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Exploring the Nexus Between Technological Innovation, Environmental Regulation, Human Capital, and Low-Carbon Economy

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Abstract: This paper examines the panel data from 43 countries along the "Belt and Road" Initiative from 2000 to 2022 against the backdrop of global green low-carbon economic development. First, it explores the mechanism of action between technological innovation (TN) and the low-carbon economy (LE) using a panel fixed-effects model. Second, by introducing environmental regulation (ER) and human capital (EDU) as moderating variables, it constructs a panel threshold model to investigate the nonlinear moderating effects in the relationship between TN and low-carbon economic development. Finally, the paper further categorizes these countries into samples to analyze the potential heterogeneity of the aforementioned effects. The empirical results indicate that (1) TN has a negative effect on the LE of countries along the "Belt and Road"; (2) ER plays a positive moderating role in the influence of TN on the LE of these countries, while EDU exhibits a negative moderating role. Further research reveals a significant double-threshold effect of EDU in the relationship between TN and the LE, indicating that the negative effects of TN on the LE diminish as EDU increases. (3) This threshold effect displays significant heterogeneity at different levels of economic development and EDU.

Keywords: low-carbon economy, technological innovation, environmental regulation, human capital, threshold effect

1. Introduction

Since the 1990s, the conflict between global economic development and environmental issues has intensified, with anthropogenic climate change having a disastrous negative impact on public welfare and health. The International Energy Agency "2022 CO_2 Emissions Report" indicates that the energy crisis caused by the Russia-Ukraine conflict has continued to spur coal consumption in Asia, resulting in a 1.6% increase in coal emissions —far exceeding the average growth rate over the past decade. Therefore, reducing carbon dioxide emissions and continuously promoting low-carbon development have become shared goals and guiding principles pursued by countries around the world [1].

Technological innovation (TN) is one of the most powerful tools for reducing carbon emissions and promoting economic growth [2], and it is widely applied in energy conservation and emission reduction efforts. TN, characterized by increasing returns to scale, can enhance productivity and achieve higher economic growth [3]. Additionally, innovation helps reduce environmental pollution, further promoting the sustainability of both the economy and the environment [4]. Some scholars argue that TN fosters economic development and helps reduce environmental pollution [5], while others contend that TN often relies on the extensive use of energy, potentially posing environmental challenges in the form of carbon emissions [6]. Therefore, the role of TN in the low-carbon economy (LE) may be influenced by multiple factors, leading to uncertainties that warrant further investigation for clearer understanding.

With the deepening research into low-carbon economic development, scholars have discovered, based on Porter's hypothesis, that environmental regulation (ER) plays an essential role in low-carbon development. On the one hand, some researchers argue that ER may increase the environmental management costs for enterprises, reduce marginal profits, and subsequently inhibit their development [7]. On the other hand, other scholars contend that appropriately designed environmental policies can help companies adopt environmentally friendly technologies, thereby reducing pollution or emissions [8, 9]. Therefore, whether the improvement of ER and the application of TN can proceed in synergy will be an issue worth thoughtful consideration.

Human capital (EDU) is often regarded as a key resource playing a crucial role in achieving the green economy transition [10]. EDU can offset the negative impacts of diminishing marginal returns to physical capital, thereby enabling sustained economic growth [11]. Moreover, improvements in EDU levels contribute to better resource utilization efficiency, guiding the economy toward a greener direction and facilitating carbon reduction [12]. In addition, countries with higher levels of EDU are more likely to adopt new technologies to reduce the consumption of fossil-based resources and are generally more concerned about environmental issues [13]. In developing

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countries, whether the improvement of EDU and the application of TN can generate dual advantages remains to be further tested.

The countries along the “Belt and Road” Initiative represent one of the most economically vibrant and promising regions in the world, yet they are also characterized by high carbon emission intensity. Effectively developing a LE in this region could significantly contribute to global emission reduction efforts [14]. At the same time, the wave of global technological revolution presents both opportunities and challenges for sustainable development in these countries [15]. Therefore, it is particularly important and urgent to coordinate actions related to green technology and resource utilization to achieve a LE along the “Belt and Road”.

In this context, this paper utilizes panel data from 43 countries along the “Belt and Road” from 2000 to 2022 to address the following questions: (1) Does TN have a positive impact on the LE of the “Belt and Road” countries? (2) How do ER and EDU play a role in this impact? (3) Do these impacts and roles exhibit heterogeneous characteristics?

Exploring these questions holds significant theoretical and practical importance for assessing the relationship between TN and the LE of the “Belt and Road” countries. On the one hand, this paper uses the threshold effect model to deeply analyze the dynamic nonlinear characteristics of TN’s impact on the LE in specific industries, thereby expanding the research perspective on TN and LE. On the other hand, while analyzing the impact of TN on the LE, the paper also takes into account the roles of ER and EDU, as well as regional development disparities, providing important reference and theoretical basis for the formulation of LE strategies.

2. Literature Review and Hypotheses

2.1. TN and LE

According to the theory of TN, it is viewed as a core strategy for resolving the contradiction between environmental protection and economic development [16]. Specifically, TN can drive the creation of low-carbon products, the introduction of low-carbon production methods, and the exploration of new markets, thereby promoting the continuous optimization of industrial structures. This leads to the elimination of outdated, energy-intensive, and polluting production capacities, while facilitating the rise of green, low-carbon industries [17]. In other words, environmentally related TNs can broadly impact every link in the industrial chain by improving production processes, reducing costs, and enhancing product quality, ultimately increasing the overall green production efficiency of enterprises and further boosting economic gains. At the same time, TN reduces reliance on polluting raw materials and semi-finished products, lowers waste emissions, prevents ecological pollution, and ultimately contributes to the green and high-quality development of the economy [18].

However, some scholars argue that whether TN can consistently reduce carbon emissions, lower environmental pollution, and realize a LE globally remains a topic of debate [19]. First, improvements in energy utilization efficiency may lead to a decrease in fossil fuel prices; if the prices of other factors do not decrease correspondingly, the cost and investment pressures from TN may compel companies to increase their demand for relatively cheap fossil fuels to reduce production costs, thereby exacerbating carbon dioxide emissions and creating an energy rebound effect [20]. If the carbon emissions from the increased energy rebound exceed the reduction from technological advancements, then TN could lead to a net increase in carbon emissions. Second, clean energy technology is still not mature in some less developed countries, and the high risks and costs associated with these technologies may hinder their promotion and commercialization, thus reducing the expected impact of TN on carbon emission reduction [21]. Finally, for countries along the Belt and Road Initiative, the main energy sources driving industrial economic development are typically abundant and easily accessible fossil fuels like coal, and these countries may have developed a path of dependence on such energy sources in their past development [22]. Therefore, if governments and enterprises do not fully integrate clean energy across various production sectors and realize integrated development in all industries, then TN may not promote low-carbon development.

Therefore, considering the total effect of TN and the overall characteristics of the research sample in this paper, we propose the following hypotheses to further verify the role of TN in the LE of countries along the Belt and Road Initiative:

H1a: TN promotes the LE of countries along the Belt and Road Initiative.
H1b: TN suppresses the LE of countries along the Belt and Road Initiative.

2.2. TN, ER, and LE

According to the Porter Hypothesis, companies must enhance their TN capabilities to comply with a series of ERs set by the government. However, this also incurs certain costs, referred to as the “compliance cost” effect, which may hinder economic development if firms prioritize profit maximization. On the other hand, the benefits generated from TN can largely offset the increased costs of ER, leading to an “innovation compensation” effect [23, 24]. In other words, appropriate ER can compel firms to continuously enhance their R&D capabilities and technological standards over the long term, improving energy utilization efficiency (such as for coal), thereby enhancing corporate competitiveness and advancing the low-carbon initiatives of regional enterprises [25].

Moreover, institutions, as a series of behavioral rules, can indeed influence innovation and thus affect economic growth [26]. However, the formulation and implementation of environmentally related policies, as well as firms’ understanding and execution of these policies, takes time to yield results. In the early stages, the intensity of ER may be relatively weak; given the initial investment and profitability, firms may tend to reduce production scales to mitigate low-cost pollution penalties [27], which hinders the green development of regional industries. Furthermore, in the initial phase, especially in regions with lower levels of economic development, a significant portion of innovative resources may be directed toward industrial sectors aimed at economic growth, thereby exacerbating carbon dioxide emissions [28]. However, as the intensity of ER continues to expand, firms must strengthen technological transformation to enhance production and energy efficiency, counteracting the costs of environmental supervision [29]. Moreover, economic actors, through enhanced production skills and awareness of low-carbon environmental protection, can optimize the efficiency of production factor allocation, promote the research and application of clean production technologies, and foster a social atmosphere conducive to energy conservation and emission reduction [30]. This ultimately allows TN, under the influence of ER, to also progress toward low-carbon outcomes.

In summary, this paper will explore the relationship between TN, ER, and the LE within the framework of the Porter

Hypothesis. First, the Porter Hypothesis argues that strict ERs not only do not hinder business development but can actually stimulate TN, driving the research and application of low-carbon technologies [31]. Second, technological progress can reduce the compliance costs associated with ERs, making it easier for companies to meet regulatory requirements and potentially opening up new market opportunities [32]. Therefore, the goals of a LE depend not only on the advancement of TN but also on effective policy guidance to promote the innovation and dissemination of green technologies.

Thus, this paper selects ER as a moderating and threshold variable to study its moderating and threshold effects in the process of TN impacting the LE of countries along the "Belt and Road". The following hypotheses are proposed:

H2a: In the process of TN impacting the LE of countries along the "Belt and Road", ER has a disruptive moderating effect.

H2b: The above moderating effect exhibits nonlinear threshold characteristics, meaning that as ER moves from a low-threshold range to a high-threshold range, the magnitude of TN's impact on the LE of countries along the "Belt and Road" also changes accordingly.

2.3. TN, EDU, and LE

EDU can directly drive economic growth and improve environmental issues [10, 12, 33]. On the one hand, according to EDU theory, EDU, as a significant resource within economic resources, brings economic benefits that far exceed those from material resources [34]. It can be cultivated through investment in education, vocational training, and skill development, facilitating the accumulation of EDU and thereby promoting sustainable economic growth [35]. On the other hand, enhancing EDU levels contributes to improving resource efficiency, steering the economy toward greener development and ultimately aiding in the reduction of carbon emissions [36].

Additionally, EDU has advantages in innovation efficiency, technological structure upgrading, and environmental optimization [10]. According to endogenous growth theory, the high-quality development of EDU not only leads to high production efficiency but can also achieve efficient energy utilization through research and development, thereby promoting low-carbon development [8]. As the structure of EDU continues to optimize, and resources are accumulated and allocated effectively, TN can achieve rapid economic growth by enhancing total factor productivity, while also playing a significant role in incentivizing the green transformation of economic development [37].

In summary, this paper will explore the relationship between TN, EDU, and the LE within the framework of endogenous growth theory. On the one hand, TN can significantly enhance the productivity and sustainability of the LE [38]. On the other hand, EDU, as a key factor in endogenous growth theory, directly affects the capacity and efficiency of TN [39]. Therefore, in the context of a LE, developing EDU with environmental awareness and innovation capabilities will be a key driving force in advancing green technologies and promoting LE development.

Thus, this paper selects EDU as a moderating and threshold variable to examine its moderating and threshold effects in the process of TN affecting the LE of countries along the "Belt and Road" initiative, proposing the following hypotheses H3a and H3b.

H3a: In the process of TN affecting the LE of countries along the "Belt and Road" initiative, EDU plays a disruptive moderating role.

H3b: The moderating role exhibits nonlinear threshold characteristics, meaning that as EDU moves from a low-threshold range to a high-threshold range, the impact of TN on the LE of countries along the "Belt and Road" initiative also changes accordingly.

3. Model and Data

3.1. Model

This study employs a fixed-effects model for the following reasons: On one hand, it is based on the panel structure of the dataset. This study uses a balanced panel dataset of 43 countries along the "Belt and Road" Initiative from 2000 to 2022, and the fixed-effects model is one of the commonly used methods in econometrics for panel data analysis [40]. On the other hand, it is based on the inherent possibility that omitted variables may be correlated with the independent variables. Ostadzad [41] suggests using fixed effects when omitted variables are likely to be correlated with the regressors, as this helps reduce estimation errors caused by omitted variable bias.

Therefore, this paper uses both multiple linear regression and threshold regression models to examine the linear and nonlinear impacts of TN on the LE. At the same time, ERs and EDU are included as moderating variables to explore their potential moderating roles in the aforementioned relationship. Additionally, considering the heterogeneous characteristics of the mechanisms due to factors such as economic development levels, this paper further conducts subsample regression analysis. First, to verify the mechanism of TN in the LE of countries along the Belt and Road Initiative (H1a, H1b), the paper constructs the following baseline regression model:

$$LE_{it} = \alpha_0 + \alpha_1 TN_{it} + \alpha_2 Control_{it} + \alpha_3 \sum \mathrm{id} + \varepsilon_{it} \tag{1}$$

In this context, LE_{it} represents the level of the LE in country i at time t, while TN_{it} indicates the level of TN in country i at time t. $Control_{it}$ is control variables, which include urbanization (URB), trade openness (TRADE), fiscal expenditure (FE), and energy consumption (EC). $\sum \mathrm{id}$ accounts for individual factors, ε_{it} denotes the error term.

Next, to analyze the moderating effects of ERs and EDU on the impact of TN on the LE (H2a, H3a), the paper constructs the following model:

$$LE_{it} = \beta_0 + \beta_1 TN_{it} + \beta_2 ER_{it} + \beta_3 TN_{it} * ER_{it} + \beta_4 Control_{it} + \beta_5 \sum id + \varepsilon_{it} \tag{2}$$

$$LE_{it} = \delta_0 + \delta_1 TN_{it} + \delta_2 EDU_{it} + \delta_3 TN_{it} * EDU_{it} + \delta_4 Control_{it} + \delta_5 \sum id + \varepsilon_{it} \tag{3}$$

In this context, ER_{it} represents the strength of ERs in country i at time t, and EDU_{it} indicates the level of EDU in country i at time t. The interaction term coefficients β_3 and δ_3 represent the direction of the moderating effects of ERs and EDU in the process through which TN impacts the LE. The signs of these coefficients indicate the direction of the moderating effects.

To further test whether there are threshold effects in the analysis above (H2b, H3b), this paper adopts the panel threshold regression model proposed by Hansen [42]. The single-threshold regression model is expressed as:

$$LE_{it} = \varphi_0 + \varphi_1 TN_{it} * I(ER_{it} \le \gamma) + \varphi_2 TN_{it} * I(ER_{it} > \gamma) + \varphi_3 Control_{it} + \varphi_4 \sum id + \varepsilon_{it} \quad (4)$$

$$LE_{it} = \omega_0 + \omega_1 TN_{it} * I(EDU_{it} \le \gamma) + \omega_2 TN_{it} * I(EDU_{it} > \gamma) + \omega_3 Control_{it} + \omega_4 \sum id + \varepsilon_{it} \quad (5)$$

In this model, ER_{it} and EDU_{it} are the threshold variables, γ is the threshold value, TN_{it} is the explanatory variable, and LE_{it} is the dependent variable. I(·) represents the indicator function, which takes the value of 1 when the condition inside the parentheses is satisfied, and 0 otherwise. The empirical analysis is conducted using STATA 17. Furthermore, based on Equations (4) and (5), the empirical test can be extended to account for dual-threshold and multi-threshold effects, which will not be elaborated on further here.

3.2. Variables

3.2.1. Dependent variable

LE. This paper follows the methodology of Du et al. [43] by using the gross domestic product (GDP) carbon emission indicator, which is the ratio of real per capita to carbon emissions.

3.2.2. Core explanatory variable

TN. In this paper, following the study by Meng et al. [44], TN is measured by the number of patent applications from residents and non-residents.

3.2.3. Moderating and threshold variables

ER. This paper refers to the work of Lin et al. [45] and uses the Environmental Performance Index, which is published jointly by Yale University and Columbia University. This measurement method increases comparability within countries for the Belt and Road Initiative.

EDU. This paper follows the study by Yameogo et al. [46] and uses the enrollment rate in higher education as the measurement.

3.2.4. Control variables

To control for the influence of other factors on the main empirical analysis, this paper selects URB, TRADE, FE, and EC as control variables.

1) URB. URB may increase the consumption of resources such as energy, water, and land, leading to a higher ecological footprint in the region. However, URB could also concentrate EDU, thereby promoting knowledge dissemination and skill development, which indirectly supports sustainable economic growth. Therefore, there is an important connection between URB and LE [47]. This paper follows the methodology of Yameogo et al. [46] and measures URB as the proportion of the urban population to the total population.
2) TRADE. TRADE is considered a key factor in attracting foreign investment and accelerating capital flows, and it may facilitate the dissemination of green technologies, promoting LE [48]. Following the approach of Doğan et al. [49], TRADE is measured by the import and export value between a country and its trading partners.
3) FE. Fiscal policy reflects the functions of government. Sufficient fiscal revenue could provide ample funding for TN, thereby promoting the development of LE [50]. This paper refers to the study by Han et al. [51] and measures FE as the ratio of local government FE to GDP, reflecting the relative scale of fiscal spending.
4) EC. On the one hand, it can promote economic development. On the other hand, the consumption of non-renewable energy accelerates environmental degradation. Therefore, EC plays a crucial role in the development of LE [52]. This paper follows Zhang et al. [53] and measures EC by total EC, which reflects the relationship between economic growth and EC intensity.

The specific definitions and measurement methods for all variables are shown in Table 1.

3.3. Data

The sample data used in this paper come from the World Bank's publicly available database, focusing on panel data from countries along the Belt and Road Initiative. The study covers a period from 2000 to 2022. After compiling data for all available variables and excluding countries with significant data gaps, linear interpolation was used to fill in missing values for countries with

Table 1
Variable measurement and data sources

Variables	Symbol	Measure	Data sources
Low-carbon economy	LE	Ratio of real GDP to carbon emissions	World Bank
Technological innovation	TN	Patent applications by residents and non-residents	World Bank
Environmental regulation	ER	Environmental Performance Index	Environmental Performance Index Database jointly published by Yale University and Columbia University
Human capital	EDU	Higher education enrollment rate	World Bank
Urbanization	URB	The proportion of urban population in the total population	World Bank
Trade openness	TRADE	Import and export volume of domestic destinations and sources	World Bank
Fiscal expenditure	FE	Ratio of local government fiscal expenditure to GDP	World Bank
Energy consumption	EC	Total energy consumption	World Bank

Table 2
Distribution of sample target countries

Region	Sample countries
Asia	Armenia, Azerbaijan, Bangladesh, Georgia, Indonesia, Kazakhstan, Kyrgyzstan, South Korea, Sri Lanka, Mongolia, Malaysia, Saudi Arabia, Thailand, Tajikistan, Turkey
America	Chile, Uruguay
Africa	Algeria, Egypt, Morocco, Mozambique, Sudan, Tunisia
Europe	Albania, Austria, Bulgaria, Belarus, Czech Republic, Estonia, Greece, Croatia, Hungary, Italy, Luxembourg, Moldova, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Slovenia, Ukraine

Table 5
Multicollinearity test

Variables	VIF	1/VIF
TN	3.04	0.328922
TRADE	2.78	0.360024
EC	2.73	0.366584
URB	2.17	0.460481
FE	1.86	0.536660
EDU	1.75	0.571094
ER	1.53	0.653368
Mean VIF	2.27	

a small amount of missing data. Ultimately, 43 countries along the Belt and Road Initiative were selected as the research subjects. The specific countries included in the study are listed in Table 2.

Table 3 presents the descriptive statistics for the variables related to the model.

Before conducting the empirical analysis, this study performed unit root tests and collinearity checks on the sample data to avoid potential issues such as spurious regression and multicollinearity that could interfere with the research results. Table 4 presents the statistical analysis and results of the correlation between variables. Table 5 reports the variance inflation factor (VIF) test results for the variables, where the VIF values for all variables do not exceed 10. Additionally, the VIF values are mainly concentrated between [1,4], with an average of 2.27 for all variables. This indicates that after performing first-order difference, the unit root test confirms the data is stationary, and there is no multicollinearity issue among the variables in the research model.

Table 3
Descriptive statistical analysis results

Variables	Obs.	Mean	Sdv.
LE	989	14.29	0.82
ER	989	54.66	12.29
TI	989	6.70	2.22
EDU	989	50.06	25.60
TRADE	989	23.71	1.83
URB	989	4.03	0.34
FE	989	28.69	11.07
EC	989	7.40	0.85

4. Results

4.1. Fixed-effects regressions

In order to examine the mechanism through which TN affects the LE in this study, as well as the potential moderating roles of ER and EDU in the impact of TN on the LE, this paper constructs an individual panel fixed-effects model, fixing countries for the fixed-effects regression and empirical analysis. The specific empirical regression results and analysis are presented below.

Before conducting the specific empirical analysis, this study performed the Hausman test to further determine the appropriateness of using the fixed-effects model. As shown in Table 6, the p-values are all less than 0.01, leading to the rejection of the null hypothesis and the selection of the fixed-effects model.

4.1.1. Impact of TN on the LE

In order to test the promotional effect of TN on the LE, i.e., to verify H1a and H1b, this paper intends to use a panel fixed-effects model to perform regression on Equation (1). The specific regression results are shown in Table 7.

In Column (1) of Table 7, from the perspective of the direct effect, the results from Equation (1) show that the coefficient of TN at the 1% significance level is −0.1056. This result suggests that TN has a negative inhibiting effect on the LE. This finding

Table 4
Correlation coefficient matrix

	LE	ER	TN	EDU	TRADE	FE	EC	URB
LE	1.000							
ER	0.414***	1.000						
TN	−0.142***	0.022	1.000					
EDU	0.105***	0.338***	0.305***	1.000				
TRADE	0.247***	0.121***	0.786***	0.302***	1.000			
FE	0.295***	0.543***	−0.008	0.483***	0.135***	1.000		
EC	0.008	0.445***	0.406***	0.557***	0.410***	0.489***	1.000	
URB	0.060*	0.343***	0.335***	0.543***	0.307***	0.365***	0.710***	1.000

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

Table 6
Hausman test results for models

	Model 1	Model 2	Model 3
Chi2	111.51	181.51	77.50
P	0.0000***	0.0000***	0.0000***
Conclusion	FE	FE	FE

Note: Test of H0: Difference in coefficients not systematic; "RE" stands for random effects; "FE" stands for fixed effects. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 7
Fixed-effects regression results

LE	(1)
TN	−0.1056***
	(0.0120)
INVE	0.6100***
	(0.0170)
FE	0.0039
	(0.0017)
EC	−0.5338***
	(0.0524)
URB	0.3197***
	(0.1705)
Fixed-effect	√
N	989
R2	0.9601

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

contrasts with the conclusions drawn by some scholars. For example, Deka [54] argues that the development of the LE is inseparable from technological progress. However, some scholars have pointed out that in the initial accumulation phase of TN, phenomena such as resource misallocation caused by patent bubble effects, as well as a limited number and poor quality of innovative products, often occur, leading to a low contribution to the LE [6]. Therefore, the innovation of this study lies in further exploring the potential nonlinear relationships and regional differences between the TN and the LE under the Belt and Road Initiative, providing theoretical insights for existing research.

4.1.2. Moderating role of ER and EDU in TN

To verify the moderating effects of ER and EDU in the process of TN's impact on the LE, i.e., to test H2a and H3a, this paper intends to use the panel fixed-effects regression method. The results are shown in Table 8.

In Column (1) of Table 8, from the perspective of the moderating effect, the results from Equation (2) show that the interaction term has a coefficient of 0.0003, indicating that ER plays a positive moderating role in the process where TN inhibits the LE. This means that the improvement of ER and TN work in synergy, further strengthening the inhibitory effect of TN on the LE. However, this effect does not pass the significance test. This result partially supports the view of some scholars. For example, Han et al. [9] argue that ER helps improve the level of marketization, perfect the relationship between government and market, and enhance the development of factor markets and R&D intensity, thus improving the efficiency of green TN. However, some scholars, such as Xu et al. [32], have argued that TN, under the influence of ER, can contribute to a LE. In contrast, the empirical results of this study find that the moderating effect of ER does not improve the inhibitory effect of TN on the LE. This conclusion seems to differ from the findings of the aforementioned scholars. In response to this phenomenon, this paper suggests that factors such as national policy direction and the degree of environmental emphasis may contribute to this difference, which will be further analyzed in Section 6.

Table 8
Moderating effect regression results

LE	(1)	(2)
TN	−0.1230***	−0.0934***
	(0.0268)	(0.0196)
ER	0.0053***	
	(0.0032)	
EDU		0.0094***
		(0.0023)
TN*ER	0.0003	
	(0.0004)	
TN*EDU		−0.0001
		(0.0003)
Control	√	√
Fixed-effect	√	√
N	989	989
R^2	0.9553	0.9740

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

In Column (2) of Table 8, from the perspective of the moderating effect, the results from Equation (3) show that the interaction term between TN and EDU has a coefficient of −0.0001, indicating that EDU has a negative moderating effect on the process through which TN promotes the LE. However, this effect is not statistically significant. This empirical result suggests that, in the process of promoting the LE in countries along the Belt and Road, EDU may have a certain degree of inhibitory effect on TN, although this effect does not pass the significance test. This finding contrasts with the study by Liao et al. [12]. In light of this phenomenon, this paper also suggests that possible causes for the observed effects could include differences in economic development level, geographical location, resource endowments, and policy orientation, which will be discussed in more detail later in the paper.

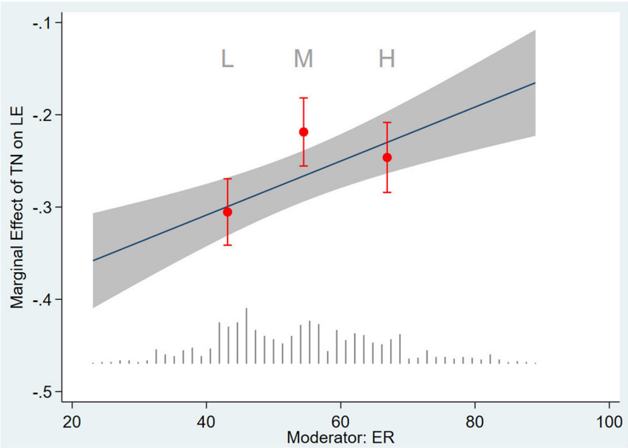
4.2. Threshold-effects regressions

In the previous sections, we have used econometric models to verify the moderating effects of ER and EDU on the relationship between TN and the LE, finding significant differences. Therefore, the next step of this paper is to further explore the nonlinear threshold relationship between ER and EDU in the above process, i.e., to test H2b and H3b. Drawing from the research of Guo and Cai [55], this paper uses box-type estimators and the Wald test. Figures 1 and 2 present the box-type estimator plots of the nonlinear moderating effects, while Tables 9 and 10 report the threshold values and confidence intervals derived from 500 bootstrap samples.

4.2.1. Threshold regression analysis of ER

As shown in Figure 1, the box-type estimators for the low (L), medium (M), and high (H) levels in Equation (2) not only deviate from the model's fitting line but also clearly show a distribution on both sides. This suggests that ER exhibits nonlinear characteristics in moderating the impact of TN on the LE.

Figure 1
Nonlinear impacts revealed in model (4)

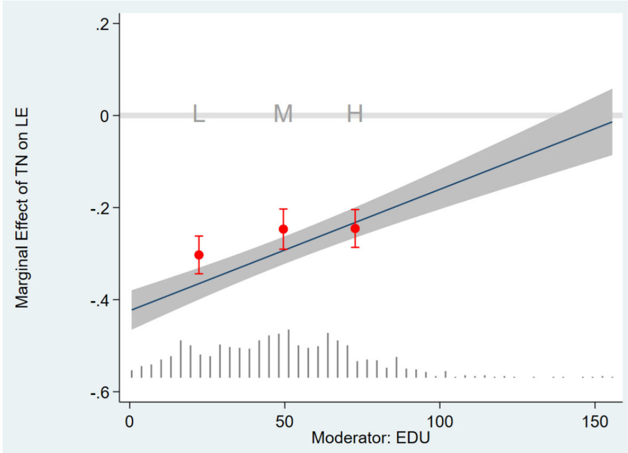


However, as seen in Table 9, the threshold test results for Equation (4) show that when ER is treated as a threshold variable, neither the single-threshold nor the double-threshold models pass the significance level test based on the *F*-values. Therefore, it can be concluded that there is no threshold effect of ER in the process where TN inhibits the LE in Belt and Road countries. This phenomenon will be analyzed in detail in Section 6.

As shown in Figure 2, the box-type estimators for low (L), medium (M), and high (H) levels in Equation (5) exhibit deviations from the model's fitting line and are distributed on both sides. This indicates that EDU has a nonlinear moderating effect in the process of TN impacting the LE.

According to Table 10, the threshold test results for Equation (5) show that when EDU is treated as a threshold variable, both the single-threshold and double-threshold models have *F*-values that are significant at the 1% and 10% levels. Therefore, it can be concluded that EDU exhibits a double-threshold effect in the process where TN inhibits the LE in Belt and Road countries. The two threshold values are 4.9337 and 70.3589. Based on these thresholds, EDU is divided into three ranges, which will be further analyzed in subsequent regression analysis. The specific regression results are shown in Table 11.

Figure 2
Nonlinear impacts revealed in model (5)



As shown in Column (1) of Table 11, the regression results for Equation (5) indicate that EDU has a significant double-threshold effect on the LE at the 1% significance level. Specifically, the inhibitory effect of TN on the LE in Belt and Road countries varies dynamically as the level of EDU increases. More specifically, when EDU surpasses the first threshold value (4.9337), the regression coefficient for TN is 0.2275. When EDU is between the first threshold value (4.9337) and the second threshold value (70.3589), the regression coefficient for TN is −0.1080. When EDU exceeds the second threshold value (70.3589), the regression coefficient for TN is −0.0692. Figure 3 shows the likelihood ratio function of model (5), and the dual-threshold estimates are 4.9337 and 70.3589, where we can clearly observe that the threshold is valid.

As shown in Figure 4, under the influence of EDU levels, the relationship between TN and LE approximates an inverted U-shape. This is consistent with the results of our threshold effect model and further supports the nonlinear relationship between TN and LE.

In the earlier Section (4.1) in Table 8, the regression model for Equation (3) already revealed that TN has an inhibitory effect on the LE. However, in this section, it is observed that after introducing EDU as a threshold variable, the effect of TN on the LE shifts from positive to negative, exhibiting an energy rebound phenomenon. However, the negative effect gradually weakens. This phenomenon will be explained in detail in the conclusion analysis Section (6.1).

Table 9
Threshold value and confidence interval of ER

		F-statistic		Threshold estimates		95% Confidence interval	
Model	Threshold variables	Single threshold	Double threshold	Single threshold	Double threshold	Single threshold	Double threshold
(5)	EDU	88.19***	82.82*	4.9337	70.3589	[3.5774,5.5961]	[70.0377,70.4689]

Note: $^*p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$, "—" indicates that the threshold test has not passed.

Table 10
Threshold value and confidence interval of EDU

Model	Threshold variables	*F*-statistic		Threshold estimates		95% confidence interval	
		Single threshold	Double threshold	Single threshold	Double threshold	Single threshold	Double threshold
(4)	ER	53.90	—	62.0246	—	[61.4764,62.1465]	—

Note: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$, "—" indicates that the threshold test has not passed.

Table 11
Threshold effect regression results of model (5)

Model Variables	(1) Coefficient	 *P*-value
TN*I(EDU≤4.9337)	0.2275*** (0.0379)	0.000
TN*I(4.9333<EDU≤70.3589)	−0.1080*** (0.0111)	0.000
TN*I(EDU≤70.3589)	−0.0692*** (0.0116)	0.000
INVE	0.5896*** (0.0158)	0.000
FE	−0.0012 (0.0016)	0.455
EC	−0.5604*** (0.0483)	0.000
URB	0.5113*** (0.1580)	0.001
Fixed-effect	√	√

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

Figure 4
The nonlinear relationship between TN and LE

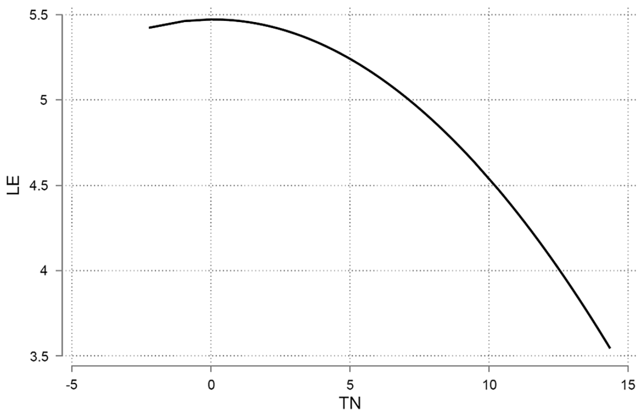
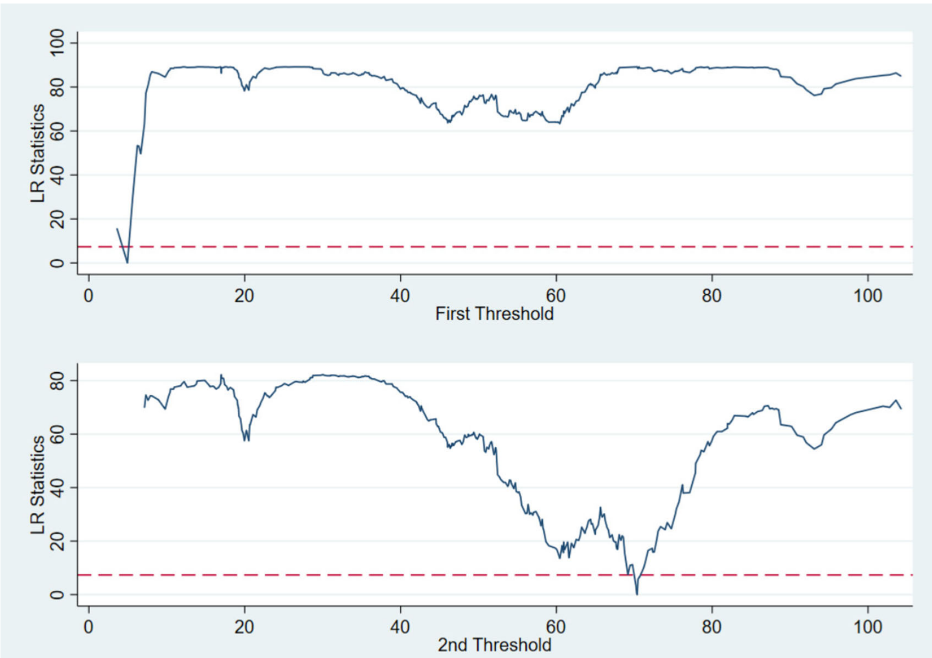


Figure 3
LR values in model (5)



4.3. Heterogeneity analysis

Based on the threshold values of different variables in Table 11, the specific number of countries falling within each threshold range from 2000 to 2022 is summarized in Table 12 below.

Table 12
Number of countries with different EDU thresholds

Threshold range	2000	2005	2010	2015	2022
TN*I(EDU≤4.9337)	2	1	1	0	0
TN*I(4.9333<EDU≤70.3589)	40	38	36	33	24
TN*I(EDU>70.3589)	1	4	6	10	19

From the results in Table 12, it can be observed that between 2000 and 2022, for the two thresholds of EDU, the number of countries in the low-threshold range has gradually decreased, while the number of countries in the medium- and high-threshold ranges has steadily increased. Furthermore, as the year progresses, the number of countries in the high-threshold range nearly encompasses all the countries in the study. This suggests that during the study period, EDU in these countries made significant progress, and with the continuous improvement of EDU, ER and TN have played an important role in promoting the LE of the Belt and Road countries.

To further verify the heterogeneity of EDU in the process where ER and TN influence the LE—especially in relation to factors such as economic development level—this paper employs two different classification methods to perform threshold regression analysis.

4.3.1. Analysis based on differences in economic development level

Referring to Guo and Cai [55], this paper takes the year 2000 as the base year, and the average per capita real GDP of each country from 2000 to 2022 is calculated. The countries are then ranked in a descending order based on their average GDP. Countries with a per capita GDP above the median are classified into the high economic development level sample, while those with a per capita GDP below the median are classified into the low economic development level sample. Threshold regression is performed separately on these two samples to explore the impact of economic development level differences on the regression results. The specific regression results are shown in Table 13.

Table 13
Threshold regression results for high economic development levels

Variables	(1) High
TN*I(EDU≤γ_1)	−0.1124***
	(0.0139)
TN*I(γ_1<EDU≤γ_2)	−0.8750***
	(0.0140)
TN*I(EDU>γ_2)	−0.0017
	(0.0185)
Control	√
Fixed-effect	√

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

From the results in Table 13, it can be observed that the regression results for the high economic development level sample are generally consistent with the overall regression results, but there are also some differences. Specifically, there are clear disparities in the threshold regression results for EDU across different samples. For TN, as the level of EDU increases, the inhibitory effect of TN on the LE weakens. More specifically, when EDU is below the first threshold, the coefficient for the inhibitory effect of TN on the LE is −0.1124 at the 1% significance level. When EDU is between the first and second thresholds, the coefficient for the inhibitory effect increases to −0.8750, indicating an energy rebound phenomenon. However, when EDU exceeds the second threshold, the coefficient becomes −0.0017, but it is not significant.

From the results in Table 14, it can be observed that the regression results for the low economic development level sample are generally consistent with those for the high economic development level sample, though there are some differences. In this sample, EDU has only a single-threshold effect in moderating the impact of TN on the LE. For ER, as the level of EDU increases, its promotional effect on the LE gradually weakens. Specifically, for TN, as EDU increases, the effect of TN on the LE shows a pattern of first promoting and then inhibiting the LE. More specifically, when EDU is below the threshold value, the coefficient for the effect of TN on the LE is 0.2365 at the 1% significance level, indicating the maximum promotional effect of TN on the LE. When EDU exceeds this threshold value, the effect of TN on the LE shifts from promotion to inhibition, with a coefficient of −0.0999, which is statistically significant at the 1% level.

Table 14
Threshold regression results for low economic development levels

Variables	(1) Low
TN*I(EDU≤γ)	0.2365***
	(0.0425)
TN*I(EDU>γ)	−0.0999***
	(0.0142)
Control	√
Fixed-effect	√

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

In response to this phenomenon, this paper suggests that the possible reasons for this pattern are related to factors such as the economic goals and ecological foundations of countries with different levels of economic development. A more detailed analysis of this will be provided in Section 6.1 of the conclusion.

4.3.2. Analysis based on differences in EDU levels

From the results in Table 15, it can be observed that for the sample with a high level of EDU development, the threshold effect of TN did not pass the significance test. However, for the sample with a low level of EDU development, the single-threshold effect of TN was found to be significant. Subsequently, the paper further conducts a threshold regression on the

Table 15
Threshold values and confidence intervals at different EDU levels

Model	Variables	*F*-statistic		Threshold estimates		95% confidence interval	
		Single threshold	Double threshold	Single threshold	Double threshold	Single threshold	Double threshold
High EDU	TN	26.56	—	—	—	—	—
Low EDU	TN	4.62***	—	87.01	—	[3.7367,5.2272]	—

Note: $*p < 0.1$, $**p < 0.05$, $***p < 0.01$, "—" indicates that the threshold test has not passed.

single-threshold effect observed in the low EDU development level sample. The results are shown in Table 16.

The threshold regression results in Table 16 show that for the sample with a low level of EDU development, the effect of TN on the LE first promotes and then inhibits the economy as EDU levels increase. Specifically, when EDU is below the threshold value, the coefficient of TN on the LE is 0.2978 at the 1% significance level. When EDU exceeds the threshold value, the coefficient becomes −0.0629 at the 1% significance level. This regression result differs significantly from the results of the heterogeneity regression based on economic development levels. A detailed analysis of this phenomenon will be provided in Section 6.1 of the conclusion.

Table 16
Threshold regression results of ER and TN under low EDU

Variables	(1) Low
TN*I(EDU≤γ)	0.2987***
	(0.0424)
TN*I(EDU>γ)	−0.0629***
	(0.0143)
Control	√
Fixed-effect	√

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

5. Robustness Test

To verify the robustness of the above conclusions, and considering the potential impact of sample homogeneity and the influence of extreme values on the empirical results, which may lead to errors, this study adopts the following methods to conduct robustness checks: removal of extreme values, the one-period lag method.

5.1. Outlier removal test

To avoid the influence of extreme values on the results of this study, we follow the method proposed by Guo and Cai [55]. Specifically, we sequentially remove the top and bottom 1%, 5%, and 10% of EDU samples from the dataset. We then perform group regressions on the remaining subsamples consisting of 41, 39, and 37 countries, respectively. The results of these regressions are presented in Table 17.

Table 17
Outlier removal test results

Variables	(1)		
	41	39	37
TN*I(EDU≤γ_1)	−0.0639***	−0.0624***	−0.0357***
	(0.0126)	(0.0129)	(0.0128)
TN*I(γ_1<EDU≤γ_2)	−0.0982***	−0.0996***	−0.0796***
	(0.0110)	(0.0110)	(0.0108)
TN*I(EDU>γ_2)	−0.0661***	−0.0686***	−0.0601***
	(0.0115)	(0.0116)	(0.0111)
Control	√	√	√
Fixed-effect	√	√	√

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

As shown in the results of Table 17, the regression results for subsamples 41, 39, and 37 are generally similar to those in Table 11, which suggests that the conclusions of this paper are robust.

5.2. Lagged one-period test

Considering the time effect, it may take some time for EDU to take effect and impact the LE. Therefore, with reference to the study by Wang et al. [56], this paper introduces EDU with a one-period lag into the regression model and conducts threshold regression.

As shown in the results of Table 18, the regression results for the lagged one-period EDU threshold variable are also generally similar to those in Table 11. This further corroborates the robustness of the findings in this paper.

Table 18
One-period lag test

Variables	(1)
TN*I(EDU≤γ_1)	0.2736***
	(0.0384)
TN*I(γ_1<EDU≤γ_2)	−0.0937***
	(0.0113)
TN*I(EDU>γ_2)	−0.0619***
	(0.0118)
Control	√
Fixed-effect	√

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

6. Conclusion

6.1. Conclusion and discussion

Based on the fixed-effects regression results of TN, overall, TN tends to hinder the LE in countries along the "Belt and Road" initiative. The possible reasons for this phenomenon, as discussed in this paper, are as follows: First, many countries along the Belt and Road are still at an underdeveloped stage, with low production capacity and limited resources for innovation, such as a lack of a conducive innovation environment and talent [57]. As a result, these countries face significant constraints in the production and manufacturing of green emerging technologies and related products, making it difficult for the innovation effects brought about by technological progress to materialize. Second, TN is characterized by high investment costs, large risks, and long return periods [58], requiring substantial financial support. However, some countries along the Belt and Road are still in the early stages of economic development and are unable to meet the broad funding needs for TN, thus hindering technological development and weakening the potential innovation effects [59]. On the other hand, if the limited TN capabilities are skewed toward promoting economic growth, the continuously increasing level of TN will only lead to greater EC, which, although promoting economic growth, also significantly increases carbon dioxide emissions [60].

Regarding the moderate effect, when ER is considered as a moderating variable, its result further strengthens the inhibiting effect of TN on the LE in countries along the Belt and Road. The possible reasons for this, as discussed in this paper, are as follows: First, considering that many Belt and Road countries are still at relatively low levels of development and in the early stages of environmental governance, they lack experience and tools in policy-making. Blind environmental policies may increase production costs for businesses, causing these countries' environmental measures to often have a cost effect greater than the compensatory effect of innovation, thereby obstructing low-carbon development [61]. Second, the intensity of ER strengthens with economic development, but the level of ER varies between different countries or regions. In the pursuit of economic profit maximization, enterprises often tend to transfer high-pollution, high-emission industries from countries or regions with high ER levels to those with lower ER levels [62, 63]. This could result in a weakened synergistic effect between ER and TN in the long term, thus making the effect less detectable.

When EDU is considered as a moderating variable, it further improves the negative effect of TN on the LE in countries along the "Belt and Road" initiative, and its nonlinear moderating effect has been validated through the significance test of box estimation diagrams. To further analyze the changes in the trends of this effect, this paper conducted a threshold regression. According to the results of the threshold effect, as the level of EDU increases, TN first promotes and then suppresses the LE, though the negative effect weakens over time. The possible reasons for this phenomenon, as suggested in this paper, are as follows: First, in the early stages, the carbon emission levels in these countries are not very high. Even if only a small amount of technology products is applied to environmental protection, they can still improve energy efficiency and reduce environmental pollution, achieving a relatively good LE. Second, as the technological level improves, some countries, in an attempt to better absorb technology, may blindly invest in education and attempt to leapfrog in terms of EDU structure. This approach may not only fail to enhance economic performance but could also lead to a mismatch of EDU and a significant loss of talent, ultimately exacerbating the negative effects of TN on the LE. However, as the EDU structure continues to be optimized and upgraded, and as the technological capabilities of these countries improve, this phenomenon may be improved to a certain extent.

From the results of the heterogeneity regression, it is found that for different levels of economic development, the overall regression results for high and low economic development levels are generally consistent with those for the total sample, but some differences do exist. For countries with lower levels of economic development, TN continues to exert a suppressive effect on the LE, but this effect first strengthens and then weakens, with a rebound effect on EC also appearing. The main reasons for this, as discussed in the paper, are as follows: First, in more economically developed regions, businesses tend to use introduced technologies for economic expansion, which in turn stimulates large-scale EC. The environmental effects brought about by TN are far outweighed by the economic effects, thereby suppressing the LE. Second, the siphoning effect of TN also attracts talent to these industries, which not only further exacerbates the promotion of extensive economic growth but also leads to an imbalance of human and other resources, negatively affecting the LE in surrounding regions.

Regarding different levels of EDU, the threshold effect is only observed in the low EDU sample. As EDU levels rise, the role of TN in the LE shifts from promoting it to suppressing it. The possible reasons for this, according to this paper, are as follows: First, in the early stages of social development, the technical levels of countries are relatively low, and the demand for EDU is also low, meaning that lower levels of EDU can still meet the needs of a LE. Second, although the economic environment is continuously improving, many regions, especially those with low levels of EDU, still suffer from unequal distribution of EDU. This not only hinders the collision of new knowledge, skills, and ideas but also reduces the match between technology and EDU, leading to a potentially negative effect of both on the LE.

6.2. Managerial implication

First, continually develop green products and processes to drive the growth of the green economy through innovation. On the one hand, businesses in all countries (especially high-emission, high-energy-consuming industries) should actively participate in exchanges and cooperation with high-tech industries, low-energy-consuming industries, and strategically emerging industries-seeking mutual assistance. This will encourage companies to constantly update and develop green products, promoting low-carbon development across the entire industrial chain. On the other hand, there should be a balance between applying technology to economic growth and environmental protection. In particular, in more economically developed regions, it is important to avoid concentrating advanced technologies excessively in high-energy-consuming and high-pollution industries that aim for rapid short-term economic growth. Instead, focus on green industries with vast growth potential to ensure the effective use of technological resources and a sustainable, healthy development of the economy.

Second, fully leverage the positive impacts of ER in the LE. First, governments should establish sound environmental regulatory systems to ensure that ERs effectively penetrate and are efficiently implemented across all industries. Second, the implementation of environmental protection policies should be gradual to avoid a "race to the bottom" where businesses relocate to less-regulated regions. Finally, when strengthening supervision and enforcement, governments should ensure that the intensity of the policies matches the country's capacity to implement them, avoiding situations where excessive resource investment squeezes other vital areas. This would contribute to the sustainable development of a LE.

Third, increase investment in EDU and optimize its structure. On the one hand, Belt and Road countries should continue to increase investments in education, aiming to maximize the overall education level of their populations. On the other hand, they should avoid adopting blind or one-size-fits-all talent policies. It is essential to thoroughly understand local resources and needs to better match talent resources with the demands of the economy.

Fourth, suggestions from heterogeneous results.

Based on the analysis of differences in economic development levels, for high-income countries, improvements in EDU can effectively change the negative impact of TN on the LE. The government should increase investments in education, particularly in innovation-driven industries and low-carbon technology fields, to cultivate more high-skilled talent. For low-income countries, which often face technological deficits, to reduce the suppressive effects of TN, efforts should be made to strengthen technology transfer and international cooperation, particularly with high-income countries and regions, in areas such as low-carbon technologies, clean energy, and environmental management. At the same time, improving domestic talent compensation is essential to promote the continuous optimization and upgrading of the EDU structure and reduce talent mismatches. For countries that have already experienced energy rebound effect, policies should further promote innovation and the widespread application of green technologies. Investment in renewable energy sources such as solar, wind, and hydro-electricity should be increased, with fiscal subsidies or tax incentives provided to encourage businesses to invest in the research and development of clean energy and low-carbon technologies.

Based on the analysis of economic development level differences, for countries with low EDU, the government should first address the issue of unequal distribution of EDU by increasing investments in basic education and reducing educational disparities. Secondly, it should improve the match between technology and EDU, optimize EDU allocation, and promote the effective flow of resources, thereby avoiding "brain drain". Finally, the government should strengthen the innovation environment, reduce reliance on imitation, and promote indigenous innovation. This includes not only absorbing foreign technologies but also encouraging local enterprises to adapt and localize imported technologies, driving the innovative application of these technologies, and avoiding simple technological imitation.

6.3. Limitation and further research

First, the sample used in this study still requires expansion. In the future, with a more comprehensive database, the findings of this study could be further refined and enriched.

Second, future research could explore spatial spillover effects, examining how neighboring countries influence one another, which could provide additional suggestions and insights for the low-carbon economic development paths of countries along the Belt and Road initiative.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support this work are available upon reasonable request to the corresponding author.

Author Contribution Statement

Jianquan Guo: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Xuning Zhao:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization.

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