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Nonlinear relationship between intellectual property protection and renewable energy innovation in 27 countries

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In the pursuit of global sustainability, renewable energy innovation (REI) plays a pivotal role in mitigating climate change and reducing reliance on fossil fuels. However, the development of renewable energy technologies is fraught with significant challenges, such as high upfront capital costs and technical uncertainties. Intellectual Property Protection (IPP) emerges as a crucial mechanism in this context, promoting knowledge diffusion and incentivising innovation. This study investigates the nonlinear relationship between IPP and REI across 27 countries, which together account for over 90% of global REI, while also considering heterogeneity in resource rents and political stability. In addition, it explores the moderating role of urbanisation in this nonlinear nexus and investigates the threshold effect of financial development (FD). To achieve these objectives, this study employs a fixed effects model and a threshold effects model. Outcomes confirm the existence of an inverted U-shaped relationship. The heterogeneity analysis reveals that this nonlinear effect is present only in groups with above-average resource rent and political stability. Urbanisation strengthens the inverted U-shaped relationship, while FD serves as a threshold variable, with higher FD weakening the negative effects of IPP. Lastly, specific policy recommendations are proposed to enhance renewable energy innovation.

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Introduction

According to IEA (2021), an increasing number of nations are committing to achieve net-zero emissions in the coming decades; however, fully realising these commitments remains a challenge, particularly in reaching the 2050 net-zero target. Although attaining this target is still a long way off, renewable energy has made significant strides. For example, the capacity of renewable electricity hit historic highs in 2022 (Renewables - Energy System, 2023). A number of policies, such as China's 14th Five-Year Plan and the United States' Inflation Reduction Act (IRA), are being implemented to encourage the growth of renewable energy (Renewables - Energy System, 2023).

Since most renewable energy resources are heavily affected by climatic variability, certain projects carry substantial risks. Furthermore, green projects require substantial upfront capital and face considerable uncertainty (Lee & Zhong, 2015; Pfeiffer & Mulder, 2013). As argued in Lee & Zhong (2015), reaching the breakeven point often requires a considerable time horizon, limiting renewable energy from being widely adopted. However, advances in green energy can improve the output of renewable energy, providing opportunities to raise demand while lowering expenses and risks (Luo et al., 2023). As a result, prioritising renewable energy innovation has become a key focus for governments and researchers worldwide.

Intellectual property rights protection (IPP) can influence innovation. As a comprehensive legal framework, IPP safeguards knowledge against duplication and encourages knowledge creation (Papageorgiadis & Sofka, 2020). By allowing innovators to benefit from the commercial rewards of their inventions, strengthening IPP motivates local businesses to increase research and development (R&D) investment. However, overly stringent IPP can hinder further innovation by stifling competition and fostering complacency (Hou et al., 2023).

Innovation is a vital component of achieving sustainable development (Innovation Needs in the Sustainable Development Scenario - Clean Energy Innovation - Analysis, 2020). While there are significant upfront capital expenses and technical obstacles associated with renewable energy, these problems can be lessened with the advancement of technology. IPP promotes the spread of knowledge and offers a supportive platform for technological innovation. However, recent research has primarily focused on the linear impact of IPP (Hudson & Minea, 2013; Lerner, 2009) or its effect on overall innovation (Allred & Park, 2007; Chen & Puttitanun, 2005; Gangopadhyay & Mondal, 2012), leaving the nonlinear effects of IPP specifically on renewable energy innovation (REI) and its underlying mechanisms underexplored. Understanding the role of IPP in influencing REI is therefore crucial for evaluating its effectiveness in fostering technological progress, promoting green transitions, and advancing long-term sustainability.

Considering the above motivation, this study collected a balanced panel dataset of 27 countries between 1998 and 2017, based on data availability, and conducted the analysis using a fixed effects model. The nonlinear effect of IPP on REI was analysed by introducing the squared term of IPP. Then, heterogeneity analysis was carried out and the sample was categorised according to the median values of political stability and resource rent. Moreover, a moderating effect model was used to examine the mechanism behind the nonlinear effect. Finally, a threshold effect model was introduced to analyse the threshold effect of financial development (FD). The results reveal an inverted U-shaped relationship between IPP and REI, which persists in country groups characterised by above-average resource rents and political stability. Moreover, urbanisation is found to amplify this curvilinear relationship, while FD serves as a threshold factor in shaping the relationship between IPP and REI.

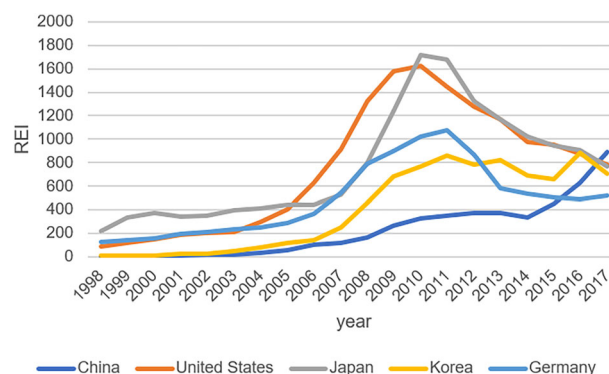


Fig. 1 REI for the top five countries as ranked in 2017 from 1998 to 2017.

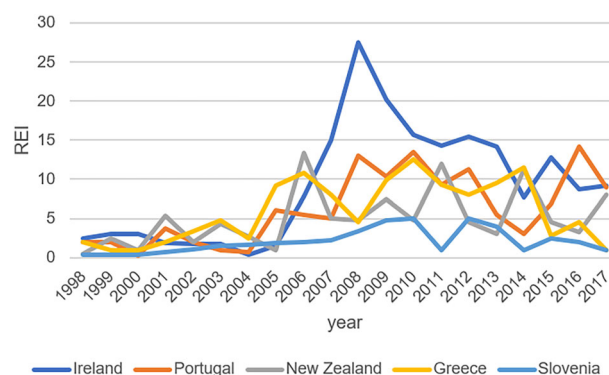


Fig. 2 REI for the bottom five countries as ranked in 2017 from 1998 to 2017.

The proportion of REI from the sample countries relative to global REI exceeded 90% across all observation years according to the OECD statistical database (OECD, 2024), demonstrating the representativeness of the sample in terms of REI. Additionally, the development trends of REI in the top five and bottom five countries as ranked in 2017 are presented in Figs. 1 and 2. As shown, Korea, the United States, Germany, and China consistently ranked high across almost all observation years. Notably, 2011 marked a significant turning point, as REI began to decline, eventually exhibiting an overall downward trend. One possible explanation for this could be the persistently falling global crude oil prices, which peaked at over \$100 per barrel between 2011 and 2013 before steadily declining with occasional spikes (Bp, Statistical, 2020). The induced-innovation effect (Herman & Xiang, 2019) indicates that the decline in fuel energy prices could have made renewable energy R&D less attractive, thereby reducing REI.

In comparison with previous research, this study presents several novelties. First, in terms of study content, previous studies on the relationship between IPP and innovation have mostly relied on a database developed by Park & Ginarte (1997), which offers quinquennial data from 1975 to 2000. However, the most recent database, published by Papageorgiadis et al. (2014) and Papageorgiadis & Sofka (2020), spanning the 20 years from 1998 to 2017, has not been widely used by academics. Furthermore, no prior research has generally had examined the effect of IPP on REI. In order to fill this knowledge gap, this work adds to the corpus of research on renewable energy by empirically examining the influence of IPP on REI. Second, although nonlinear effects have been documented in the contexts of IPP and innovation (Hudson & Minea, 2013), scientific output (Jia et al., 2025), entrepreneurship (Hou et al., 2023), and emissions (Cheng et al., 2024), the nonlinear nexus between IPP and REI remains unexplored. This study extends the existing

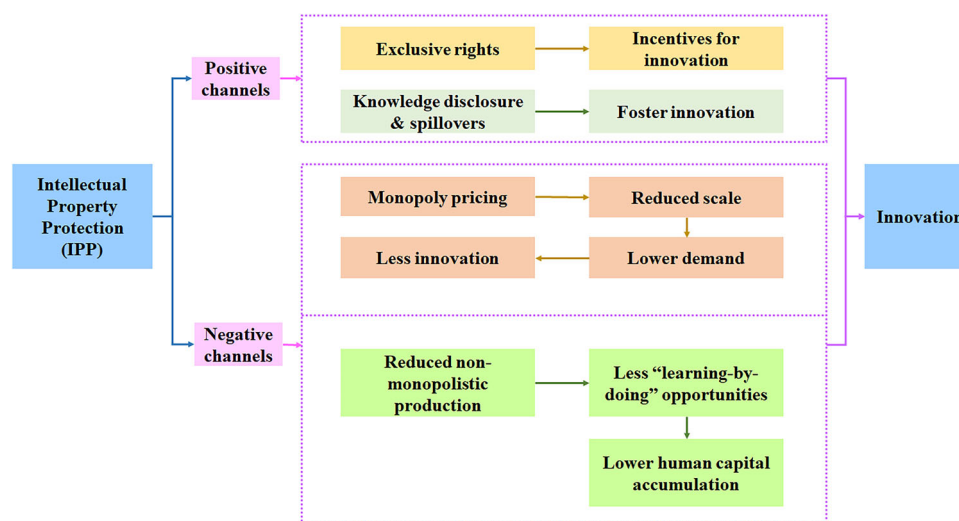


Fig. 3 Summary of theoretical framework.

literature by examining whether IPP exerts an inverted U-shaped effect on REI. Third, a quadratic moderating effect model was employed to explore the transformation mechanism of the inverted U-shaped effects of IPP in relation to urbanisation. This provides insights into optimising the role of IPP and understanding how IPP impacts REI, leading to favourable external situations. Lastly, the threshold effect of FD is examined in this study.

The subsequent sections are structured as follows: the literature review summarises relevant studies; the methods and data section describes the research design and data sources; the empirical results section presents and discusses the findings; and finally, the conclusion provides a summary along with recommendations.

Literature review

Theoretical background. IPP refers to the laws and regulations created to protect creators' rights. IPP, which grants exclusive rights, guarantees that authors or owners may manage how their works are used, distributed, and marketed. This promotes innovation and creativity while guarding against infringement or unapproved usage. According to Papageorgiadis & Sofka (2020), IPP primarily involves imitation costs, such as servicing costs, property rights costs, and monitoring transaction costs. IPP fosters innovation by granting the opportunity to financially benefit from holding a monopoly position in commercialisation (Raiser et al., 2017; World Trade Organisation (WTO), 2014). Besides that, patent holders are often compelled to share their knowledge rather than keep it confidential, which further promotes innovation (Allred & Park, 2007). Therefore, information spillovers ought to encourage innovation.

Two theoretical strands attempt to explain the depressed effect of IPP: one takes scale effects into account, while the other does not. Regarding the former, Furukawa (2007) explained the nexus with the scale effect, suggesting that higher levels of IPP contribute to monopolistic pricing, which in turn reduces industrial scale and accumulated experience. A decreased scale lessens the demand for goods, which decreases the motivation to innovate. In short, high IPP lowers the productivity of the final sector, reduces innovation, and hampers economic growth. In terms of the latter, Furukawa (2010) investigated the link between IPP and innovation by developing an endogenous growth model without scale effects. Strengthening IPP was found to reduce the production of non-monopolistic goods, leading to fewer opportunities for learning by doing. As a result, this hinders the

accumulation of human capital. Figure 3 summarises the theoretical framework.

The IPP-REI nexus. While outlining the theoretical background may be straightforward, empirical research is needed to determine the impact of IPP on REI. Existing scholars have focused on the impact of IPP on innovation but have not specifically examined its effects on REI. Moreover, there was no consensus regarding the impact of IPP on innovation due to differences in samples and econometric methods.

Some scholars have argued that IPP increases innovation. For example, Sweet & Maggio (2015) proposed that the Economic Complexity Index (ECI) reflects the potential for innovation in relation to economic growth and the efficient manufacture and export of novel goods. As such, this index captures innovations embedded in the expansion of the product frontier. They concluded that IPP increased ECI, and this was significant only in developed countries when conducting subsample analysis. Using annual patent grant volume as a proxy for IPP, Xu et al. (2022) concluded that IPP enhanced the impact of subsidies on firms' ability to innovate in China. Legal protection was found to encourage firms to develop and invest in new areas without expecting immediate returns.

Using a quasi-natural experiment, Gao & Zhao (2023) examined how IPP policy affected Chinese firm-level creativity and discovered that IPP fostered innovation. This was achieved by lessening funding restrictions and lowering R&D spillover losses. Similarly, Qayyum et al. (2022) employed provincial data from China to explore the nexus between IPP and innovation. IPP was measured by the ratio of property rights transactions to GDP, while innovation was represented by invention patent grants. The study found that a one-unit increase in IPP led to a 3.83% rise in innovation. This occurred because higher IPP enabled regional businesses to benefit from the commercial rents of innovation, thereby prompting them to drive up R&D spending. A similar positive effect of IPP on innovation was also observed in sub-Saharan Africa (Amankwah-Amoah & Medase, 2024), Saudi Arabia (Sarabdeen & Ishak, 2024), China (Cao et al., 2023) and Yangtze River Delta Region (Gao et al., 2020).

Conversely, past studies have also documented a negative relationship. Lerner (2009) analysed the IPP-innovation nexus using data from the top 60 GDP-ranked countries and found that stronger IPP actually reduced innovation, as represented by

patent applications from residents. Strengthening IPP also did not lead to an increase in innovation. The researchers attributed this to the use of patent applications by residents as an inaccurate proxy for innovation, as well as the limited time frame of the study.

A U-shaped link has also been frequently reported in extant studies. Hudson & Minea (2013) investigated the connection between IPP and innovation and concluded that IPPs that were more stringent had a negative impact on innovation. The connection took a U shape when the squared term of IPP was introduced. Stricter IPPs had the main effect of hindering innovation. Furthermore, the U-shaped relationship may be influenced by GDP per capita. Allred & Park (2007) discovered a U-shaped relationship between IPP and innovation, proxied by domestic patenting. This occurred because, under weak IPP, imitation was restricted, while under strong IPP, appropriability was enhanced, encouraging knowledge disclosure and further innovation. Chen & Puttitanun (2005) employed the database developed by Park & Ginarte (1997) as the proxy of IPP and examined the nexus between economic growth, IPP, and innovation for 64 developing countries. They came to the conclusion that when the economy expanded, the IPP level first declined but then rose upon reaching a tipping point. Moreover, IPP refuted the prevailing wisdom by fostering indigenous innovation in developing nations. Jia et al. (2025) discovered an inverted U-shaped nexus between IPP and scientific output. While excessive IPP may monopolise resources and limit knowledge exchange, which would impede scientific advancement, moderate IPP can encourage more scientific engagement. Hou et al. (2023) argued for a U shape between IPP and entrepreneurship: IPP can encourage entrepreneurship in its early stages, but as it gets stricter, the cost of gaining expertise will unavoidably rise. As a result, there are fewer chances to generate new information, limiting the diffusion of existing knowledge and ultimately curbing entrepreneurial potential. Cheng et al. (2024) observed an inverted U-shaped nexus between IPP and emissions. Initially, IPP promotes investment in manufacturing processes and technologies characterised by high emissions. However, as IPP strengthens and environmental awareness increases, it increasingly supports the development and dissemination of low-carbon products and technologies.

In more advanced economies, the effects of IPP appear to be more pronounced. Apart from promoting innovation, IPP is essential to the establishment of a functional market system. Papageorgiadis & Sharma (2016) combined IPR regulation strength (Park & Ginarte, 1997) and enforcement (Papageorgiadis et al., 2014) to provide a more comprehensive impact of IPP. They contended that there was a U-shaped link between innovation and IPP, with more patents produced in response to stronger IPP. Gangopadhyay & Mondal (2012) introduced an economic theoretical model and ultimately analysed the results, demonstrating the existence of an inverted U-shaped relationship between IPP and innovation. On one hand, stronger IPP was found to increase the anticipated benefits from developments; on the other hand, it reduced knowledge spillover, thereby constraining innovation.

The Urbanisation-REI nexus. The influence of institutional contexts has produced a range of results in extant literature due to variations in study periods, sampling countries, and proxies for innovation. For instance, Bertinelli & Black (2004) introduced the urban economics framework and emphasised the importance of urbanisation for development. Population movement to urban regions entailed the accumulation of human capital, thereby

driving technological advancements in the process. Wang et al. (2024) examined the impact of urbanisation on REI in 60 countries and concluded that urbanisation was beneficial for REI. As urbanisation rose, human capital and economic growth congregated, further stimulating the development of new technology. Chen et al. (2020) argued that urbanisation spurred regional innovation in Chinese provinces.

Urbanisation can facilitate the convergence of key production factors, such as venture capital, creative talent, and skilled labour, leading to a technological spillover effect for green innovation. The growth of urbanisation facilitates knowledge diffusion, reducing barriers to communication and education and encouraging the emergence of novel practices (Rosenthal & Strange, 2004). Based on the Chinese sixth national census, Lyu et al. (2019) showed that urbanisation aided in the knowledge economy's growth. Urbanisation, which is characterised by the movement of talent and cultural variety, has greatly aided in the advancement of city innovation. In particular, cultural diversity can enhance creativity by attracting and concentrating human resources within cities. A similar positive sign between urbanisation and REI was also documented in 87 economies by Zheng et al. (2021). However, Li & Shao (2021) reported a negative nexus between urbanisation and REI in a subcategory analysis for OECD countries.

Literature on FD and REI. Innovation in renewable energy, in contrast to conventional fuels, has been found to face significant financial limitations (Wen et al., 2022). Levine et al. (2017) examined the impact of FD on innovation across 94 economies and concluded that FD increased innovation. By removing credit barriers that prevent capital from flowing to more profitable projects, FD can encourage R&D financing while also facilitating innovation activities (Hsu et al., 2014). However, some studies have reported a negative impact. Zhu et al. (2020) examined the impact of FD on innovation based on 50 countries and concluded that FD impeded innovation. Excessive financial operations have the potential to divert resources towards the financial sector rather than productive activities, thereby inhibiting innovation (Tobin, 1984). Besides that, higher financial activities lure employees—particularly skilled workers—into low-productivity sectors offering high salaries (Boustanifar et al., 2018), which in turn slows down innovation.

Literature gap. Although scholars have made substantial progress in examining IPP and REI, several gaps remain. First, while previous research has examined how IPP affects innovation, little attention has been given to its specific impact on REI, especially when proxied by patent applications in renewable energy technologies. This omission is important, as REI plays a central role in promoting green technological progress and advancing sustainable development. Moreover, existing studies have predominantly assumed a linear relationship, overlooking the possibility that IPP may exert nonlinear influences on REI. Second, the moderating role of urbanisation in the nonlinear relationship between IPP and REI remains under-researched. Lastly, little discussion has addressed the threshold effect of FD in shaping the influence of IPP on REI.

Therefore, the following hypotheses were proposed:

Hypothesis 1: There exists an inverted U-shape link between IPP and REI.

Hypothesis 2: Urbanisation can steepen the inverted U-shape link between IPP and REI.

Hypothesis 3: FD acts as a threshold variable in the nexus between IPP and REI.

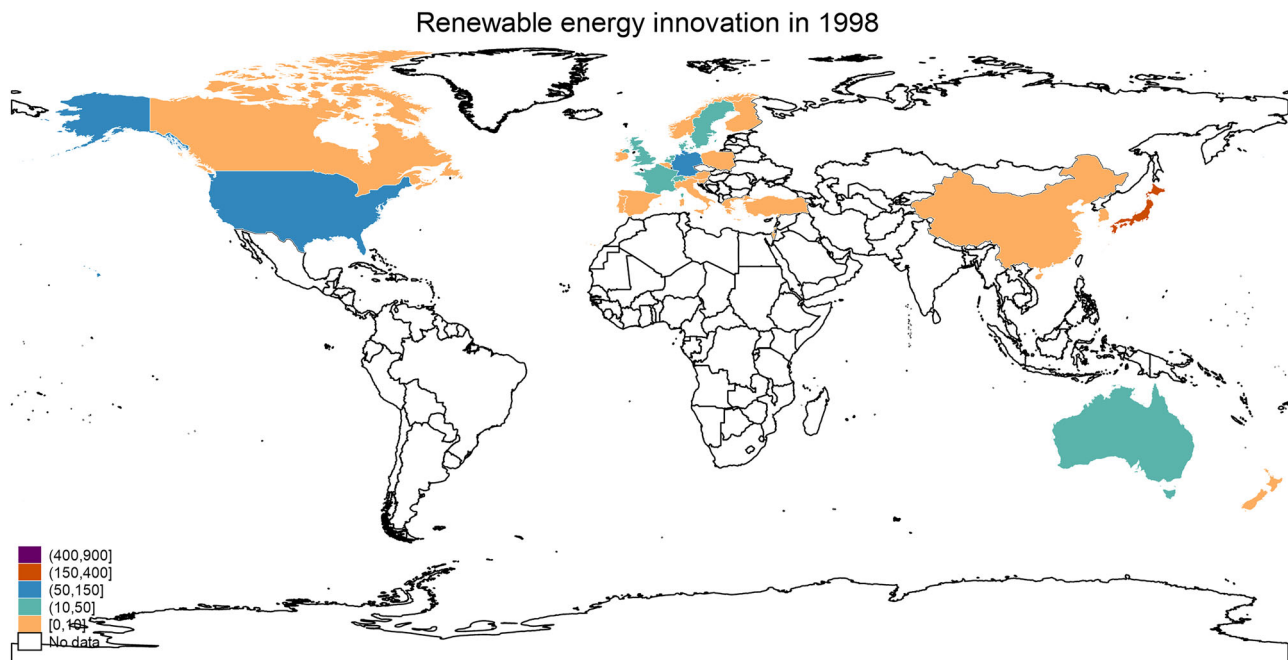


Fig. 4 Renewable energy innovation in 1998.

Methods and data

The empirical model. To find out the impact of IPP on REI, this study adopted Model (1) to explore the nexus between IPP and REI by referring to Chen et al. (2022) and Lee & Ho (2022). If the parameter of α_1 is positive, it can be inferred that a positive link exists between the explanatory and explained variables, and vice versa.

$$REI_{it} = \alpha_0 + \alpha_1 IPP_{it} + \sum_{a=1}^3 \beta_a CC_{it} + V_i + \varepsilon_{it} \quad (1)$$

where REI is the explained variable, capturing the degree of REI. IPP is the explanatory variable, reflecting the level of intellectual property protection. CC is a set of control variables including FDI, Fiscal, and Trade. i, t is country and years, respectively. V_i refers to the fixed effects, and ε_{it} denotes the error term. As per Lee et al. (2024a, 2024b), this model incorporates only individual fixed effects. Furthermore, year dummies can sometimes exacerbate multicollinearity and undermine the reliability of coefficient estimates, according to Lee et al. (2024a).

By incorporating the squared term of IPP, Model (2) was established. If the parameter of α_2 was positive and statistically significant, this would indicate a U-shaped link. Conversely, if α_2 was negative and significant, it would suggest an inverted U-shaped link. If the computed parameter α_2 was significantly positive, then hypothesis 1 would be validated. Model (2) is presented below.

$$REI_{it} = \alpha_0 + \alpha_1 IPP_{it} + \alpha_2 IPP_{it}^2 + \sum_{a=1}^3 \beta_a CC_{it} + V_i + \varepsilon_{it} \quad (2)$$

where IPP2 is the squared term of IPP while other variables are in line with model (1).

Data. The empirical sample consisted of 27 countries ranging from 1998 to 2017, constrained by data availability. The REI data was constructed from the OECD statistical database (OECD, 2024) while IPP data was sourced from (Papageorgiadis et al. (2014) and Papageorgiadis & Sofka (2020). Control variables were obtained from the World Development Indicators (WDI). Merging these datasets and ensuring a balanced panel dataset resulted

in a database comprising 27 countries over 20 years, yielding 540 observations.

Explained variable. Innovation is often measured by R&D expenditures, the number of patents (Chen & Puttitanun, 2005), publication-based indicators. Publications capture research activities; however, their linkage to real-world applications is often insufficient (Zhang et al., 2025). Besides, cross-country differences in financing efficiency may substantially influence the extent to which R&D spending translates into innovation (Zhang et al., 2025). Moreover, most developing countries do not have data on R&D expenditures, patents can be used as a cross-national proxy for innovation (Chen & Puttitanun, 2005). While patents do not capture all types of innovation and not all patent signify a true technological breakthrough, they nonetheless provide publicly available information about new technologies, methods, or products. This information is valuable for tracking technological development trends and assessing the scope and depth of innovation. Moreover, patent applications are preferred as a proxy for REI over awarded patents, since the granting process of the latter is often lengthy and differs across countries (Bhuiyan et al., 2025). For REI, this study employed the number of patent applications related to renewable energy, following the approach of Wang et al. (2024). The data was sourced from the OECD statistical database (OECD, 2024), and $\log(1 + \text{data})$ was used as the REI measure.

The development of the number of patent applications for renewable energy for the years 1998 and 2017 is depicted in Figs. 4 and 5. A larger number of patents indicates higher REI; the lowest range was 0–10, and the highest was 400–900. There had been a notable improvement in REI from 1998 and 2017, as evident from the comparison between Figs. 4 and 5.

Explanatory variable. The explanatory variable was the strength of IPP, which referred to imitation costs. Taking into account the reliability and credibility of the data, this study employed the IPR index released by (Papageorgiadis et al. (2014) and Papageorgiadis & Sofka (2020) and referring to Viglioni et al. (2024). Incorporating new proxies from diverse information sources, this index encompassed a wide range of property rights protection costs, or “transaction costs”, arising from the patent system of a

Renewable energy innovation in 2017

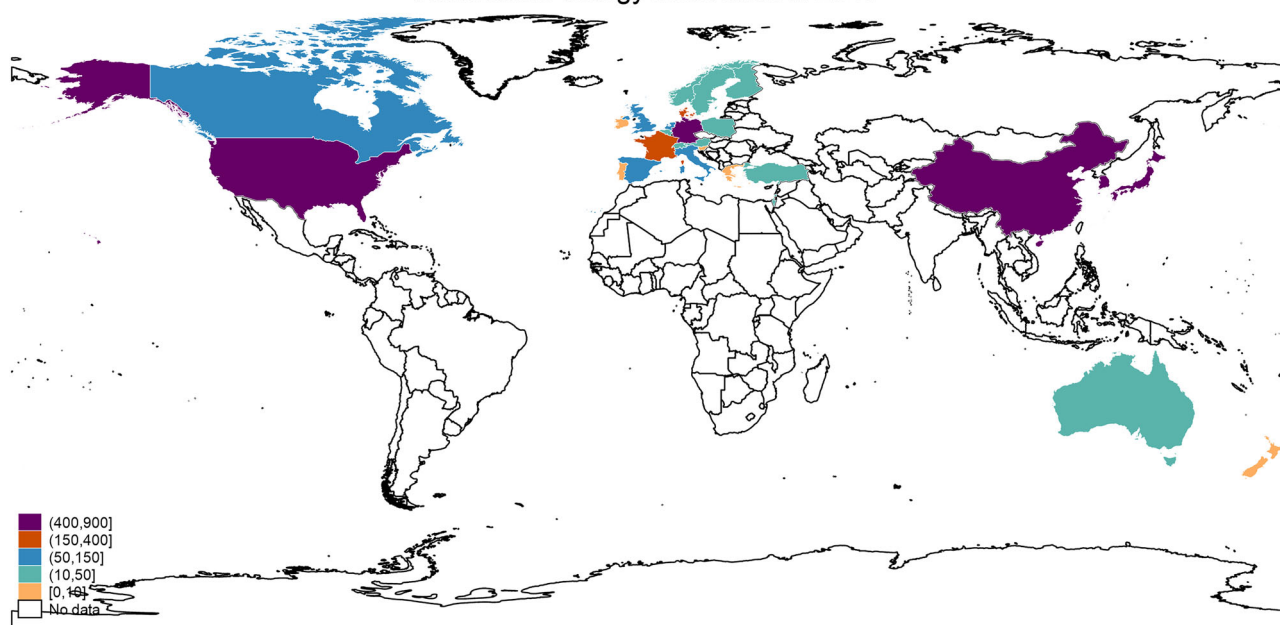


Fig. 5 Renewable energy innovation in 2017.

specific nation. This index ranged from 0 to 10, with higher values indicating greater imitation costs, such as servicing costs, property rights costs, and monitoring transaction costs (Papa-georgiadis & Sofka, 2020).

Control variable. In accordance with previous literature, this study controlled for a certain set of country-level factors.

- (1) FDI was proxied by FDI net inflows as a percentage of GDP. FDI could impose a significant impact on REI. FDI accelerates the transition to sustainable technologies and makes innovation activities more environmentally-friendly through technology transfer and knowledge sharing (Luo et al., 2021; Raihan et al., 2025a; Riaz et al., 2025; Yin et al., 2022). Besides that, FDI has been documented to aid in the promotion of innovation in geothermal energy (Li & Shao, 2021).
- (2) Fiscal was denoted by general government consumption expenditure as a share of GDP. According to the externality theory, government funding is expected to encourage private businesses to increase their innovation activities (Li et al., 2021).
- (3) Trade was proxied by the ratio of trade activities to GDP. Trade liberalisation makes it easier for components to move across international boundaries, thereby reducing costs for renewable energy projects (Hussain et al., 2021; Mandelman & Waddle, 2020). Besides that, the movement of goods across borders promotes the acquisition of green technologies and the flow of green raw materials—all of which help bring forth new green inventions (Zhang et al., 2022).

The variable descriptions and descriptive statistics are displayed in Table 1. The mean value of REI was 3.518, while IPP had a mean value of 7.065. The IPP maximum and minimum values were 2.6 and 9.7, respectively, indicating considerable variation in the level of IPP across countries.

Empirical results

Pre-benchmark tests. Table 2 displays the correlation diagnostics results. The table indicates that IPP and REI may have a positive

association. The maximal VIF value of 1.44, together with the low correlation coefficients, indicates a minimal risk of multicollinearity. Furthermore, as the results of the slope heterogeneity (SH) test included in Table 3 were significant at the 1% level, they corroborated the existence of heterogeneity. Additionally, in order to examine the existence of cross-sectional dependence (CD), this study adopted the Pesaran CD, Pesaran scaled LM, and Breusch-Pagan LM tests (Breusch & Pagan, 1980; Pesaran, 2004, 2004). The significant outcomes presented in Table 4 suggest that there was CD among the variables. The stationarity of variables was tested using the unit root test developed by Pesaran (2007). REI, IPP, and FDI were found to be stationary at the level, while Fiscal and Trade became stationary at the first difference, as indicated by the significance levels presented in Table 5.

Baseline model. In this section, Model (2) was empirically tested to analyse the impact of IPP on REI. Table 6 displays the baseline model results in columns (1) through (3), where control variables were progressively added. The indications of IPP and IPP2, with IPP being positive and IPP2 being negative, remained significant when comparing the model without control variables to the one including all controls. Column (3) of Table 6 represents the final outcomes.

It can be observed that the parameters for IPP and IPP2 were 0.927 and -0.099 , respectively, both significant at the 1% level. Therefore, hypothesis 1 was validated. The inverted U-shaped association between IPP and REI was provisionally validated by this parameter. Before reaching the inflection point, IPP was beneficial to the REI; once past it, the opposite was true. Figure 6 shows an inverted U-shaped fitting curve to further support this link. The nonlinear fitted curves were shown to be more effective in explaining the relationship between IPP and REI. In line with (Lee & Yan, 2024), this study conducted a U-shaped test and the outcomes are presented in Table 7.

According to the results, the upper bound and lower bound slopes were -0.988 and 0.413 , both significant at the 1% level. Additionally, the overall test, significant at 1%, confirmed the existence of curvilinear relationship. The turning point of 4.693 fell within the observed range of IPP, allowing for the observation

Table 1 variable descriptions and descriptive statistics.

Label/ Abbr	Variable	Source	Description	Mean	Min	Max
REI	Renewable energy innovation	OECD statistical database (OECD, 2024).	Log (1+patent applications related to renewable energy)	3.518	0.223	7.448
IPP	intellectual property protection	IPR index released by (Papageorgiadis et al. (2014) and Papageorgiadis & Sofka (2020))	Original value	7.065	2.6	9.7
FDI	Foreign direct investment	WDI	Original value	4.81	-7.417	86.48
Fiscal	Fiscal policy	WDI	Original value	19.2	10.42	27.93
Trade	Trade	WDI	Original value	76.55	18.13	227.7

Table 2 Correlation diagnostics.

variable	REI	IPP	FDI	Fiscal	Trade
REI	1				
IPP	0.231	1			
FDI	-0.091	0.196	1		
Fiscal	0.023	0.309	0.07	1	
Trade	-0.256	0.187	0.542	0.139	1
VIF	-	1.15	1.44	1.12	1.44

Table 3 SH test.

Test	Statistics
$\Delta\sim$	11.119 ^a
$\Delta\sim_{adj}$	13.290 ^a

^a $p < 0.01$, Null Hypothesis: slope coefficients are homogenous.**Table 4 CD tests.**

Test	Statistics
Pesaran CD test	23.947 ^a
Pesaran scaled LM test	31.641 ^a
Breusch-Pagan LM test	1763.79 ^a

^a $p < 0.01$.**Table 5 Unit root test.**

Variable	I(0)	I(1)	Level of integration
REI	-3.381 ^a		I (0)
IPP	-3.048 ^a		I (0)
FDI	-3.646 ^a		I (0)
Fiscal		-3.722 ^a	I (1)
Trade		-3.532 ^a	I (1)

^a $p < 0.01$.**Table 6 Baseline outcomes.**

	(1)	(2)	(3)
IPP	1.637 ^a (0.35)	1.418 ^a (0.31)	0.927 ^a (0.28)
IPP2	-0.157 ^a (0.03)	-0.124 ^a (0.02)	-0.099 ^a (0.02)
FDI	-0.000 (0.01)	0.008 (0.01)	-0.002 (0.00)
Fiscal		0.336 ^a (0.03)	0.285 ^a (0.03)
Trade			0.034 ^a (0.00)
constant	1.250 (1.20)	-5.561 ^a (1.22)	-3.649 ^a (1.12)
Fixed effect	YES	YES	YES
N	540	540	540
R ²	0.748	0.800	0.838
adj. R ²	0.734	0.788	0.828

Standard errors in parentheses.

^a $p < 0.01$.

of a complete inverted U-shaped curve. In addition, Table 8 presents the time points when countries crossed the turning point.

The results showed a curvilinear link between IPP and REI, suggesting that the protection level would affect how IPP impacts innovation. Specifically, a low level of IPP was found to positively impact REI, while a higher level of IPP had a negative influence.

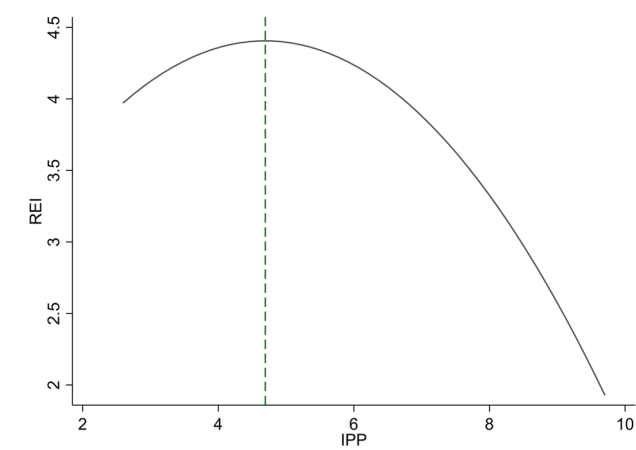


Fig. 6 The link between IPP and REI.

Table 7 The result of Inverse U shape test.		
	Lower bound	Upper bound
Interval	2.599	9.7
Slope	0.413	−0.988
t-value	2.357	−5.433
P > t	0.009	4.30E-08
The p-value of Overall Inverse U shape = 0.009. Inflection point = 4.693.		

Table 8 Time point for countries to cross the turning point.	
country	Year
China	Never
Greece	Never
Italy	2016
Korea	2000
Poland	2011
Slovenia	2001
Turkey	Never
Countries absent from the list had crossed the turning point prior to the study period. For those present on the list, the turning point was crossed in their respective specified years. Countries annotated as ‘never’ had not reached the turning point by the end of 2017.	

Before the tipping point, IPP promoted REI by providing companies with a secure environment to protect their ideas and recover R&D investments.

As discussed in Section 2.1, IPP holders benefit financially from monopolising commercialisation efforts (Raiser et al., 2017; World Trade Organisation (WTO), 2014). This incentivises innovators to invest in renewable technologies without fear of imitation. However, once IPP is strengthened beyond the tipping point, its positive effects would diminish. Excessive IP protection may slow innovation, restricting the diffusion of new technologies, curbing the commercialisation of inventions, and stifling competition (Hou et al., 2023), as firms become less motivated to innovate after securing a dominant market position. Furthermore, strong IPP can deter new entrants, particularly smaller firms, due to the high costs of acquiring or licensing patents (Acs & Sanders, 2012; Reed et al., 2012). In industries like renewable energy, where firms often work on similar technologies, elevated IP barriers can stifle the exploration of new ideas. This inverted U-shaped relationship aligns with the findings of Jia et al. (2025), who identified such a nexus between IPP and scientific output, and Cheng et al.

(2024), who reported a similar relationship between IPP and emissions.

Trade was positively connected with REI. By supplying low-pollution intermediaries and enabling the dissemination of cutting-edge technology, international trade can promote the development of novel renewable energy sources (Wang et al., 2021). Greater trade openness can promote domestic REI if the local economy is capable of absorbing the possible benefits of commerce (Canh et al., 2019). A similar positive sign was documented in Qayyum et al. (2022) for China.

Fiscal was found to increase REI in the sample countries. According to Carley et al. (2017), Rasheed et al. (2025) and Shen & Luo (2015), grants from governments stimulate renewable energy projects by lowering upfront expenditures. Tax incentives lower the cost of financing, thereby boosting equity investors’ profits (Shen & Luo, 2015) and increasing investors’ interest in green projects. Hassett & Metcalf (1995) further showed that the likelihood of investing in the renewable sector might rise by 24% with a 10% increase in tax policy. The positive nexus between Fiscal and REI is consistent with the findings of Marques & Fuinhas (2012) for European countries and Bird et al. (2005) for United States.

FDI was found to be negatively correlated with REI, though the relationship was insignificant, indicating that FDI did not contribute to an increase in REI. This outcome is consistent with research conducted by Zhang et al. (2022) for China. This could be explained by the pollution haven effect; when multinational corporations invest across borders to evade costly environmental legislation and abatement measures in their own countries, this prevents the spread of green knowledge (Ahmed et al., 2025; Fu et al., 2020; Rasheed et al., 2024; Shen et al., 2020).

Robust test

Omit control variable. Good governance was found to be beneficial for REI. Benavides-Franco et al. (2023) concluded that good governance fosters renewable energy in Project Finance. They clarified that securing abundant financing requires a high degree of transparency regarding the project’s specific characteristics, while good governance is essential for gaining investors’ trust. Islam et al. (2022) and Wang et al. (2024) argued that bad governance damages ecological sustainability and suppresses REI. Bad governance shifts resources to address violent episodes. Therefore, this study constructed an IQ index by averaging five indicators from ICRG: (1) law and order, (2) corruption control, (3) democratic accountability, (4) bureaucratic quality, and (5) government stability, following Luo & Sun (2024). This new control variable was included in the model, and the results are reported in column (1) of Table 9. The parameter of IPP and IPP2 were positive and negative, further validating Hypothesis 1.

Other estimate technique. The Dynamic Common Correlated Effects Model (DCCE) proposed by Ditzen (2019) can address issues related to cross-sectional dependence and slope heterogeneity, as noted by Hondroyannis et al. (2022). Taking into account the possible heteroskedasticity and autocorrelation problems, this study adopted feasible generalised least squares (FGLS) for the robustness test, in line with the research conducted by Liu et al. (2023). In line with Aslan et al. (2024) and Voumik et al. (2024), this study also adopted Driscoll and Kraay’s (DK) standard errors (Driscoll & Kraay, 1998) technique. Data with cross-sectional “spatial” and temporal dependence may yield more robust outcomes with DK standard errors. The outcomes reported in columns (2)– (4) of Table 9 indicated that the parameter of IPP was significantly positive, while that of IPP2 was significantly negative. Therefore, the basic outcomes were robust.

Table 9 Robust test.

	(1) Omit control variable	(2) DCEE	(3) FGLS	(4) DK standard errors	(5) Exclude the influence of outliers
IPP	0.824 ^a (0.28)	6.534 ^b (2.92)	0.588 ^a (0.07)	0.927 ^a (0.17)	0.631 ^b (0.26)
IPP2	−0.085 ^a (0.02)	−0.390 ^b (0.17)	−0.039 ^a (0.01)	−0.099 ^a (0.01)	−0.075 ^a (0.02)
FDI	−0.004 (0.00)	−0.011 (0.02)	0.001 ^c (0.00)	−0.002 (0.01)	−0.001 (0.00)
Fiscal	0.262 ^a (0.03)	0.033 (0.05)	0.043 ^a (0.01)	0.285 ^a (0.02)	0.288 ^a (0.02)
Trade	0.031 ^a (0.00)	−0.002 (0.01)	−0.004 ^a (0.00)	0.034 ^a (0.01)	0.033 ^a (0.00)
IQ	−0.328 ^a (0.10)				
constant	−0.328 (1.49)	−28.062 ^b (12.81)	0.698 ^b (0.28)	−5.806 ^a (0.70)	−2.881 ^a (1.03)
Fixed effect	YES				YES
N	540	540	540	540	500
R ²	0.842				0.852
adj. R ²	0.832				0.843

Standard errors in parentheses.
^ap < 0.1, ^bp < 0.05, ^cp < 0.01.

Exclude outlier. According to Oyekola et al. (2024), the influence of outlier samples may have an impact on the robustness of the outcomes. The OECD statistical database (OECD, 2024) provides data on renewable related patent applications, where China and the US recently scored highly. Data from EIA (2022) also showed that energy production from renewable sources in the U.S. and China amounted to 16.368 and 14.734 quadrillion Btu, respectively, while France, in third place, produced 3.417 quadrillion Btu. This highlights the crucial role that the U.S. and China play in renewable energy production. This section excluded these two countries to check the existence of an inverted U-shaped relationship in the remaining sample. The outcomes reported in columns (5) of Table 9 show a positive coefficient for IPP and a negative coefficient for IPP2, confirming the existence of an inverted U-shaped link.

Heterogeneity test. Natural resource endowments, extraction costs, market accessibility, economic structures, and government stability vary significantly across countries. These differences result in varying levels of natural resource rents and governance quality, which make these issues important to take into account. This study further conducted a heterogeneity analysis to examine regional differences in the IPP-REI link. Based on whether the sample was above or below the median, the samples were divided into groups of high and low natural resource rents, as well as high and low government stability.

The heterogeneity test results for natural resources are presented in columns (1) and (2) of Table 10. The results show that the coefficients for IPP2 and IPP were −0.163 and 1.788, respectively, significant at the 1% level, within high-natural resource rent regions. Nevertheless, these factors were not statistically significant in low-natural resource rent groups. The results of this test indicate that the curvilinear relationship in the IPP-REI holds only in high-nature resource contexts. A possible explanation is that an abundance of natural resources could function as a “blessing”, facilitating the establishment and development of the local economy (Nawaz et al., 2019). High-natural resource rent groups typically experience higher levels of economic growth and FD. Significant financial resources generated from natural resource rents could be directed toward a variety of industries, including the finance sector. Nations with substantial resource rents have the opportunity to establish sovereign wealth funds and accumulate large amounts of capital (Okolo et al., 2024). Moreover, an abundance of resources generates foreign exchange earnings and increases exports, which in turn stimulates economic growth (Okolo et al., 2024). In

contrast, low-natural resource rent groups lack these advantages, which results in an insignificant impact.

The heterogeneity test outcomes for government stability are presented in columns (3) and (4) of Table 10. Similar to the previous heterogeneity test, the curvilinear relationship was found to exist only for high-government stability groups. According to the institution-based concept, innovation activities cannot occur without sound governance (He & Tian, 2020). As argued by Crain & Crain (2006), elements contributing to instability, such as terrorist attacks, are negative to economic activities because they create psychological capital loss and discourage foreign investment. The uncertainty associated with an unstable environment hinders green innovation technologies advancement (Zheng et al., 2021) and delays investment (Julio & Yook, 2012), especially in capital-intensive sectors like renewable energy.

Mechanism test

Moderating effect. The direct effects of IPP on the REI were examined in the previous model to analyse the moderating role of urbanisation. Following this, this study introduced Model (3) as below.

$$REI_{it} = \alpha_0 + \alpha_1 IPP_{it} + \alpha_2 IPP2_{it} + \alpha_3 IPP_{it} * Urban_{it} + \alpha_4 IPP2_{it} * Urban_{it} + \alpha_5 Urban_{it} + \sum_{a=1}^3 \beta_a CC_{it} + V_i + \varepsilon_{it} \quad (3)$$

where the meanings of the other variables remained the same as previously mentioned. Here, Urban was the moderator variable, representing the level of urbanisation. This moderating analysis primarily focused on the curvature of the U-shaped relationship, the presence of any reversal, and the shifting of the turning point within a quadratic term moderation model. According to Haans et al. (2016), the sign of α_4 determines whether the initial U-shaped relationship is steepened or flattened. A negative sign would steepen the inverted U-shaped relationship, while a positive sign would flatten it or result in an inverted slope. The shift of the knee point is determined by the value of $\alpha_1\alpha_4 - \alpha_2\alpha_3$. If the value is positive, the knee point would move to the right; otherwise, it would move to the left (Du & Lin, 2022; Lee & Yan, 2024; Liu et al., 2024).

The outcomes presented in column (5) of Table 10 show that the parameter of α_4 was significantly negative at the 1% level and $\alpha_1\alpha_4 - \alpha_2\alpha_3$ was not significant. The conclusion that could be drawn is that the moderator steepened the curve. Therefore, hypothesis 2 was validated. Figure 7 further illustrates that, as the value of Urban increased, the inverted U-shaped relationship

Table 10 The heterogeneity test and moderating effect.					
	(1) High-nature resource rent	(2) Low-nature resource rent	(3) High- political stability	(4) Low- political stability	(5) Moderating effect of Urbanisation
IPP	1.788 ^a (0.38)	−0.601 (0.53)	2.871 ^a (0.45)	−0.407 (0.32)	−2.522 (1.54)
IPP2	−0.163 ^a (0.03)	0.015 (0.04)	−0.246 ^a (0.04)	−0.010 (0.03)	0.327 ^b (0.13)
FDI	−0.031 ^c (0.02)	−0.002 (0.00)	0.006 (0.01)	−0.001 (0.01)	−0.007 (0.00)
Fiscal	0.235 ^a (0.05)	0.271 ^a (0.03)	0.379 ^a (0.05)	0.222 ^a (0.03)	0.221 ^a (0.03)
Trade	0.022 ^a (0.01)	0.036 ^a (0.00)	0.043 ^a (0.00)	0.027 ^a (0.00)	0.026 ^a (0.00)
IPP*Urban					0.042 ^c (0.02)
IPP2*Urban					−0.005 ^a (0.00)
Urban					0.093 (0.06)
Fixed effect	YES	YES	YES	YES	YES
constant	−4.814 ^a (1.52)	−1.538 (1.97)	−19.949 ^a (1.85)	2.736 ^b (1.29)	−9.280 ^b (4.11)
N	260	280	260	280	540
R ²	0.826	0.854	0.863	0.814	0.878
adj. R ²	0.813	0.844	0.853	0.801	0.870

Standard errors in parentheses.
^cp < 0.1, ^bp < 0.05, ^ap < 0.01.

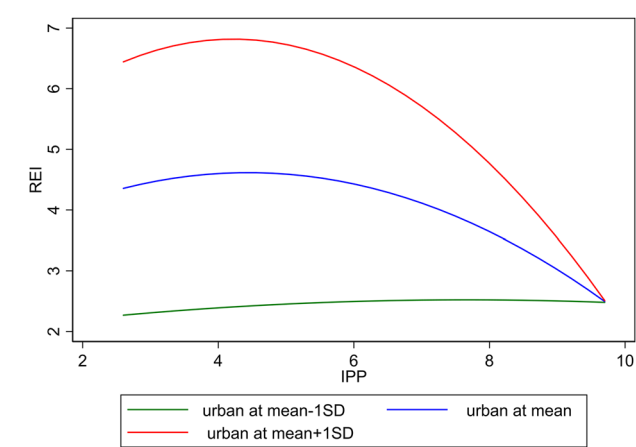


Fig. 7 Plot of moderating effect of urbanisation.

between IPP and REI steepened and a higher level of REI could be observed with higher Urban.

Urbanisation plays a critical role in fostering technological advancements and innovation through the concentration of labour, knowledge, industries and resources. On the one hand, urbanisation that results from rural labourers moving to cities leads to advancements in technology and increases in productivity (Brunt & García-Peñalosa, 2022). Kwilinski et al. (2023) also contended that urbanisation promotes the spread of cutting-edge technology and knowledge, closing inequalities in living standards and lowering the cost of services. The city’s growth and spatial concentration create lively atmosphere that has gotten better when it comes to interpersonal relationships. People communicate more, and cities become hubs of information. In addition, urbanisation generates knowledge externalities, further promoting innovation (Raihan et al., 2025b; Tappeiner et al., 2008). On the other hand, urbanisation growth encourages the spatial clustering of industries, resulting in the externalisation of technology and increasing innovation (Fujita et al., 1999). Urban places are more efficient at converting creative ideas into workable solutions because they have access to trained labour and cash. In urban settings, moderate levels of IP protection might already produce higher REI compared to less urbanised areas because of the richer innovation ecosystem. The research

conducted by Lin & Zhu (2021) and Wang et al. (2021) also supports the positive impact of urbanisation on innovation. Cities with higher industrial concentrations may experience increased company competition (Glaeser et al., 1992), particularly in knowledge-intensive sectors where access to intellectual property is crucial. However, under stringent IPP, this heightened competition does not necessarily foster innovation. Instead, smaller or latecomer firms may be compelled to divert substantial resources to licensing, legal disputes, or defensive patenting strategies, thereby crowding out productive R&D investments. Furthermore, the market dominance of leading companies with sizable patent portfolios tends to be reinforced by the concentration of firms in urban areas. This strengthens monopolistic power, enabling established firms to impose higher technology costs and limit the spread of information.

Threshold effect. One of the most important factors influencing how IPP influences innovation in renewable energy is a healthy financial market. The rise in IPP levels stimulates the demand for a well-developed financial market. For instance, FD facilitates innovation financing and reduces entry barriers related to IP protection. The challenges to REI—such as capital requirements, lengthy R&D cycles, and enhanced hazards—make it increasingly difficult to obtain financing for innovation operations (Allred & Park, 2007; Luan & Lin, 2022). Where FD is high, firms find it easier to access the financing needed for innovation, particularly for expensive and high-risk renewable energy initiatives. Innovation can overcome possible barriers created by IPP when they have access to a wide range of funding options, including loans, green bonds, and venture capital, thanks to a robust financial system.

This study referred to the threshold model proposed by Hansen (1999) to test the threshold effect of FD. FD was proxied by the Financial Development Index from IMF (2024), which captures the depth, access, and efficiency of both financial institutions and financial markets. To check for the presence of single, double, and triple thresholds, a threshold effect test was conducted using Stata. The outcomes reported in Table 11 reveal that the single and double thresholds were significant, while the third threshold was not. Therefore, the impact of IPP on RNI had a double threshold effect.

Additionally, threshold values estimated in Table 12 indicated that the corresponding threshold values were 0.427 and 0.7705.

Table 11 Results of the threshold effect test.

Threshold variables		RSS	MSE	F stat	Prob	Crit10	Crit5	Crit1
FD	Single	222.3257	0.4275	76.29	0.03	59.6786	71.0938	89.0793
	Double	195.5861	0.3761	71.09	0.0167	48.539	56.8239	102.7805
	Triple	179.0279	0.3443	48.09	0.7867	130.4055	146.7073	174.2368

Table 12 Threshold estimation results.

Threshold Variables	Threshold Value	Lower	Upper
FD	0.427	0.407	0.4397
	0.7705	0.7546	0.7743

Furthermore, in accordance with the threshold effect’s criteria, the threshold value was represented by the matching γ value as the LR value got closer to zero (Liu et al., 2024). The LR diagram depicted in Fig. 8 further confirmed these two threshold values. Therefore, the threshold Model (4) below was established.

$$\begin{aligned} REI_{it} = & \alpha_0 + \alpha_{11}IPP_{it} * I(FD < \gamma_1) + \alpha_{12}IPP_{it} * I(\gamma_1 < FD < \gamma_2) \\ & + \alpha_{13}IPP_{it} * I(FD > \gamma_2) + \sum_{a=1}^3 \beta_a CC_{it} + \varepsilon_{it} \end{aligned} \tag{4}$$

where $I(\cdot)$ was the index function. γ was the various threshold value. These two threshold values divided the range into three intervals. By examining the threshold effect, the parameter of IPP could be determined within each interval. According to the outcomes presented in Table 13, when FD exceeded 0.7705, the parameter of IPP was -0.352 , which was significant at the 5% level. When FD lay between 0.427 and 0.7705, the coefficient was -0.463 , significant at the 1% level. For FD values below 0.427, the estimated coefficient was -0.804 , also significantly negative at the 1% level. Therefore, hypothesis 3 was validated.

Based on the results, the lower the FD, the more significant the effect of IPP on REI. This phenomenon can be explained by the following. It is well-established that entry barriers are driven by the significant capital requirements and the ease of access to low-cost financing (Bain, 1956). Low financial development conditions make it difficult for businesses to obtain outside funding for innovation, and they mostly rely on IPP to guarantee returns on investment. The monopolistic effects of IPP become more pronounced in these situations, limiting other companies’ ability to enter the market and reducing industry-wide innovation. But as FD advances, innovators can use a variety of funding options to support research, even in the face of formidable intellectual property obstacles.

Besides that, small and medium-sized businesses’ (SMEs) ability to access the market is enhanced by FD, even in the face of robust IPP. SMEs can overcome obstacles like patent fees and legal expenditures when they have access to adequate finance through a well-developed financial system. This enables them to bypass IP-related barriers and join the market. Therefore, enterprises can use financial market assistance to engage in innovative activities even with strong IPP, lessening the inhibitory effect of IPP on innovation.

Conclusion and Policy recommendations

Conclusion. REI is essential for the transition to sustainable energy systems, reducing greenhouse gas emissions and mitigating the impacts of climate change. Its advancement is essential to maintaining long-term economic and environmental resilience, particularly in light of the world’s energy concerns. IPP serves as a stimulus for REI in the meantime. This study examines the link

between IPP and REI using data from 27 distinct countries, and the empirical analysis yields the following findings.

First, there is an inverted U-shaped relationship between IPP and REI, where the direction of IPP’s influence on REI depends on the relative strength of its positive and negative effects. The commercialisation incentives and information diffusion that IPP promotes are the main causes of its beneficial effects. Conversely, the adverse impact stems from two factors. The first is the obstacles IPP places on late market entrants due to the high costs of obtaining or licensing patents. Secondly is the reduced incentive for innovation that arises from the monopolistic positions granted by IPP. The detrimental impacts of IPP outweigh its advantages after the inflection point is crossed. Second, this curvilinear relationship holds for countries with above-average level resource rents or government stability. Third, the curvilinear relationship between IPP and REI is steepened by urbanisation. Lastly, threshold effects imply that the adverse effect of IPP on REI is mitigated by more advanced financial markets.

Policy implications. First, governments should create a flexible IPP framework that includes differentiated mechanisms for renewable technologies. For example, rather than uniformly extending protection, governments could experiment with shorter patent durations combined with complementary mechanisms like patent pools, which allow firms to share critical technologies under standardised licensing agreements. Such mechanisms reduce duplication costs and speed diffusion. In parallel, formal incentives—such as tax credits or competitive grants—could be provided to firms and research institutions that adopt open-source innovation models or actively participate in informal knowledge-sharing networks. The IPP rules should then be periodically reviewed to ensure that protection is adequate to reward early innovators while avoiding excessive barriers to entry and knowledge dissemination.

Second, governments should implement renewable-energy-specific policy mechanisms that directly mitigate political and market risks. For instance, they could implement feed-in tariff schemes supported by legally binding long-term contracts, thereby guaranteeing price stability for renewable electricity producers. In resource-dependent economies, a portion of natural resource rents could be earmarked for competitive green innovation funds. These funds should be allocated through transparent calls for proposals, with evaluation criteria explicitly linked to carbon-reduction potential and technological scalability. Such targeted measures reduce investor uncertainty, improve the efficiency of rent allocation, and create concrete incentives for private actors to commit to long-term renewable energy projects. In economies with low resource rents, governments might instead employ innovation-friendly tax schemes or shorten patent durations for renewable technologies, rather than applying uniform protection, thereby lowering entry barriers, accelerating knowledge diffusion, and offsetting the limited resource-based incentives for renewable investment. In politically unstable contexts where IPP alone is insufficient to drive renewable innovation, reforms could be paired with mandatory knowledge-transfer requirements in foreign direct investment contracts. For example, companies benefiting from patent rights might be

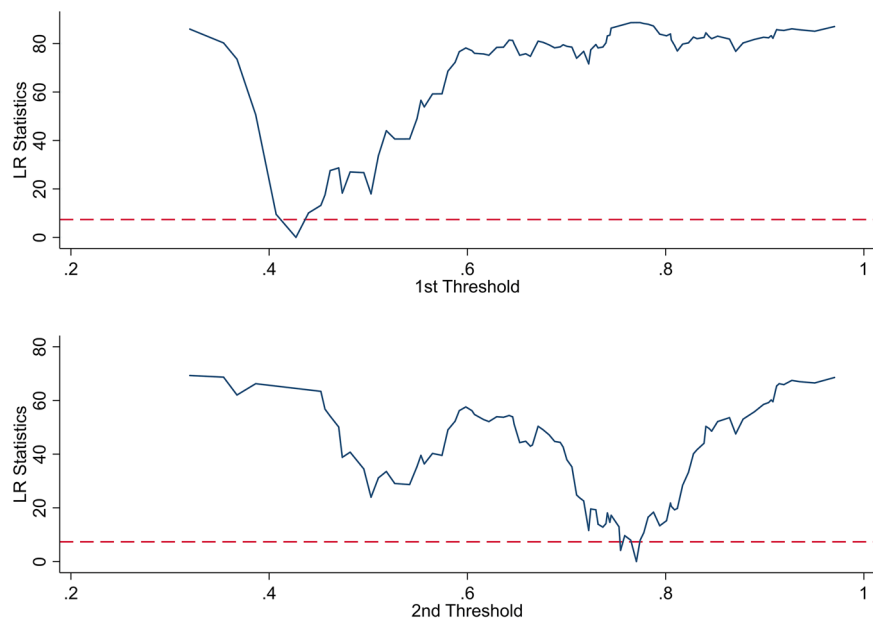


Fig. 8 LR graph for the threshold test of FD.

Table 13 Results of panel threshold regression.		
Threshold Variable	FD Coefficient	P > t
IPP{FD < 0.427}	−0.804	0.002
IPP {0.427 < FD ≤ 0.7705}	−0.463	0.009
IPP{ FD ≥ 0.7705}	−0.352	0.04
FDI	0.000	0.965
Fiscal	0.268	0
Trade	0.036	0
constant	−1.364	0.496
observations	540	

obliged to form joint ventures with local research institutions, embedding innovation outcomes more firmly in domestic capabilities and reducing susceptibility to instability.

Third, governments should enhance urban infrastructure, such as transportation and communication networks, to facilitate the effective flow of ideas and commerce. These improvements can foster innovation and collaboration among firms. Additionally, creating forums for companies, academics, and policymakers to collaborate and exchange knowledge in urban areas can help disseminate cutting-edge concepts and best practices for renewable energy.

Finally, governments might implement specific green finance mechanisms that specifically address the limitations brought about by strong IPP, rather than fostering the growth of financial markets generally. Examples include the establishment of renewable technology venture funds co-financed by public and private investors, or the issuance of green bonds earmarked for renewable energy start-ups. Financial institutions employing these instruments might also be granted specific tax incentives, such as lower capital requirements for banks financing patent-intensive renewable energy projects. By channelling financial resources to innovative firms that might otherwise face barriers to entry under stringent IPP regimes, such measures would enhance competition and stimulate innovation.

Future directions. There are still some limitations. First, this paper examines REI only at the country level, lacking micro-

level analysis of firm-specific REI. Second, due to data availability, this study is restricted to 27 countries, most of which are developed nations. Third, the sample period ends in 2017, which prevents the analysis from capturing the potential impacts of the COVID-19 pandemic. Future research could explore other proxies of IPP and REI, covering countries with diverse levels of economic and technological development and longer period to draw more generalisable conclusions. Moreover, the specific channels through which the inverted U-shaped effect of IPP on REI operates remain underexplored. Although estimation biases were mitigated using DKSE, FGLS, and DCCE models in the robust test, future studies could employ more robust techniques, such as machine learning algorithm approaches (Ali et al., 2025) and Lewbel technique, to further strengthen the outcomes.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

HL: conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft, writing—review and editing, and visualization. LZ: conceptualization, methodology, resources, writing—review and editing. YS: conceptualization, methodology, supervision. FK: conceptualization, methodology, supervision. AS: conceptualization, methodology, supervision.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

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