives for green innovation, and even increase investment in pollution control, thereby crowding out R&D investment. When the value of the ER index exceeds 3.465, the coefficient of technological innovation increases to 0.1550 and is significant, indicating that the efficiency improvement effect of technological innovation still exists, and the promotion intensity has increased. It is not difficult to find that as the intensity of environmental regulation increases, the efficiency improvement effect of technological innovation shows a significant positive nonlinear characteristic.

TABLE 6 Threshold regression results.

Variables	Coef.	Std. Err.	t	P>|t|	95% Conf. Interval
LNSV	0.2593	0.0395	6.57	0.000	[0.1816, 0.3370]
LNES	−0.1831	0.0455	−4.02	0.207	[−0.2726, −0.0935]
LNEXP	−0.0365	0.0551	−0.66	0.508	[−0.1450, 0.0719]
LNIMP	0.0744	0.0323	2.30	0.022	[0.0108, 0.1380]
LNSS	−0.0524	0.0449	−1.17	0.244	[−0.1408, 0.0359]
_CONS	−0.6002	0.3419	−1.76	0.080	[−1.2729, 0.0725]
GI_1	0.0765	0.0544	1.41	0.159	[−0.0230, 0.1831]
GI_2	0.1550	0.0358	4.33	0.000	[0.0846, 0.2254]
R^2	0.6043	Sigma_u	0.2250		
F value	69.17***	Sigma_e	0.1602		

5 Conclusion and recommendations

Based on panel data of 27 manufacturing industries in China, this paper uses GMM model and threshold model to study the impact of environmental regulation and technological innovation on green energy efficiency. Our findings show that technological innovation promotes green energy efficiency in both pollution-intensive and clean industries, and its promotion effect is more pronounced in pollution-intensive industries. Environmental regulation not only directly improves the green energy efficiency of polluting industries and clean industries, but also plays a positive intermediary role between technology and green energy efficiency. The impact of technological innovation on GEE has a threshold effect of environmental regulation. The promotion effect of technological innovation on GEE will increase with the strengthening of environmental supervision. Therefore, the government should formulate reasonable environmental regulations according to the industry heterogeneity to vigorously promote the green energy efficiency of the manufacturing industry.

For different industries, the government needs to formulate differentiated environmental regulation policies. For pollution-intensive industries, the government needs to relax environmental regulations and policies to avoid occupying the production, operation and R&D funds of enterprises. When formulating high-intensity environmental regulations, the government should give companies a certain amount of pollution control compensation, and guide pollution-intensive industries to increase investment in pollution control research and development by means of financial subsidies and low-interest loans. It is necessary to promote the transformation of enterprises from traditional industries to green industries. The government should supervise the environmental technology and pollution prevention and control enterprises that do not meet the standards. The government should shut down those small enterprises with low technical capabilities and serious pollution, which promotes the concentration of factor resources in enterprises with high technical level and good environmental benefits. For polluting industries, the government should appropriately strengthen environmental regulations and force enterprises to find the best technical path for energy conservation and emission reduction. It is conducive to giving full play to the driving role of environmental regulation in the substantive innovation of enterprises and promoting the green development of the manufacturing industry.

Technological innovation is an effective means to improve energy efficiency. Considering the existence of "cost effect" and "innovation compensation effect", the promotion effect of technological innovation on improving energy efficiency may not be obvious in the short term. However, as the "innovation compensation effect" of later-stage enterprises compensates for the cost effect exceeding environmental regulation, technological innovation will promote the improvement of energy efficiency. Therefore, the government should continue to encourage enterprises to strengthen technological innovation and fundamentally improve energy efficiency. In addition, the government should rely on technological progress to solve resource and environmental problems. It is necessary for the government to comprehensively use fiscal, tax, credit, subsidies, and environmental policies to increase support for green production and scientific research and encourage innovation. It can improve the energy efficiency and clean production capacity of enterprises, and guide the technological progress to change in the direction of energy saving and environmental improvement.

To guide enterprises to increase the research and development of invention patents, the government should cultivate the environmental protection awareness of enterprise executives. On the one hand, the government should use industry associations and executive training courses to publicize environmental protection policies and laws and regulations to enterprises, thus improving the environmental protection awareness of enterprise management and enhancing environmental protection responsibility. On the other hand, the government can increase the publicity of green consumption and guide the masses to adjust their consumption structure and choose low-carbon products. It is necessary to increase the environmental protection knowledge training for other staff of the enterprise to enhance the implementation effect of environmental regulations. Enterprises should strictly abide by environmental laws and regulations, actively abide by environmental regulations and policies, attach importance to green technology innovation, and achieve cleaner production.

This paper makes an exploration of the influence of environmental regulation and technological innovation on GTFEE, but there are still limitations that can be further expanded in the future. First, due to the availability of data, we use indirect methods to measure the intensity of environmental regulation. We also did not analyze the heterogeneous impact of technological innovation on the energy efficiency relationship under different types of environmental regulatory policies (eg, market-based policies and command-and-control policies). Future research can further subdivide environmental regulation according to policy characteristics, and study the heterogeneous impact of different environmental regulation types on energy efficiency. Second, technological innovation and technological introduction are the two main paths of technological progress. This paper only examines how environmental regulation affects the relationship between technological innovation and energy efficiency, without examining whether environmental regulation can affect energy efficiency by changing technology introduction. Therefore, future research can expand the analysis from the perspective of technology introduction.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

MZ: Conceptualization, Project administration, Formal analysis, Writing—original draft, Funding acquisition, Supervision. MD: Writing—review editing, Methodology, Data curation, Validation.

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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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