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Diffusion of technology and renewable energy in the G10 countries: A panel threshold analysis

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A B S T R A C T

The paper analyzes the threshold effect of technology innovation on renewable energy in the G10 countries through the panel threshold method. The outcome shows that technology innovation has a low impact on renewable energy when technology innovation is below the threshold value. However, technology innovation has a strong positive effect on renewable energy when the threshold value is above because of the expansion of spending on energy and technology. Moreover, digitalization makes renewable integration possible, analytic and artificial intelligence improve production. The findings explore that carbon emission has a negative impact on renewable energy. However, knowledge stocks, imported oil prices, economic growth, and electricity consumption positively affect renewable energy. The countries must develop more cost-effective, mature, and accessible renewable energy technology. Also, the focus should be on implementation instead of investing in existing infrastructure. A political commitment to phase out nuclear power and fossil fuels can improve the underwhelming performance.

1. Introduction

Climate change and energy security necessitate exploring solutions to minimize greenhouse gas emissions while guaranteeing energy supply security [1]. The transition process is helpful because it lowers the negative environmental impacts of production and consumption. In this regard, renewable energy (REN) has the potential to accomplish environmentally sustainable development, minimize dependency on imported resources and fulfill energy demand while simultaneously growing the economy [2]. The growing expense of fossil fuels and the depletion of energy supplies are driving forces behind REN growth. Meanwhile, technological innovation (TI) may serve as a technical basis for REN and a key development component [3]. Moreover, innovative technology is employed to ensure the best use of REN sources to meet energy demand [4]. This diffusion of technology with renewables can aid long-term economic growth while also addressing environmental problems [5]. Meanwhile, TI has digitalized, allowing for REN integration and output optimization using analytic and artificial intelligence. Similarly, renewable energy technologies contribute significantly by increasing plant efficiency and ensuring constant output [6]. However, REN is more expensive and less commercialized than fossil energy which can undermine REN [7,8]. A growing trend of low-carbon technology has been seen recently, accounting for the majority of all patents in environmental technologies. As a result, TI will significantly influence the growth of RENs and the global energy pattern [1].

This study evaluates the threshold effect of TI on REN in the G10 countries, namely “Belgium, Canada, France, Germany, Italy, Japan, the Netherlands, Sweden, Switzerland, the UK, and the U.S.” It assumes that relationships behave differently in different regimes due to many contributing factors. These are the most inventive and economically

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powerful countries and leaders in the energy transition to fulfill environmental goals [9]. Similarly, the countries lead the world in REN production and produce enough electricity to power their economies. Similarly, the nations have set goals, such as obtaining most of their energy from renewable sources by 2030, and are optimistic about the future of REN. These countries have set a goal of completely decarbonizing their power supply by 2035, which can accelerate technology advancements and infrastructural development. Moreover, governments initiate policies to keep up with the energy transformation process because they are the major energy users and carbon emitters. Furthermore, innovation is vital to attaining environmental sustainability by creating energy-efficient technology to maintain economic growth while minimizing environmental [5]. Similarly, the innovation fosters a shift toward environmentally friendly technology and increases market efficiency, contributing to the change to low-carbon technologies. The transition from conventional to REN is reliant on economic development. As a result of their strong economic growth, the G10 countries have adequate resources to invest in energy transition and reach net-zero emission targets. On the other hand, intellectual property is critical to technology transfer and implementation plans for growing reliance on renewables. Some countries have the most patents for renewable energy technologies, highlighting the technology's environmental and economic benefits. The underlying nations are thought to consume significant electricity primarily generated from imported fossil fuels. Imported energy prices translate into higher manufacturing costs, contributing to inflation and environmental pollution. The countries' endeavor for net-zero emissions following the international pledge and energy transition has been steadily progressing toward environmental and energy sustainability.

Green patents have shown a rapid increase in these countries, notably after 2005, which may provide a push for renewables. Moreover, public policy, environmental regulation, and greater energy prices support this trend in low-carbon technological advances. However, patent registration has slowed since the financial crisis of 2008 and even decreased in several technology industries. Furthermore, the crisis has slowed the REN's development, restricting the flow of loans from banks to renewable projects. Also, the crisis reduces subsidies for innovative green projects because of investor concerns [10]. Furthermore, the energy policy of these countries rapidly changed in the wake of the Fukushima disaster in 2011, requiring them to phase out nuclear power and develop renewable energy technologies to make up for the shortfall in electricity supply [9,10]. The oil price drop in 2014 has reduced the value of future energy savings or fossil fuels and the desire for green energy. Similarly, since 2014, growth has slowed due to REN productions inability to generate enough energy while avoiding environmental risks. Meanwhile, changes in the energy system are triggered by TI, which allows for a multi-directional and highly integrated energy system. Smart electricity grids have been created in the energy industry to efficiently incorporate dispersed REN sources into the system. However, economic growth in these countries is hampered by the coronavirus (COVID-19), which suppresses environmental concerns and hinders the energy transition process [11]. This uncertainty causes a drop in renewable investment and several countries have decreased REN development. Furthermore, the closure of renewable energy production plants due to the pandemic might negatively influence REN [9]. As a result, the correlation between TI and REN in G10 nations is relevant because of their prominence in the global economy, technological advancement, and environmental challenges.

The research contributes substantially to the current body of knowledge. First, the study evaluates a possible threshold effect of TI on REN in the G10 countries. It assesses REN behaviour at a different level of TI or the various regimes that show different associations. The nature of the association between REN and TI can be different if the value of TI is above or below the threshold value. Thus, the underlying study explains the different responses of REN to the different threshold values of TI. Second, it offers insight into the diffusion of TI and REN due to environmental issues, power use, knowledge stock, economic growth, and imported energy costs, all of which have impacted REN behaviour. Last, it investigates the asymmetric influence of TI on REN in two regimes through panel threshold regression. The paper analyzes the threshold effect of TI on REN in the G10 countries. The outcome shows that TI has a low impact on REN when technology innovation is below the threshold value. However, TI has a strong positive effect on REN when the threshold value is above because of the expansion of spending on energy and technology. Moreover, digitalization makes renewable integration possible, and analytic and artificial intelligence improve production. The findings explore that carbon emission has a negative impact on REN. However, knowledge stocks, imported oil prices, economic growth, and electricity consumption positively affect REN. The countries must develop more cost-effective, mature, and accessible renewable energy technology. Also, the focus should be on implementation instead of investing in existing infrastructure. A political commitment to phase out nuclear power and fossil fuels can improve the underwhelming performance.

Section 2 of the study contains a literature review. Section 3 explains the methodology process. The data summary is shown in section 4, whereas in part 5, the most critical analysis of the data is presented, followed by the conclusion in section 6.

2. Review of literature

The nexus between TI and REN is essential, and several studies have discussed the phenomenon. Geng and Ji [1] investigate the relationship between TI and REN and conclude the long-run bidirectional causality. He et al. [12] confirm that greater technological expenditures cause renewable development in Chinese provinces. According to Palage et al. [7], the development of new technologies significantly impacts REN usage. Shivakumar et al. [10] find the link between REN and TI as solar system control and expansion boost REN. Adom and Kwakwa [13] demonstrate that technological development is lowering energy use and prices and lowering the energy-inducing influence of population trends. According to Xie et al. [14], developing new technologies significantly impacts REN consumption. On the other hand, existing technologies cannot significantly impact REN. Salvarli and Salvarli [15] explore that REN has taken the lead in future power generation, which can help mitigate environmental risks. Li et al. [16] confirmed that human capital, energy productivity, energy pricing, and eco-innovation are all significant variables in determining the use of REN. Su et al. [17] study that REN is the essential variable in the energy transition, which may help resolve environmental issues. Zheng et al. [18] investigate how TI supports REN, and the findings show that TI leads to an increase in REN in a province, with a contagion effect on provinces due to technological diffusion. Amin et al. [19] assess the relationship between research spending and REN development and conclude that countries that rely on imported fossil fuels are more likely to invest in REN. Su et al. [9] look into the association between TI and REN and conclude that economic stability bolsters the link. Edziah et al. [20] revealed that machinery imports and REN use significantly cut carbon dioxide emissions. On the other hand, foreign R&D increases carbon dioxide emissions in the region. Li et al. [21] explore that knowledge flow to REN is more critical for countries with small R&D.

Different studies assess the relationship between knowledge stock and REN development. Park [6] explores that patent is a useful instrument for promoting the diffusion of green technology. Johnstone et al. [22] provide evidence of public policy's role in promoting renewable energy technologies innovation. They conclude that patent plays an important role in REN progress. Pop et al. [23] explain that patenting activity is the potential factor of REN supply. Furthermore, patenting activity significantly impacts the distribution of REN in developed countries. Gattari [24] shows that patent protection boosts the profitability of green energy investments and speeds up the advancement of green energy technologies. Adom et al. [25] concluded that adjusting the industrial sector's production mix to favor less energy demanding products enhanced energy efficiency. Rai et al. [26] explore that weak patent rules are barriers to the progress of low-carbon technologies because the weak rights increase to realization time of investment returns. Gao and Zhai [27] demonstrate that there is no relationship between patent rules and the REN industry because of a lack of innovation. Ben Youssef [28] shows that resident and non-resident patents have a long-term relationship with REN consumption. Sobolieva and Harashchenko [29] investigate the evolution of technologies and patents and demonstrate that solar has the most patents, whereas wind has the fewest. Li et al. [30] find that patent protection does not substantially influence REN usage. This shows that intellectual rights are not an issue for global energy transition, implying that strong efforts must be made to influence economic inputs that influence REN operation. Tee et al. [31] investigate the impact of patents on REN development. The findings show that patents drive REN advancement because increased patent protection rights increase energy production from renewable resources and motivate the development of renewable energy technologies. Stevens and Rouhollahi [32] conclude that research and development (R&D) investment in REN has a long-term, significant, and positive impact on complementary technology innovation.

Some of the studies have used the panel threshold approach. For example, Su et al. [33] investigate the effect of house prices on marriage using a panel threshold regression. The answers suggest that house prices have a positive impact on marriage. Khan and Su [34] use the panel threshold regression method to examine the optimal level of urbanization on its effect on carbon emissions. The finding suggests urbanization has a negative impact on carbon emissions. Yin and Su [35] conclude that the birth rate is significantly negatively impacted when house prices are above a certain level. Su et al. [36] use panel threshold regression to infer that there is an ideal level of R&D intensity in Chinese defense businesses. According to the literature review assessment, there is a significant link between TI and REN. In addition, some studies have investigated the influence of other factors on REN development, such as knowledge stock, patent protection, and R&D spending. Nonetheless, there are still some gaps in the literature. For example, some research indicates that patent protection stimulates REN progress, while others demonstrate that it has little effect on REN usage. Furthermore, some studies show a short-term relationship between carbon emissions and REN, but others suggest that REN has no substantial influence on carbon emissions. Moreover, several research has concentrated on the association between TI and REN in certain locations or nations, limiting the generalizability of their conclusions. Also, there has been little research into the impact of government policies and economics in encouraging REN development.

3. Methodology

The previous literature lacks studies about the panel threshold effect of TI on REN. The linear model, which measures dependent and independent variables in a straight line, has been employed in most investigations. However, this assumption of linearity presence and validity is inappropriate in all circumstances [33]. Also, the conventional approaches may favor the mean of both variables while ignoring the extremes. Furthermore, because policy changes are frequent and asymmetrically adjusted time series may occur, the linear model is not a reliable or consistent estimate of expected effects [34]. However, the panel threshold method offers significant benefits compared to previous nonlinear approaches. It can make various linkages in signs and magnitudes available, contributing to the heterogeneity problem. It investigates the link between and among variables under multiple regimes. Moreover, the threshold effects are not dependent on the nonlinear equation derived from endogenously based sample data. Similarly, evaluating the asymmetric connection may not detect sharp turning points. The panel threshold approaches, on the other hand, can see turning points. Furthermore, the approach can investigate further sample splits and fixed effects to find co-movement produced by exogenous shocks.

Assuming fixed effects, the threshold regression technique that Hansen [37] described explains the structural break threshold and divides the data into multiple regimes. For example, it might be either above, below, or in the middle of the threshold value. "The TI is chosen as a threshold variable, and the single threshold regression of the model is estimated as follows:

$$REN_{it} = \begin{cases} \mu_t + \beta_1 TI_{it} + \alpha x_{it} + \varepsilon_{it}, if\ TI\ is \leq \gamma \\ \mu_t + \beta_2 TI_{it} + \alpha x_{it} + \varepsilon_{it}, if\ TI\ is > \gamma \end{cases} \quad (1)$$

$$\alpha = (\alpha_1, \alpha_2, \alpha_3)^{'}\ x_{it} = (CE_{it}, KS_{it}, EP_{it}, GDP_{it}, EC_{it}) \quad (2)$$

where REN_{it} is the dependent variable; TI is the independent and threshold variable. x_{it} is set of a controlled variable which affect REN". The carbon emission (CE_{it}), knowledge stocks (KS_{it}), energy price (EP_{it}), gross domestic product (GDP_{it}) and electricity consumption (EC) as control variables. Several studies have used the knowledge stock, eleFctricity consumption, and economic growth impact on renewable diffusion with technology. In this regard, Pop et al. [23], Tee et al. [31], and Zhao et al. [38] have shown that knowledge stock and economic development play an essential role in technological diffusion to renewable energy. Similarly, Geng and Ji [1] conclude that gross domestic product (GDP), crude oil price, and CE are the driving factors of renewable energy. Moreover, electricity consumption is one of the important drivers of REN diffusion with technology innovation [12]. To maintain economic growth, the majority of the countries in the region rely mainly on imported resources. Alternative energy systems, such as REN, are crucial for long-term sustainability to reduce dependency on imported energy [39]. " μ_i is the fixed effect; the value of the threshold is γ; β_1 and β_2 variable coefficient; $\alpha = (\alpha_1, \alpha_2, \alpha_3)^{'}$ are the estimated coefficient of the control variables. ε_{it} is the error term having zero mean and finite variance.

Equation (2) is rearranged in the following regression format;

$$REN_{it} = \mu_{it} + \beta_1 TI_{it} I(TI \leq \gamma) + \beta_2 TI_{it} I(TI > \gamma) + \alpha^{'} x_{it} + \varepsilon_{it} \quad (3)$$

where I () is an indicator function.

In the case of double threshold regression, as follow;

$$REN_{it} = \begin{cases} \mu_t + \beta_1 TI_{it} + \alpha x_{it} + \varepsilon_{it}, if\ TI\ is \leq \gamma_1 \\ \mu_t + \beta_2 TI_{it} + \alpha x_{it} + \varepsilon_{it}, if\ \gamma_1 < TI\ is \leq \gamma_2 \\ \mu_t + \beta_3 TI_{it} + \alpha x_{it} + \varepsilon_{it}, if\ TI\ is \geq \gamma_2 \end{cases} \quad (4)$$

$$REN_{it} = \mu_{it} + \alpha^{'} x_{it} + \beta_1 TI_{it} I(TI \leq \gamma) + \beta_2 TI_{it} I(\gamma_1 < TI \leq \gamma_2) + \beta_3 TI_{it} I(TI_{it} > \gamma_2) + \varepsilon_{it} \quad (5)$$

Thus, the method is suitable for analyzing threshold effects in different regimes and detecting the turning points". The panel threshold approach has no prerequisite for the nonlinearity equation. The analysis outcomes explore that TI has a significant threshold effect on REN in different regimes.

4. Data

This study examines the threshold effect of TI on REN in the G10 countries from 2000 to 2021. The beginning period of the study coincides with rising investment in renewable technology, which improves REN growth [9]. Meanwhile, environmental concerns, rising oil prices, and technological innovation drive the energy transition towards REN, offering a more sustainable long-term energy supply [34]. The G10 economies with resources to invest in energy transition and net-zero emissions goals are crucial to this transition [40]. The percentage of a country's GDP spent on research and development (R&D) in both current and capital forms is equal to TI [3]. REN is the contribution of renewables to total primary energy, measuring the share of REN sources (including hydro, geothermal, solar, wind, and tide) in a country's total primary energy production [34]. It is measured in thousand toes (tons of oil equivalent) and is obtained from the Organization for Economic Cooperation and Development (OECD). Moreover, knowledge stocks are patent data examining how technical improvements have influenced renewable energy investment. Patent applications contain a plethora of information on the invention and the applicant [23]. Furthermore, carbon emissions are the direct emissions from human activities and the direct emissions from fuel burning, both of which are quantified in tonnes per capita and obtained from the OECD. Moreover, the crude oil import price is obtained by dividing the value by volume as recorded by customs administrations. Electricity consumption is the consumed amount of electrical energy in these countries. GDP is a crucial indicator of economic activity because it captures the value added produced by producing goods and services in these countries. Table 1 illustrates the summary of variables. The skewness values indicate that variables are skewed to the right except for GDP and carbon emission. The kurtosis value shows that variables are leptokurtic distributed except REN and imported energy prices. The Jacque Bera values explore the non-normal distribution.

5. Empirical results

The threshold number is specified for the estimation of the model. The *F*-statistics are obtained using the bootstrap method, and the threshold effect findings are illustrated in Table 2. It indicates that the *F*-statistics of the single threshold is 53.618, greater than the 1% critical value of 35.041. It confirms the single threshold with a value of 2.043% of GDP, which is significant. The single threshold effect shows that TI plays a vital role in REN. It validates the single threshold with a significant value of 2.043% of GDP. The single threshold effect illustrates the importance of TI in REN.

Table 3 illustrates the threshold values $\gamma_1 = 2.043\%$ of GDP specifies the dividing points. The data show that if the TI is below the dividing line (2.043) % of GDP, the estimated $\widehat{\beta}_1$ is 4.531, with significant *t*-statistics for homogeneous and heterogeneous standard errors. It explains the positive impact of TI on REN and shows that a 1% increase in TI leads to a 4.531% increase in REN development. The outcomes indicate that magnitude of REN development is slow when the TI is below the threshold value, meaning that energy transition may be a new phenomenon and infancy phase. Thus, in the initial stage, there is less diffusion of technology to renewable and the percentage of a country's GDP spent on R&D is low, which does not make a substantial contribution to REN growth. The countries are the hub of innovation that touches every sector, including fashion technology, big data, mobile broadband, and digital technology integration. However, renewable innovation is limited because these countries rely on fossil fuels. Meanwhile, nuclear energy provides substantial shares of electricity due to slow renewable technological progress, as well as the application and deployment of R&D. Moreover, the shares of REN in the total energy supply are low as compared to nuclear and fossil fuels which can be a reason that TI does not translate into REN. A lack of administrative staff and lengthy permitting processes mainly prompt the delivery gap. Similarly, implementing support mechanisms has been confusing and time-consuming. Furthermore, the electric power fleet is aging, and private investments in large-scale capacity expansions are not forthcoming owing to a lack of long-term clarity on the electricity mix. The policy for transforming the energy system does not identify technology priorities [41]. Renewable energy technologies do not contribute substantially because innovation primarily focuses on improving plant efficiency and assuring suitable production [42]. However, the lack of innovation policy in renewable energy technologies cannot be diffused and adopted. The problems in policy design with economic rationale and empirical evidence to bring new technologies to penetrate a market are not adopted. Political judgment and biasness may be the main reasons for the lackluster performance of technology development in REN. Similarly, TI has a slow impact on renewable generation because the largest renewable source is hydroelectric.

On the other hand, when the TI value is above the threshold value, the estimated $\widehat{\beta}_2$ is 8.151. It recommends the positive impact of TI on REN and explains that a 1% increase in TI results in REN by 8.151%. The dividing points of the threshold values (2.043) % of GDP suggest that exceeding a specific limit, the speed, and the significance level of TI increases the impact on REN. This might be possible because at the beginning of the renewable technology development, the scale of growth is low, which has no considerable implications for REN. However, when the research investment rises later and the development of renewable energy technologies increases and the percentage of a country's GDP spent on R&D is high, which is reflected in the vigorous renewable progress. The countries have the sophisticated advanced infrastructure, high-tech systems, and creative sectors and can meet high expectations for the energy transition. Furthermore, countries are at the forefront of deploying energy-producing technology, which serves as a stimulus for the development of REN. The respective governments have set the roadmap for realizing the energy transition and expanded R&D expenditure, with energy and technology receiving the largest public funds [2]. Offshore wind innovation has advanced, new expectations have emerged, and offshore oil and gas prices have plummeted. Similarly, larger-scale projects and the industry is performing well in translating innovation into REN [43]. Moreover, technology diffusion reduces production costs and enables the development of REN. The process of digitalization makes renewable integration possible, and analytic and artificial intelligence improve production [9]. Renewable energy technologies contribute substantially by improving plant efficiency and assuring optimal production. Meanwhile, some onshore wind and biomass boiler technologies mature because of innovation and can contribute considerably to renewables. Massive sums have been earmarked to stimulate offshore and marine technology innovation, which may boost REN. As the cost of batteries declines, so does the rate of innovation in battery technology, which is crucial for the next generation of electric vehicles.

Several control variables include carbon emissions, knowledge stocks, GDP, imported energy prices, and electricity consumption. The results are illustrated in Table 4. The coefficient of $\widehat{\alpha}_1$ of carbon emissions indicates a negative impact on REN in these countries, implying that if carbon emissions increase, REN reduces. The results are like Saidi and Omri [44], who state that carbon emissions and REN have a

Table 1
Descriptive statistics.

	REN	TI	CE	EP	GDP	KS	EC
Mean	2.346	11.113	8.965	62.891	1.332	47.907	1.664
Std. Dev.	0.676	9.121	4.078	28.336	2.405	12.342	3.810
Skewness	0.012	1.431	0.967	0.375	−1.704	−0.784	1.408
Kurtosis	1.944	4.805	3.140	1.978	7.118	3.506	5.206
Jarque Bera	10.735***	110.226***	36.202***	15.464***	275.017***	26.149***	441.024***

Note *** shows significance at 1% levels. REN denotes renewable energy; TI is technology innovation; CE is carbon emission; EP is oil's imported price; GDP is economic growth; KS is knowledge stocks; and EC is electricity consumption.

Table 2
Tests for the threshold effects of TI on REN.

Test	Threshold estimates	*F* statistics	p values	Critical values		
Single Threshold	2.043***	53.618	0.000	35.041	42.700	48.556
Second threshold	1.472	36.608	0.500	22.637	29.629	44.496
	2.043					
Triple threshold	2.923	4.557	0.650	15.759	23.831	27.603
	1.472					
	2.043					

1. p-value and F-statistics are obtained by repeating the bootstrap procedures 10000 times for every test.
2. *** indicates significance at the 1% level.

Table 3
Estimated coefficients of the renewable energy.

	Coefficients	OLS se	t_{OLS}	White se	t_{White}
$\widehat{\beta}_1$	4.531	1.452	3.120***	2.071	2.187***
$\widehat{\beta}_2$	8.151	2.692	3.027***	2.727	2.988***

1. "OLS se (White se) refers to homogeneous (heterogeneous) standard errors. 2. β_1 (β_2) indicates that the coefficient estimates are smaller (larger) than the threshold value. 3. *** indicate significance level 1%."

Table 4
Estimated coefficients of the control variables.

Variables	Coefficients	OLS se	t_{OLS}	White se	t_{White}
CE $\widehat{\alpha}_1$	−1.604	0.250	6.416***	0.268	5.985***
EP $\widehat{\alpha}_2$	0.020	0.013	1.538	0.010	2.000**
GDP $\widehat{\alpha}_3$	0.401	0.123	3.260***	0.197	2.035**
KS $\widehat{\alpha}_4$	0.114	0.048	2.375**	0.054	2.111**
EC $\widehat{\alpha}_5$	0.121	0.026	4.653***	0.048	2.520**

1. " $\widehat{\alpha}_1$, $\widehat{\alpha}_2$ and $\widehat{\alpha}_3$ indicates the coefficient estimates per capita GDP, female education level, and unemployment rate, respectively. 2. ** and *** indicate significance at 5% and 1%, respectively".

bidirectional causality in the short run. Most governments have recognized the harmful effects of growing carbon emissions levels in the atmosphere and are taking initiatives to minimize the climate risks. Following the 2015 Paris Agreement, these countries have made the necessary steps toward green energy to ensure environmental sustainability. Similarly, the energy transition process can provide a solid framework for REN development due to its high economic position and technological advancement [3]. The countries are on the path to reaching net-zero emissions through growing low-emission electricity sources, such as renewables, and phasing out fossil fuel-generated electricity. As a result, the countries adopt measures to further green their consumption and manufacturing processes, ensuring that economic growth and environmental development are complementary [45–49]. The fossil fuel dependency decrease helps mitigate carbon emissions in these countries.

On the other hand, the coefficient $\widehat{\alpha}_2$ of the imported oil price has a positive impact on the panel threshold impact of TI on REN. It implies that rising imported energy price is one of the driving factors of the energy transition in these countries. The results are in line with Amin et al. [19], who conclude that countries that rely on imported fossil fuels are more likely to invest in REN. Most countries are heavily dependent on imported resources to maintain economic growth. Energy security becomes more critical amid geopolitical crises that can disrupt energy supplies. Thus, to reduce reliance on imported energy, an alternative energy system in the form of REN is essential for long-term sustainability [39]. The imported energy prices translate into greater production costs, leading to inflationary pressure and environmental emission. Subsequently, the countries strive for net-zero emissions in the wake of international commitment. The energy transition process in these countries has been making steady progress toward environmental and energy sustainability. Some countries are success stories of the REN and achieving the net-zero emissions target mainly caused by solid technological background, greater R&D, environmental issues, and imported energy prices. The coefficient $\widehat{\alpha}_3$ of GDP has a positive effect on REN. The energy transition process from conventional to renewables heavily depends on these countries' economic positions. Energy production/consumption strongly correlates with economic growth because energy dictates economic and social development. The growth in GDP leads to an increase in energy demand, which reflects in higher emissions [46–48]. The greater economic growth can be reflected in the development of rapid renewable. G10 countries have robust economic growth, providing ample energy transition resources and achieving net-zero emission targets. The consumption of REN appears to be linked to economic growth. This association, however, is more robust in these nations because of higher GDP [47]. The higher economic growth attracts investors to deploy REN, which creates employment opportunities and promotes human welfare. Thus, higher economic growth increases the energy demand and pushes REN development.

The coefficient of knowledge stock $\widehat{\alpha}_4$ has a positive impact on REN in G10 countries. It shows that intellectual property is important in technology transfer to renewable and application strategies for increased reliance on renewables. Some countries have the largest number of patents in renewable energy technologies, indicating REN's environmental and economic benefits. Moreover, the higher percentage of investment in the renewable industry and patent protection for REN encourage private financing. Renewable energy technologies patenting has boomed in the last decade, decreasing the cost of implementation and improving performance technologies. Renewable technology transfer is possible by removing the intellectual property barriers which mitigate climate change. Given their natural resources and legacy infrastructure, these countries provide a unique potential for REN. The coefficient $\widehat{\alpha}_5$ of electricity consumption has a positive impact on REN. The finding suggests that rising electricity consumption and REN are directly related, meaning greater energy consumption reflects emissions and encourages transition toward REN. The underlying countries consume substantial electricity mainly produced from imported fossil fuels. These countries emphasize renewable development more to lessen their dependency on conventional energy sources. Moreover, the higher technological innovation combined with the R&D supports the knowledge stock and facilitates diffusion with REN. Similarly, the countries are on the front path against environmental hazards and international commitments such as the Paris Agreement and COP26 enhance the responsibility to obtain sustainable development goals (SDG). Consequently, energy prices and diminishing energy resources have boosted the process of energy conversion from non-renewable to REN. The successful energy transition will ensure a sustainable energy supply to fuel their respective economies and help achieve net-zero emissions.

6. Conclusion

The paper analyzes the threshold effect of TI on REN in G10 countries utilizing the panel threshold regression approach. The outcome shows that TI positively impacts the REN when TI is below the threshold value, but the impact is slow. This might be possible due to slow technological progress and the application and deployment of R&D. Moreover, the shares of REN in the total energy supply are low compared to nuclear and fossil fuels, which might be why TI does not translate into REN. On the other hand, TI has a positive effect on REN when the TI is above the threshold. The explanation is the recent rapid transition of these countries to renewables because of the expansion of spending on energy and technology. Renewable technology diffusion reduces production costs and enables the development of REN. Moreover, digitalization makes renewable integration possible analytic and artificial intelligence improve production. The control variables show that carbon emissions have a negative impact on the threshold effect. However, GDP, knowledge stocks, imported oil prices, and electricity consumption positively impact TI's threshold effect on REN.

The study makes policy recommendations in the following respects. First, the results imply that TI is one of these countries' most essential elements of REN development. As a result, these countries may develop more cost-effective, mature, and accessible renewable energy technology. Furthermore, these governments should focus on implementation instead of investing in existing infrastructure. Most countries have advanced technological backgrounds that must be reflected in green energy and developed into REN-valued technologies. However, because of the slow pace of REN innovation, there are fewer renewable energy sources to use. As a result, the development of renewable energy technologies must be prioritized to restructure the energy system and create technological priorities. Second, depending on fossil fuels and nuclear energy could hinder the development and dissemination of renewable technologies, resulting in less attention to renewable technology. A political commitment to phase out nuclear power and fossil fuels could improve this underwhelming performance. Furthermore, these countries emphasize low-carbon electricity but do not specify the sources and technical possibilities. As a result, renewable energy technologies lack innovation policy and cannot be disseminated and adopted. The solid TI foundation has the potential to play a key role in the development of technologies required to reach the ambitious climate goal. Last, offshore and onshore winds, as well as solar, will play an important role in the future energy supply. As a result, integrating REN into the electricity grid is a major endeavor. Moreover, weather-related generation changes must be balanced. The existing electrical infrastructure must be used, and a smart grid with greater REN storage capacity must be built. The REN's variable electricity supply causes power grid upgrades and new communication equipment to detect any obstructions quickly.

Policies should be implemented to promote and safeguard intellectual property rights in the REN sector. To encourage innovation, information exchange, and dissemination, governments should incentivize the patenting of REN technology. It can be accomplished through sponsoring REN initiatives and research programs. Moreover, collaboration among industry, universities, and governments can also help to improve knowledge transfer and technological dissemination. Furthermore, governments should support investment in REN sources to lessen reliance on imported fossil fuels. This can be achieved through REN project incentives like tax credits and subsidies and the development of REN infrastructure. Similarly, regulations should be implemented to encourage energy conservation and efficiency, such as incentives for energy-efficient appliances, construction codes, and energy labeling programs. Smart grid technology can help with effective energy management and waste reduction. Implementing energy efficiency requirements for appliances, buildings, and cars can also help to minimize power use. Finally, governments should prioritize REN infrastructure investment, which may drive economic growth while lowering greenhouse gas emissions. The threshold regression model can be useful in identifying nonlinear relationships; it ensures that the model is appropriate for the data and the research question. Moreover, using control variables can help mitigate the effects of confounding factors. However, the study has limitations, including that it solely focuses on the G10 countries, which may not be typical of other countries or areas with different socioeconomic situations. Furthermore, while the study assumes that technological advancement is the primary driver of REN growth, other variables, like societal acceptability and political will, may also play a role. Future studies can look into how digitalization and artificial intelligence are boosting the growth of REN and identify the conditions under which they are most effective. Moreover, it can investigate the influence of various climate policies, such as carbon pricing or REN mandates, in encouraging REN adoption and lowering carbon emissions.

Credit author statement

Yi-Ming Li. Methodology, Software, review and editing**. Khalid Khan**: Conceptualization, Methodology, Software, Writing original draft. **Aitazaz A Farooque**: Visualization, Data curation, writing original draft preparation. **Muntasir Mushed**: Writing, review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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