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Patent Systems and Carbon Dioxide Emissions: Short and Long Run Perspectives on Economic Development and Sustainability

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ABSTRACT

This study explores the relationship between patent system strength and carbon dioxide (CO₂) emissions across 46 developed and developing countries from 1998 to 2017 using Fixed Effects (FE) and Autoregressive Distributed Lag (ARDL) models. The findings reveal that stronger patent regimes in developed countries are initially associated with higher emissions, suggesting that innovation may first drive industrial growth before transitioning to cleaner technologies. In developing economies, this effect is weaker, likely due to potentially lower innovation capacity and dependence on imported technologies. The findings refine the Environmental Kuznets Curve (EKC) hypothesis by illustrating how IPRs can shape its trajectory. Additional factors—such as renewable energy use, which consistently reduces emissions, trade openness and urbanization, which yield mixed and positive effects, respectively—highlight the complexity of the emissions-patent nexus. We conclude that patent strength alone cannot deliver emissions reductions; complementary policies such as renewable energy support, carbon pricing, and technology sharing are essential to align innovation systems with climate goals.

JEL Classification: F21, L6, O33, O38

1 | Introduction

The pressing need to address climate change has placed the reduction of carbon dioxide (CO₂) emissions at the forefront of global policy discussions. Innovation, particularly in green technologies, has been widely acknowledged as a key factor in achieving these reductions while sustaining economic growth (Popp 2002). Patent systems play a pivotal role in fostering innovation by providing inventors with incentives to develop and commercialize new technologies (Alexiou 2023).

Existing research has established that patent systems can drive innovation by securing returns on research and development (R&D) investments (Peters et al. 2012). Studies have also demonstrated that technological progress, particularly in green energy and efficiency improvements, can significantly reduce

CO₂ emissions (Johnstone et al. 2010). However, the interplay between patent systems and environmental innovation remains less clear, particularly in a global context where countries vary widely in their institutional frameworks, innovation capacities, and environmental policies (Schultz et al. 2024). Furthermore, there is limited empirical evidence on how these dynamics evolve over time and whether patent protection incentivizes the type of innovation necessary to address environmental challenges (Peters et al. 2012).

Additional studies have drawn growing attention to the role of intellectual property rights (IPRs) in shaping environmental outcomes, via their influence on innovation and the diffusion of green technologies. More specifically, Fei et al. (2024) show that patent transfers can significantly reduce CO₂ emissions in Chinese cities, especially when reinforced by strong

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government interventions and IPR enforcement, while Li, Siu, and Zhao (2021) find a non-linear relationship between innovation and emissions in China, where patenting initially increases emissions but leads to reductions beyond a certain threshold. By extending this perspective, Ma et al. (2022) highlight that while innovation generally supports emission reductions in BRICS countries, its effectiveness depends on national capacities to absorb and apply new technologies.

The relationship between patent enforcement and CO₂ emissions presents an intriguing and critical area of study, particularly when considering the differing dynamics in developed and developing economies. Strong patent enforcement mechanisms are often credited with fostering innovation by ensuring that inventors can reap the benefits of their research and development efforts. This is particularly relevant for green technologies, where high upfront costs and long development timelines necessitate robust protections (Chen and Chen 2024).

While strict patent enforcement can incentivize innovation in developed economies with advanced markets and institutions, its benefits are not universal, as overly stringent measures may hinder the diffusion of critical green technologies in developing economies (Papageorgiadis et al. 2014). In such cases, high licensing costs and restricted access to patented innovations can create barriers, limiting the adoption of technologies essential for reducing CO₂ emissions (Alexiou 2023).

Developed economies often lead in green innovation, but achieving meaningful reductions in global CO₂ emissions requires the widespread adoption of these technologies across all countries, including developing economies. While patent systems are widely recognized for their role in spurring innovation, particularly in environmentally beneficial technologies, the extent to which they contribute to emission reductions—especially across diverse national contexts—remains a complex and underexplored area of research (Alexiou 2023).

Grounded in the Environmental Kuznets Curve (EKC) hypothesis and endogenous growth theory, this study examines the non-linear relationship between patent strength and CO₂ emissions across different stages of economic development. The EKC posits that environmental degradation initially rises with income growth but eventually declines as economies transition to cleaner technologies and stronger environmental governance (Grossman and Krueger 1995). Complementing this, endogenous growth theory (Romer 1990) emphasizes the role of innovation and knowledge accumulation in driving sustainable development. Within this theoretical framework, IPRs—particularly the strength of patent enforcement—act as institutional mechanisms that both incentivize green innovation and influence the trajectory of emissions globally. Understanding, therefore, how intellectual property rights (IPRs) influence the pace, direction, and diffusion of green innovation is critical to assessing their environmental impact.

In this direction, we employ two complementary econometric approaches: fixed effects and panel ARDL models. The fixed effects model controls for unobservable country-specific factors that may influence CO₂ emissions, minimizing omitted variable

bias (Shaari et al. 2023) while the panel ARDL model captures short- and long-term dynamics, accommodating both stationary and non-stationary variables to analyze equilibrium relationships and adjustment processes (Shahid et al. 2022). Combining these methods ensures a robust assessment of the hypothesized relationships while addressing endogeneity and dynamic heterogeneity in the panel dataset.

As such, this study advances the respective literature through its methodological rigor and comprehensive cross-country analysis of non-linear patent-emissions relationships. It represents the first empirical examination of how patent system strength affects CO₂ emissions across developed and developing economies, employing a combined fixed effects and panel ARDL models to capture both short- and long-run dynamics.

Departing from prior studies that focus narrowly on innovation outputs or green patent counts, our analysis introduces a dynamic patent enforcement index that accounts for cross-country variations in IPR regimes over time. This approach uniquely extends the Environmental Kuznets Curve (EKC) by demonstrating how patent strength not only influences emission levels but also shapes the trajectory and pace of the EKC transition. By integrating temporal dynamics and contextual distinctions, the study offers policy-relevant insights that surpass the limitations of static or single-country analyses prevalent in existing research.

The rest of the paper is organized as follows: Section 2 provides a brief review of the literature while at the same time developing the hypothesis. Section 3 touches on the empirical methodology utilized in the study, while Section 4 presents and discusses the results as well as provides policy implications and policy recommendations. Finally, Section 5 provides some concluding remarks.

2 | Literature Review

2.1 | Theoretical Foundations

The theoretical foundation of this study is anchored in the Environmental Kuznets Curve (EKC) hypothesis and the broader framework of endogenous growth theory, with an institutional lens focused on intellectual property rights (IPRs). The EKC hypothesis, first formalized by Grossman and Krueger (1995), suggests that the relationship between environmental degradation and economic development follows an inverted U-shape: in the early stages of growth, environmental harm increases, but after a certain income threshold, it declines as economies shift toward cleaner technologies and stronger environmental governance. This model underpins the study's assumption that emissions trajectories are not linear but evolve dynamically with structural and policy changes in the economy.

Complementing this, endogenous growth theory (e.g., Romer 1990) highlights the central role of innovation and knowledge accumulation in driving long-term economic growth. Within this framework, patents serve as institutional mechanisms that incentivize innovation by granting temporary monopolies to inventors. These property rights are

critical not only for encouraging R&D but also for shaping the pace, direction, and diffusion of environmentally beneficial technologies.

By integrating the EKC with insights from innovation economics and institutional theory, this study theorizes that patent system strength acts as a moderator in the growth-emissions relationship. Specifically, it explores how varying degrees of IPR enforcement can accelerate or hinder a country's transition along the EKC path—either fostering the adoption of clean technologies or, conversely, entrenching barriers to their diffusion, particularly in developing contexts.

This dual-theoretical foundation allows for a better understanding of how innovation policy, institutional quality, and economic development interact to influence environmental outcomes. It also provides the rationale for the study's empirical focus on non-linear and asymmetric effects of patent strength on CO₂ emissions across different country groups.

2.2 | Historical Perspective

The Environmental Kuznets Curve (EKC), first articulated by Grossman and Krueger (1995), posits an inverted U-shaped relationship between economic growth and environmental degradation—where emissions rise with income in the early stages of development but decline as economies mature, often due to technological adoption and regulatory improvements. While this framework highlights the role of innovation in reversing environmental damage, early EKC studies often treated innovation as a passive control variable rather than a structural driver (Stern 2004). Moreover, little attention was given to the institutional mechanisms, such as intellectual property rights (IPRs), that govern innovation processes (Alexiou 2023).

Patents play a pivotal role in promoting green innovation by incentivizing R&D and ensuring returns on investment, particularly in patent-intensive industries. Linnenluecke et al. (2019) and Zuo and Zhou (2023) emphasize the importance of institutional and policy environments—including IPRs—in fostering cleantech development. Wang, Yang, and Zhang (2012) and Gierałtowska et al. (2022) find that green patents can significantly reduce emissions in the long term, although their short-term effects are often muted. Nonetheless, these studies generally assume a linear and uniformly positive effect of patent activity on environmental outcomes.

Recent research challenges this assumption, highlighting that the strength and enforcement of patent systems may exert non-linear effects on CO₂ emissions. Alexiou (2023) introduced a composite index capturing enforcement volatility and found that overly stringent protections can hinder renewable energy adoption in developing economies. Mahmood et al. (2023) and Chui et al. (2024) demonstrate regional disparities in patent effectiveness, suggesting that context-specific IPR strategies are essential for achieving emissions reductions.

Although Popp (2002) and Johnstone et al. (2010) link innovation to environmental policy and energy prices, they overlook

how IPR regimes influence the pace and distribution of green technologies. Moreover, studies like Dechezlepretre et al. (2011) and Hall and Helmers (2013) show that while stronger IPRs may support R&D in developed economies, they can restrict technology transfer and accessibility in developing nations, where institutional capacity and affordability pose significant barriers.

Additional research highlights the important role that intellectual property rights (IPRs) play in shaping environmental outcomes, especially through the protection and transfer of green technologies. Fei et al. (2024) find that in Chinese cities, the transfer of green patents leads to lower CO₂ emissions from non-residential sectors, particularly when supported by strong government policies. Their study shows that environmental benefits from such patent transfers are more likely when IPR protections are well enforced.

Similarly, Li, Elheddad, and Doytch (2021) uncover a non-linear relationship between innovation and emissions in China. At early stages, more patents are linked to higher CO₂ levels, likely due to conventional, carbon-intensive innovation. However, once innovation reaches a certain threshold, further increases in patenting are associated with emission reductions, pointing to a shift toward cleaner technologies. Further, Ma et al. (2022) extend this view to BRICS countries, showing that while technological innovation generally helps reduce emissions, its effectiveness varies across countries depending on their institutional capacity and ability to adopt new technologies.

In parallel, the role of patents in shaping broader emission drivers—such as urbanization, renewable energy uptake, and industrial restructuring—has been increasingly recognized (Chen et al. 2022). Patents support the deployment of low-carbon technologies, reduce emissions intensity, and facilitate structural transitions toward clean energy (e.g., Li et al. 2013; Wang et al. 2022). Wu and Shen (2023) highlight insufficient public awareness and education, while Markantoni and Woolvin (2015) underscore governance challenges, particularly in rural and less-developed settings.

Furthermore, Shahid et al. (2022) illustrate how panel ARDL models can capture dynamic effects, offering tools better suited for analyzing institutional and environmental transitions over time. Despite the growing evidence, a major gap persists in the literature. Few studies integrate IPRs into the EKC framework or distinguish between short- and long-run dynamics in emissions.

This study builds on and addresses the extant gaps by conducting a non-linear, context-sensitive analysis of patent system strength and CO₂ emissions, distinguishing between developed and developing economies. It contributes to the EKC literature by demonstrating how IPRs can reshape the trajectory of emissions, either accelerating or delaying the decoupling of growth from environmental harm depending on enforcement design and economic context. This provides more granular, policy-relevant insights into aligning innovation systems with sustainability goals.

2.3 | Hypotheses Development

Building on the existing literature, we hypothesize that the strength of patent systems has differing impacts on CO₂ emissions in the short and long run, as well as varying effects between developed and developing economies. In the short run, stronger patent systems may have limited effects on reducing CO₂ emissions due to the time required for green innovations to progress from patenting to widespread adoption and implementation (Wang, Yang, Zhang, and Yin 2012). However, in the long run, robust patent systems are likely to foster sustained innovation in energy-efficient and low-carbon technologies, leading to significant reductions in emissions intensity (Li et al. 2013; Wang et al. 2022). Furthermore, we posit a differential impact between developed and developing economies. In developed economies, strong patent systems may drive green innovation more effectively due to established institutional frameworks, mature markets, and better access to R&D funding (Zuo and Zhou 2023). In contrast, in developing economies, strict patent protections may hinder the diffusion of critical green technologies due to high costs and limited institutional capacity, potentially offsetting their benefits.

The EKC hypothesis posits that there is an inverted U-shaped relationship between environmental degradation (e.g., CO₂ emissions) and economic development (e.g., GDP per capita) (Grossman and Krueger 1995). In the early stages of economic growth, environmental degradation increases, but after reaching a certain income threshold, further economic growth leads to environmental improvement (Dasgupta et al. 2001). This is often attributed to technological advancements, increased environmental awareness, and stricter regulations that accompany higher income levels.

When integrating the EKC hypothesis with the role of patents (as a proxy for innovation and technological advancement) and CO₂ emissions, we can develop our hypotheses to reflect how innovation (measured by patent strength) influences the relationship between economic development and emissions. Specifically, we can explore whether stronger patent systems (indicative of greater innovation) help countries transition faster or more effectively along the EKC, potentially reducing emissions at lower income levels or accelerating the downward slope of the curve.

In view of the above we develop the following two hypotheses:

H1. *There is a nonlinear relationship between patent strength and CO₂ emissions.*

H2. *The effect of patent strength on CO₂ emissions differs between developed and developing countries.*

3 | Empirical Investigation

For the empirical investigation, we employ two complementary econometric approaches: a fixed effects model and a panel autoregressive distributed lag (ARDL) model. The fixed effects approach is utilized to account for unobservable heterogeneity

across countries, capturing country-specific characteristics that remain constant over time but may influence CO₂ emissions. This method ensures that omitted variable bias is minimized, allowing for a more robust identification of the relationship between intellectual property rights (IPRs), control variables, and CO₂ emissions. To complement this, the panel ARDL approach is employed to analyze both the short- and long-term dynamics between the variables under investigation. This approach is particularly suitable for datasets with a mix of stationary and non-stationary variables, enabling the exploration of equilibrium relationships and adjustment processes over time. By combining these methodologies, the study ensures a rigorous examination of the hypothesized relationships while addressing potential endogeneity and dynamic heterogeneity within the panel dataset.

3.1 | Methodology

The analysis is conducted on a dataset comprising a cluster of 28 developed and 18 developing economies over the period 1998–2017. (A detailed list of the countries included in the empirical analysis is provided in Table A5 in the Appendix). To examine the relationship between patent enforcement and CO₂ emissions, additional control variables are incorporated into the model.

The fixed effects model is specified as follows:

$$\begin{aligned} \text{CO}_{2i,t} = & \alpha + \beta_1 \text{ipra}_{it} + \beta_2 \text{iprasqr}_{it} + \beta_3 \text{renew}_{it} + \beta_4 \text{trd}_{it} \\ & + \beta_5 \text{loginnov}_{it} + \beta_6 \text{gdppc}_{it} + \beta_7 \text{fdi}_{it} \\ & + \beta_8 \text{urban}_{it} + \beta_9 \text{findenv}_{it} + v_i + \xi_t + \varepsilon_{i,t} \end{aligned} \quad (1)$$

where CO_{2i,t} represents CO₂ emissions; ipra_{it} measures the strength of IPRs, iprasqr_{it} is the quadratic term capturing nonlinearities, renew_{it} denotes renewable energy consumption, trd_{it} is trade openness, loginnov_{it} denotes the logarithms of innovation, gdppc_{it} is GDP per capita, fdi_{it} is foreign direct investment, urban_{it} denotes urbanization, and findenv_{it} is a proxy for financial development. v_i is white noise, and α captures country-specific effects and ξ_t time fixed effects.

A complementary methodological approach used in the study is the Autoregressive Distributed Lag (ARDL) model, which examines long-run relationships between variables that may be integrated at different levels and allows for cointegration testing even when the underlying variables have mixed integration orders (Pesaran et al. 1999; Pesaran and Smith 1995).

The intuition behind ARDL in establishing cointegration is based on its ability to capture both short-run dynamics and long-run equilibrium relationships simultaneously. This is achieved through the inclusion of lagged levels and differences of the variables in the model. When the Error Correction Term (ECT) derived from the ARDL model is negative and statistically significant, it provides strong evidence of cointegration, indicating that any short-term deviation from the long-run equilibrium will be corrected over time (Gujarati and Porter 2009). In other words, the system naturally moves back toward equilibrium after a shock.

For the ARDL model the respective formulation is couched as follows:

$$\begin{aligned} \Delta CO_{2it} = & \lambda_i (\theta_1 ipra_{it-1} + \theta_2 iprasqr_{it-1} + \theta_3 renew_{it-1} \\ & + \theta_4 trd_{it-1} + \theta_5 loginnov_{it-1} + \theta_6 gdppc_{it-1} \\ & + \theta_7 fdi_{it-1} + \theta_8 urban_{it-1} + \theta_9 finddev_{it-1}) \\ & + \sum_{j=1}^{p-1} \delta_{1j} \Delta co_{2i,t-j} + \sum_{j=1}^{p-1} \delta_{2j} \Delta ipra_{i,t-j} \\ & + \sum_{j=1}^{p-1} \delta_{3j} \Delta iprasqr_{i,t-j} + \sum_{j=1}^{p-1} \delta_{4j} \Delta renew_{i,t-j} \\ & + \sum_{j=1}^{p-1} \delta_{5j} \Delta trd_{i,t-j} + \sum_{j=1}^{p-1} \delta_{6j} \Delta loginnov_{i,t-j} \\ & + \sum_{j=1}^{p-1} \delta_{7j} \Delta gdppc_{i,t-j} + \sum_{j=1}^{p-1} \delta_{8j} \Delta fdi_{i,t-j} \\ & + \sum_{j=1}^{p-1} \delta_{9j} \Delta urban_{i,t-j} + \sum_{j=1}^{p-1} \delta_{10j} \Delta finddev_{i,t-j} + \mu_{it} \end{aligned} \quad (2)$$

where λ_i represents the speed of adjustment toward long-run equilibrium; θ_j is the long run coefficients, δ_{kj} is the long-run dynamic coefficients; Δ is the first-difference operator; μ_{it} is the error term; The term inside parentheses is the error correction term (ECT), i.e., the deviation from long-run equilibrium.

3.2 | Variables

The dependent variable in this study is CO₂ emissions, defined as metric tons per capita. Data for this variable are sourced from Alexiou (2023) and the World Development Indicators (WDI). See Table A1 in the appendix for the definitions of variables and sources.

3.2.1 | Patent System Indices

Measuring intellectual property rights (IPRs) remains challenging despite extensive research (Allred and Park 2007). Some studies use binary indicators (Ferrantino 1993; Rapp and Rozek 1990), while others develop indices to assess IP protection strength (Mansfield 1994; Moge 1989). Allred and Park (2007) critique these methods for being time-specific and advocate for continuous indices reflecting cross-country variations.

Ginarte and Park (1997) introduced a widely used index covering over 100 countries from 1960 to 2005, measured every 5 years. It evaluates IPR strength across five dimensions: coverage, international agreements, protection loss, enforcement, and duration. More recently, Papageorgiadis et al. (2014) developed a composite patent index, updated by Alexiou (2023), spanning 1998–2017 across 49 countries. It comprises three sub-indices—servicing costs, property rights protection costs, and monitoring costs—capturing patent enforcement volatility. Scores range from 0 (weak) to 10 (strong). In this study, we employ the updated Alexiou (2023) index as the key proxy for patent strength.

3.2.2 | Control Variables

Several economic factors influence CO₂ emissions, including GDP per capita, renewable energy consumption, trade openness, innovation, FDI, urbanization, and financial development (Glavas 2024). GDP per capita is expected to increase emissions due to industrial expansion (Glavas 2024), while renewable energy consumption mitigates them by reducing fossil fuel dependence (Adebayo and Rjoub 2021). Trade impacts emissions through carbon leakage and technology transfer (Cole and Elliott 2003; Antweiler et al. 2001; Sharif et al. 2025). Innovation enhances energy efficiency and clean energy adoption (Li, Siu, and Zhao 2021; Acemoglu et al. 2012). FDI may raise emissions via the pollution haven hypothesis (Li, Elhaddad, and Doytch 2021), and urbanization increases energy demand (Poumanyong and Kaneko 2010). Finally, financial development influences emissions through energy investments (Emenekwe et al. 2023).

The EKC hypothesis suggests that economic growth initially worsens environmental degradation before improving beyond a certain income threshold, forming an inverted U-shape (Grossman and Krueger 1995). A quadratic *ipra* term is therefore inserted in the model to capture nonlinearities, reflecting diminishing, threshold, or exponential effects on emissions, depending on the technologies involved (Alexiou 2023). Table A2 presents cross-correlations, while Table A3 provides the descriptive statistics.

To address potential multicollinearity between the linear and quadratic terms of the variable *ipra*, we have implemented a centered transformation. Specifically, the variable *iprasqr* is defined as the square of the centered version of *ipra*: $iprasqr = (ipra - \text{mean}(ipra))^2$. This approach maintains the integrity of the nonlinear relationship while minimizing the risk of multicollinearity with the linear term (Aiken and West 1991). Additionally, to keep multicollinearity at bay, in all estimated models, Variance Inflation Factors (VIFs) were calculated¹. All VIF mean and individual values remained within acceptable thresholds (less than 2 and 3 respectively), confirming that multicollinearity does not pose a concern in any of the estimated specifications (Hair et al. 2010). Table A6 in the appendix provides the VIF scores for all samples.

4 | Results and Discussion

4.1 | Fixed Effects Models

Based on the fixed effects results reported in Table 1, the patent strength index (*ipra*) is found to be positive and highly significant across all samples. This evidence implies that strengthening patent laws is associated with increased CO₂ emissions across the board, although the effect is markedly stronger in developed countries. In developing economies, the positive relationship suggests that patent strengthening may also initially promote industrial activity and innovation that is not yet aligned with green outcomes, possibly reflecting a stage of development where technological advances are still resource-intensive. For developed countries, the results imply that stronger patent systems may facilitate industrial expansion or lock-in effects

TABLE 1 | Fixed effects models.

	Full sample	Developed	Developing
	CO ₂	CO ₂	CO ₂
ipra	0.878*** (10.83)	1.053*** (8.26)	0.165** (2.19)
iprasqr	0.171*** (7.72)	0.073* (1.88)	0.033 (0.73)
renew	−0.137*** (−16.06)	−0.169*** (−12.05)	−0.041*** (−4.55)
loginnov	0.064* (1.94)	−0.072* (−1.93)	0.006** (2.03)
trd	−0.007*** (−3.86)	0.001 (0.47)	−0.001 (−0.63)
gdppc	0.009* (1.87)	0.043* (1.87)	0.007 (1.06)
findev	0.002 (1.34)	0.002 (1.13)	0.0005 (0.24)
urban	0.049*** (3.34)	0.011* (−1.91)	0.172*** (9.86)
fdi	−0.001 (−0.35)	−0.002 (−0.50)	0.043** (2.15)
cons	−0.361 (−0.31)	4.666** (2.01)	−6.61*** (−6.17)
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
N	813	493	320
R-squared	0.64	0.67	0.79

Note: t statistics in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Source: Author's estimations.

in emissions-intensive sectors, despite advanced institutional frameworks.

The quadratic term (iprasqr) is positive and significant in the full sample and developed economies, but insignificant in the developing countries sample. These findings suggest a non-linear relationship where strengthening patents continues to increase emissions even beyond moderate levels of protection—contrary to the expected Environmental Kuznets Curve-type turning point. The lack of significance in developing countries indicates that the emission effects of patent intensity do not change curvature as they strengthen, possibly due to less mature innovation ecosystems.

As for the rest of the control variables, renewable energy consumption (renew) has a negative and highly significant effect in all models, confirming that greater renewable energy use substantially reduces CO₂ emissions over time (Shafiei and Salim 2014). Innovation (loginnov) shows a positive but a weak significant effect in the full sample and a positive and significant effect in developing economies, indicating that increased patent activity may reflect technological or industrial expansion that correlates with higher emissions (Acemoglu et al. 2012). In contrast, innovation is negative and weakly significant in developed countries, suggesting that patents in those countries may be more focused on environmentally friendly technologies. Trade openness (trd) is negative and significant in the full sample—in line with Antweiler et al. (2001)—but insignificant in both developed and developing samples, implying that overall trade may contribute to emissions reduction—possibly through access to cleaner technology—but that the effect is not uniform across developed and developing countries. GDP per capita (loggdppc) has

a positive and weakly significant impact on emissions in the full and developed samples, consistent with the view that economic activity is still largely emissions intensive (Grossman and Krueger 1995). However, in developing economies, the effect is not significant, suggesting either low elasticity or offsetting dynamics between growth and environmental performance. Financial development (findev) is not significant in any sample, indicating that its direct link to emissions is limited or context dependent. Urbanization (urban) significantly increases emissions across all samples, suggesting rapid urban growth without green infrastructure contributes to environmental degradation (Chen et al. 2022). Foreign Direct Investment (FDI) is positive and significant only in the developing sample, which may reflect investment in pollution-intensive sectors, aligning with the pollution haven hypothesis (Cole et al. 2011).

While our results emphasize the potentially counterproductive effects of stronger patent regimes on emissions—particularly in the absence of aligned environmental policies—they resonate with and complement broader findings in the literature. Fei et al. (2024), for instance, demonstrate that patent transfers can lead to significant CO₂ reductions in Chinese cities, but only when bolstered by strong government intervention and effective IPR enforcement. This aligns with our assertion that patent protection alone is insufficient and must be supported by targeted safeguards or complementary policy instruments to avoid technological lock-ins. Similarly, Li, Siu, and Zhao (2021) uncover a non-linear relationship between innovation and emissions in China; innovation initially raises emissions due to industrial expansion, but eventually contributes to emission reductions once a critical innovation threshold is surpassed. This mirrors the concern raised by the results that strengthening patents without policy direction might

TABLE 2 | ARDL models.

Variables	Full sample (PMG)	Developed (PMG)	Developing (PMG)
	CO ₂	CO ₂	CO ₂
Long run			
ipra	0.713** (2.28)	0.545** (2.36)	0.385* (1.76)
iprasqr	0.159* (−1.90)	0.083 (1.64)	0.207 (0.22)
renew	−0.126*** (−4.11)	−0.191*** (−3.75)	−0.003* (−1.74)
loginnov	−0.054 (−1.73)	0.051* (1.89)	−0.255 (−0.93)
trd	−0.003** (−2.12)	0.020 (1.69)	−0.009* (−1.86)
gdppc	−0.154* (9.93)	−0.087* (1.89)	−0.112 (−01.22)
findev	−0.06 (0.93)	0.004 (0.52)	0.009 (1.38)
urban	0.063* (1.86)	0.082* (1.89)	0.253*** (4.31)
fdi	−0.001 (−0.06)	−0.003 (−1.34)	−0.033 (−0.47)
Short run			
ECT	−0.185*** (−6.50)	−0.208*** (−5.21)	−0.385*** (5.28)
D1.co2	0.014** (2.56)	0.023** (2.12)	0.014** (2.25)
D1.ipra	0.068 (0.75)	0.047 (0.74)	0.035 (0.48)
D1.iprasqr	0.014 (0.55)	0.004 (0.99)	−0.084* (−1.74)
D1.renew	−0.126*** (−8.54)	−0.168*** (−7.34)	−0.045*** (−3.40)
D1.loginnov	0.067 (0.65)	0.235 (0.84)	0.040 (0.60)
D1.trd	0.0002** (2.12)	0.014 (1.42)	0.003 (1.55)
D1.loggdppc	0.041 (1.66)	0.006*** (0.84)	0.007 (0.53)
D1.findev	−0.003* (1.76)	−0.003 (−1.21)	−0.001 (−0.40)
D1.urban	−0.006 (−0.06)	0.037 (0.20)	−0.102 (−0.58)
D1.fdi	−0.001 (−0.53)	−0.001 (−0.47)	0.013 (1.12)
cons	0.732 (0.08)	−2.475 (−1.05)	2.473** (3.05)

Note: t-stat in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; the prefix D1 denotes number of lags. ECT is the error correction term.

Source: Author's estimations.

reinforce existing emission-intensive systems, rather than catalyzing sustainable innovation. Ma et al. (2022) further provide sustenance to this discourse by pointing out that innovation's impact on emissions in BRICS countries hinges on national capacities to absorb and implement new technologies. This supports our argument for a comprehensive approach—incorporating technology standards, subsidies, and pricing mechanisms—to ensure that IPRs foster environmentally beneficial outcomes.

In view of the above, the results indicate that stronger patent regimes, while important for innovation, may not automatically reduce emissions, especially in the absence of targeted environmental policy alignment. The positive and significant coefficients on both *ipra* and *iprasqr* suggest that without safeguards, patent strengthening could exacerbate emissions by reinforcing industrial or technological lock-ins. Policymakers in both developed and developing economies should therefore consider complementary green policy instruments, such as technology standards, green subsidies, or emissions pricing, to ensure that

patent protection drives sustainable innovation. The consistent importance of renewable energy also reinforces the urgency of scaling up clean energy investments.

4.2 | Autoregressive Distributed Lag (ARDL) Models

Before using an Autoregressive Distributed Lag (ARDL) model for time series analysis, it is crucial to check for the presence of a unit root in the data for several reasons. The presence of a unit root suggests that the series is non-stationary, which may have implications for the validity and interpretation of the ARDL model. One of the key advantages of the ARDL model is its ability to estimate long-run relationships even when the variables are integrated of different orders, i.e., $I(0)$ or $I(1)$ but not $I(2)$ (Pesaran and Smith 1995; Pesaran et al. 1999). In our case, we have established a mixture of $I(0)$ and $I(1)$ series. Table A4 in the appendix reports the unit root results.

Patent protection plays a crucial role in shaping CO₂ emissions, but its effects, to an extent, may vary between developed and developing economies. The results from Table 2 provide a more informative view of the relationship between intellectual property rights (IPRs) and CO₂ emissions, complementing earlier findings in the literature (Popp 2002; Verdolini and Galeotti 2011).

4.2.1 | Long-Run Impact of Patent Protection on CO₂ Emissions

In the full sample, stronger patent protection (*ipra*) is associated with a significant increase in emissions, suggesting that stricter intellectual property laws may initially stimulate industrial activity and production that remains dependent on fossil fuels. This aligns with prior literature showing that IPR strengthens incentives for firms to innovate across the board, including in emissions-intensive sectors (Acemoglu et al. 2012) or those who argue that the direction-sensitive response of emissions to innovation shocks is of paramount importance (Ma et al. 2022). The squared term (*iprasqr*) is positive and weakly significant, indicating a non-linear relationship. This implies that while stronger patents may initially drive emissions through industrial expansion, they might not eventually foster cleaner innovation, reducing emissions as the system matures. Such a transition is not consistent with research showing that advanced IPR regimes eventually support the diffusion of energy-efficient and carbon-reducing technologies (Lanjouw and Mody 1996).

In developed countries, this pattern is generally replicated, though the effect is somewhat more moderate. The coefficient on *ipra* remains positive and significant, confirming that stronger patent regimes are initially linked to rising emissions—possibly due to expansion in high-tech manufacturing and innovation-driven sectors with substantial carbon footprints. The squared term is weakly significant, suggesting that the emission-increasing effect plateaus or reverses at very high levels of patent strength. This implies that in advanced economies, emissions may rise with stronger IPR in the short-to-medium term but begin to fall as innovation becomes more aligned with environmental sustainability. These results partially support the notion of a turning point in the IPR-emissions relationship in developed economies.

In developing countries, however, the long-run relationship between patent protection and emissions is positive and only weakly significant, while the squared term is positive but not statistically significant; hence, exhibiting no evidence of an inverted U-shaped pattern. Contrary to earlier studies that suggested a negative effect of IPR on emissions in developing contexts (e.g., Dechezlepretre et al. 2011; Li, Elheddad, and Doytch 2021), the results indicate that stronger patent protection in developing countries may not yet be associated with long-run emissions reductions.

One possible interpretation is that while IPR may attract foreign investment and support technology transfer, it does not consistently ensure access to or adoption of cleaner technologies. The lack of a significant negative quadratic effect also suggests that even at higher levels of patent strength, there is no clear transition to greener outcomes, potentially due to weaker enforcement

environments, market distortions, or barriers to clean technology diffusion.

4.2.2 | Short-Run Impact of Patent Protection on CO₂ Emissions

In the short run, changes in patent protection (*D1.ipra*) are found to have no statistically significant effect on CO₂ emissions in any of the three samples. Specifically, the coefficient for *D1.ipra* is positive but insignificant in the full and developed samples and positive but still insignificant in the developing sample. These results confirm that short-term shifts in patent regimes do not immediately influence environmental outcomes, which is consistent with the literature emphasizing the lagged nature of technological diffusion and innovation impacts (Jaffe et al. 2002).

The squared term (*D1.iprasqr*) is also insignificant in both the full and developed country samples, indicating no immediate non-linear effects. However, in the developing country sample, the coefficient is negative and weakly significant, suggesting that there may be some early evidence of diminishing short-run benefits at higher levels of patent strength. This could imply that while changes in patent law might initially support cleaner transitions, overly aggressive short-term IPR tightening may slow access to external technologies, especially in resource-constrained environments.

Overall, these findings reinforce the idea that patent-driven environmental changes manifest over the long term, as innovation cycles take time to influence production methods, investment decisions, and infrastructure transitions. The short-run insignificance suggests that patent reforms alone are not sufficient for near-term emissions reduction and need to be supported by targeted complementary policies—such as R&D funding, green technology subsidies, or environmental compliance incentives—to accelerate their environmental impact.

4.2.3 | Error Correction Term (ECT) – Speed of Adjustment

The error correction term (ECT) is negative and highly significant across all samples, confirming the existence of long-run equilibrium relationships between the independent variables and CO₂ emissions. This indicates that any short-term deviation in emissions levels is partially corrected in subsequent periods, validating the use of a dynamic error correction model.

In the full sample, the ECT coefficient is -0.185 , indicating that 18.5% of the deviation from the long-run emissions path is corrected each period. For developed economies, the speed of adjustment is slightly faster at -0.208 , implying a 20.8% correction rate, which suggests these countries are more capable of reverting emissions to long-run levels, likely due to stronger institutional capacity, regulatory frameworks, and policy responsiveness. In contrast, the developing countries exhibit a much faster adjustment rate of -0.385 (38.5%), which might initially seem counterintuitive. However, this likely reflects greater volatility in emissions levels and more abrupt structural corrections,

rather than smoother regulatory mechanisms. Such adjustments may stem from reactive policy shifts, external economic shocks, or rapid changes in energy consumption, rather than deliberate, sustained environmental policy action.

These results show that although all country groups adjust emissions over time, the mechanisms and reliability of this adjustment vary. In developed economies, the process is likely driven by policy and institutional feedback loops (e.g., carbon markets, technological standards), whereas in developing countries, adjustment may result more from external or structural factors, such as commodity price fluctuations or shifts in industrial output.

4.2.4 | Control Variables

Several additional factors appear to also influence CO₂ emissions across countries. Renewable energy consumption is found to significantly reduce emissions in both developed nations with advanced infrastructure, as well as developing countries that potentially remain more reliant on fossil fuels (Shafiei and Salim 2014). According to Acemoglu et al. (2012) innovation increases emissions due to industrial expansion, but overtime adoption of cleaner technologies is expected to take place.

In the long run, trade openness is found to reduce emissions in developing countries and the full dataset suggests a technology transfer (Antweiler et al. 2001), while its impact on developed economies is insignificant. In the short run, trade expansion, however, remains insignificant in both developed and developing clusters, while for the full dataset it is found to be significant and positive, hence suggesting an increase in emissions across all economies. GDP per capita has contrasting effects—raising emissions in developed nations in the short run but reducing them over time (Grossman and Krueger 1995) hence highlighting the need for immediate policy interventions (Mohapatra et al. 2023).

Financial development is found to be negative and weakly significant in the short run (full dataset), while remaining insignificant in the rest of the estimated models both in the short and long run. Urbanization is found to strongly increase emissions across all long run estimated models while its impact in the short run is insignificant indicating potentially a gradual accumulation of environmental consequences (Chen et al. 2022). Finally, FDI does not seem to have any significant impact as according to Zarsky (1999) FDI's impact on CO₂ emissions is highly context dependent. Without strong environmental governance, absorptive capacity, and regulatory alignment, FDI may have little to no positive effect—and could even worsen carbon emissions (Cole et al. 2011). This underscores the need for policy frameworks that guide FDI toward sustainable outcomes, including incentives for green investment and enforcement of environmental standards.

The above analysis reveals that in both developed and developing economies, stronger patent protection is associated with higher long-run CO₂ emissions, though the effect is more pronounced in developed countries. This suggests that while

intellectual property rights (IPRs) may initially stimulate innovation and industrial activity, such advancements are not necessarily aligned with environmental objectives—supporting the threshold argument by Fei et al. (2024), which posits that only beyond a certain level of IPR strength do green technology transfers begin to reduce emissions. However, the insignificance of the squared IPR term across models indicates limited evidence for a robust non-linear effect within the ARDL framework.

Furthermore, the results also point to a faster adjustment dynamic in developing countries, underscoring structural and institutional differences in how patent regimes influence environmental outcomes. These findings affirm the differentiated and nonlinear nature of the patent-emissions nexus across development contexts.

In sum, the findings underscore that IPRs alone are insufficient to drive environmental progress; their effectiveness depends on complementary policies, institutional readiness, and the broader development context. As such, strong patent regimes must be carefully aligned with environmental strategies to ensure they support, rather than hinder, sustainability goals.

4.2.5 | A Locally Weighted Scatterplot Smoothing (LOWESS)-Based Exploration

To visually observe the relationship between the strength of patent enforcement and CO₂ emissions, we also present the LOWESS scatterplot, which confirms the complex and context-dependent dynamics of our estimations. In Figures 1–3 the blue dots represent observed data points, while the red line is a LOWESS (Locally Weighted Scatterplot Smoothing) curve, which captures the underlying trend without assuming a specific functional form.

In the full dataset, the LOWESS curve in Figure 1 illustrates a clear convex trend, indicating that as *ipra* increases, CO₂ emissions initially rise gradually and then accelerate more steeply. This pattern aligns with the fixed effects model results, where both *ipra* and its squared term are positive and statistically significant. The implication is that stronger patent enforcement may stimulate innovation and industrial activity, which, in the absence of environmental safeguards, leads to increased emissions.

In developed countries, the relationship is even more pronounced. The LOWESS curve in Figure 2 exhibits a sharply convex shape, with emissions rising modestly at lower levels of *ipra* and then increasing rapidly as enforcement becomes more stringent. This visual trend is consistent with the empirical findings from the fixed effects model in Table 1, where *ipra* has the strongest positive effect on emissions and the squared term is marginally significant. The ARDL long-run model in Table 2 further supports this, showing a significant positive coefficient for *ipra*. These results suggest that in developed economies, robust patent enforcement may disproportionately benefit industrial sectors that contribute to higher emissions, especially when green innovation is not prioritized.

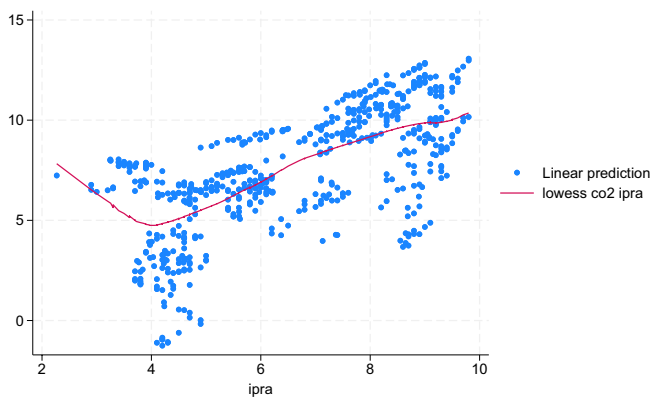


FIGURE 1 | Locally weighted scatterplot smoothing (Lowess): Full dataset. Source: Author's estimations.

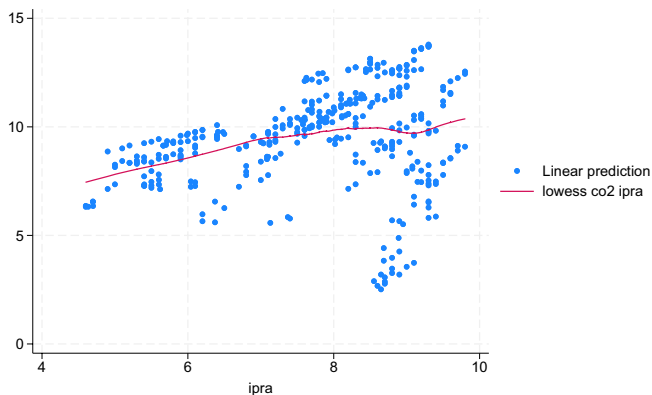


FIGURE 2 | Locally weighted scatterplot smoothing (Lowess): Developed economies. Source: Author's estimations.

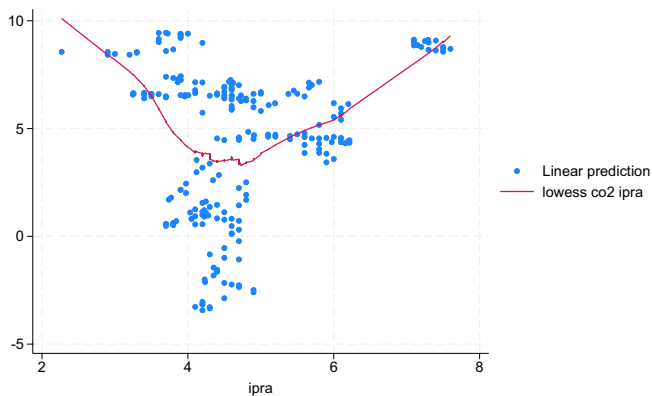


FIGURE 3 | Locally weighted scatterplot smoothing (Lowess): Developing economies. Source: Author's estimations.

Conversely, the pattern in developing economies is more nuanced. Figure 3 reveals a U-shaped LOWESS curve, where emissions initially decline with increasing ipra, reach a minimum around an ipra value of 4, and then begin to rise again. This suggests that moderate levels of patent enforcement may facilitate cleaner technologies or better regulatory compliance, thereby reducing emissions. However, beyond a certain threshold, stronger enforcement may hinder technology diffusion or stimulate industrial expansion, reversing earlier gains. The regression models also reflect this ambiguity as in Table 1, ipra is

weakly positive and iprasqr is not significant, while in Table 2, the long-run effect of ipra is marginally significant and positive, but again, the squared term lacks significance.

4.2.6 | Policy Implications

The results suggest that while patent protection can influence CO₂ emissions, its impact is complex, non-linear, and highly context dependent. In the long run, stronger patent protection is associated with increased emissions in both the full sample and developed countries, with only weak evidence of eventual emissions reduction at very high levels of protection. This implies that patent systems may initially stimulate emissions-intensive industrial and technological activity, and only under specific conditions—such as when innovation is explicitly green-oriented—do they begin to yield environmental benefits. Thus, in developed economies, policymakers should not assume that stronger intellectual property rights (IPRs) alone will foster cleaner outcomes. Instead, patent incentives must be explicitly directed toward green innovation.

In developing countries, the results offer no strong evidence that patent protection significantly reduces emissions in the long run. The expected benefits of stronger IPRs in encouraging green technology transfer and emissions reduction appear limited or delayed. This may reflect barriers such as limited absorptive capacity, weak enforcement systems, or constrained access to patented green technologies. Moreover, the positive and insignificant quadratic term suggests that overly rigid patent enforcement could even hinder progress. Therefore, developing economies should adopt a cautious, flexible approach to patent protection. While moderate IPR strength may help attract cleaner investments, excessively strict patent regimes could restrict access to critical low-carbon technologies.

The short-run results reinforce the conclusion that changes in patent protection do not yield immediate environmental effects. Across all country groups, the short-run coefficients on patent variables are insignificant, underscoring that innovation takes time to materialize and influence emissions trends. This highlights the importance of complementary policies—such as support for R&D, pilot projects, and targeted investment—to bridge the gap between innovation and implementation.

The error correction terms (ECTs) demonstrate that emissions adjust toward long-run equilibrium over time. Developed economies exhibit moderate correction speeds, likely driven by institutional quality and regulatory responsiveness. Interestingly, developing countries show faster adjustment, which may reflect volatility or reactive policy behavior rather than stable environmental governance. This suggests that building robust institutions and regulatory frameworks is crucial for managing emissions trajectories more predictably and effectively.

4.2.7 | Policy Recommendations

The empirical results call for differentiated and adaptive policy strategies to align intellectual property rights (IPRs) with climate and development objectives. More specifically, in developed economies, stronger patent protections are associated with an increase

in emissions over the long run, likely due to industrial expansion fuelled by innovation incentives that are not explicitly green-focused. To address this, patent systems should be reoriented to prioritize climate-relevant innovations. Fast-track approval for green patents, tax credits for sustainable technologies, and extended patent terms for high-impact environmental solutions can help steer innovation toward emissions reduction. Additionally, integrating environmental performance metrics into patent grant and renewal criteria may enhance alignment with climate goals.

For developing countries, excessively rigid patent regimes risk limiting the diffusion of essential low-carbon innovations. Policymakers should adopt flexible IPR frameworks that enable technology transfer while preserving innovation incentives. Tools such as compulsory licensing, open patent pools, and participation in international clean technology partnerships are critical for maximizing environmental benefits without excluding key actors from innovation uptake.

Across both country groups, the short-run effects of patent enforcement on emissions are limited. This suggests that patents alone are insufficient to drive rapid environmental change. Governments should implement complementary policies, including subsidies for renewable energy adoption, public funding for green R&D, especially in high-emission sectors, and public-private partnerships to scale low-carbon technologies. These policies help close the time lag between invention and adoption, particularly where market or institutional barriers slow down diffusion.

Renewable energy consumption consistently demonstrates a strong negative effect on emissions across all models. Governments should prioritize policies that expand access to clean energy, such as reducing import tariffs on renewable technologies, providing financial incentives for decentralized energy systems, and supporting awareness campaigns to boost public and business adoption—especially among small and medium-sized enterprises in developing regions.

The varying speeds at which emissions return to equilibrium in response to shocks highlight the role of institutional strength. To enhance environmental responsiveness, countries should improve regulatory transparency and enforcement capacity, develop specialized expertise within patent offices for evaluating green technologies, and establish monitoring systems to assess the environmental impact of IPR frameworks. Robust institutions are essential not only for emissions control but also for guiding innovation systems in a sustainable direction.

Trade openness and foreign direct investment show mixed effects, suggesting that global markets alone cannot guarantee equitable access to climate technologies. International cooperation is therefore essential. North–South partnerships, multilateral technology-sharing platforms, and inclusive innovation frameworks should be strengthened to ensure wider diffusion of green technologies without exacerbating global inequality in innovation access.

5 | Conclusions

This study investigates the complex relationship between patent system strength and CO₂ emissions using both Fixed Effects

(FE) and Autoregressive Distributed Lag (ARDL) models. These complementary methods provide insights into how intellectual property rights (IPRs) influence environmental outcomes in both the short and long run across developed and developing economies.

The FE model estimates show that stronger patent systems are associated with increased emissions in developed economies. This suggests that while patents may stimulate innovation, they can also encourage industrial expansion that is not necessarily clean or sustainable in the early stages. The non-linear nature of the relationship supports the idea that the increase in emissions becomes larger at higher levels of patent strength, indicating that patent systems might favor fossil-fuel efficiency or other carbon-intensive innovations because they are more immediately profitable than clean energy R&D. In developing economies, the effect of patent strength on emissions is present but less pronounced in magnitude; hence, indicating that the influence of IPRs is moderated by lower innovation capacity and institutional differences.

The ARDL results highlight dynamic adjustment processes, showing that the emissions effects of patents persist over time. The speed at which emissions return to equilibrium differs by development level, with faster adjustment observed in developing economies. This likely reflects their reliance on external technology transfers rather than domestically generated innovation. In the short term, changes in patent protection do not significantly influence emissions, reflecting the delayed impact of innovation on environmental performance.

Across all estimated models, renewable energy emerges as a consistently effective tool for emissions reduction, confirming its role as a key driver of environmental sustainability. Trade openness presents mixed results, contributing to emissions reductions only under specific economic conditions, while urbanization continues to drive emissions upward, emphasizing the importance of integrating climate goals into urban planning.

These findings refine the Environmental Kuznets Curve (EKC) hypothesis by illustrating how IPRs can shape its trajectory. Strong patents may delay the onset of emissions decline, as innovation first fuels general economic expansion before transitioning to cleaner technologies. Flexible IPR regimes—particularly those that enable technology access—can support a faster transition to the downward phase of the EKC by avoiding dependence on carbon-intensive pathways.

The study's key takeaway is that patents alone are not sufficient to deliver climate outcomes. While critical for fostering long-term innovation, their short-run environmental effects are limited. This necessitates complementary measures, such as renewable energy subsidies, carbon pricing, and international technology-sharing mechanisms, to enhance the environmental impact of innovation systems.

Despite its contributions, this study might be exposed to some limitations reflected by its reliance on aggregate indicators of patent system strength, which may not fully capture the nuances of how intellectual property rights (IPRs) function in

practice—such as enforcement quality, sectoral differences, or the distinction between green and non-green patents. Additionally, CO₂ emissions are used as the sole environmental indicator, which, while important, may not fully represent the broader spectrum of environmental impacts influenced by innovation and economic development (e.g., biodiversity loss, water pollution).

Future research directions can focus on exploring how patent activity in developed countries influences green technology transfer to developing nations; assessing how IPR impacts differ across industries with varying emissions intensities; or investigating how patent systems interact with other policy instruments such as carbon pricing, R&D subsidies, and environmental regulations.

Conflicts of Interest

The author declares no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Endnotes

¹ VIFs are a more comprehensive diagnostic for multicollinearity than pairwise correlations, as they account for the shared variance among all predictors simultaneously, not just bivariate relationships. For this reason, we have used VIFs as the primary diagnostic tool (see, O'Brien 2007; Wooldridge 2019).

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Appendix A

TABLE A1 | Definitions of variables.

Variable	Definition	Source
ipra	Patent strength index: The score of the index used in this study ranges from 0 to 10, with 0 indicating a weak patent system and 10 indicting a stronger patent system.	Alexiou (2023)
iprasqr	This is defined as the square of the centered version of <i>ipra</i> and calculate as follows: $iprasqr = (ipra - \text{mean}(ipra))^2$	Author's calculations
renew	Renewable energy consumption (% of total final energy consumption): This indicator measures the share of energy from renewable sources like solar, wind, hydro, geothermal, and biomass in a country's total energy consumption. It is a key metric for tracking progress toward sustainable energy goals and the transition to cleaner energy sources	World Development Indicators code: EG.FEC.RNEW.ZS
loginnov	Logarithm of patent applications filed through the Patent Cooperation Treaty procedure or with a national patent office for exclusive rights for an invention. Used as a proxy for innovation.	World Development Indicators code: IP.PAT.RESD
trd	NET trade, %GDP: This is the sum of exports and imports of goods and services as a percentage of a country's gross domestic product. This indicator measures the openness of a country's economy to international trade.	World Development Indicators code: NE.TRD.GNFS.ZS
gdppc	Logarithm of GDP per capita: This indicator measures the annual percentage change in a country's GDP per person, calculated using constant local currency to account for inflation.	World Development Indicators code: NY.GDP.PCAP.KD.ZG
co2	CO2 emissions (metric tons per capita): This indicator measures the amount of carbon dioxide emitted per person within a specific country or region, based on territorial emissions. It is a key metric for understanding a nation's contribution to climate change and its environmental impact.	World Development Indicators code: EN.ATM.CO2E.PC
fdi	Foreign direct investment, net inflows (% of GDP): This indicator measures the net inflows of investment from foreign investors as a percentage of a country's Gross Domestic Product (GDP). It reflects the flow of investment into a country, including equity capital, reinvested earnings, and other capital, minus any disinvestment or repatriation of funds.	World Development Indicators code: BX.KLT.DINV.WD.GD.ZS
urban	Urban population (% of total population): It indicates the proportion of a country's population living in urban areas, as defined by national statistical offices. This indicator is crucial for understanding demographic shifts and the pace of urbanization globally.	World Development Indicators code: SP.URB.TOTL.IN.ZS
findev	Domestic credit to private sector (% of GDP): This indicator measures the amount of financial resources provided to the private sector by financial corporations as a percentage of a country's gross domestic product.	World Development Indicators code: FS.AST.PRVT.GD.ZS

TABLE A2 | Cross correlations.

Panel A. Developed economies										
Variables	CO ₂	ipra	iprasqr	renew	innov	trd	gdppc	findev	fdi	urban
CO ₂	1									
ipra	0.197***	1								
iprasqr	−0.147***	−0.557***	1							
renew	−0.270***	0.322***	0.022	1						
loginnov	0.305***	−0.084	−0.184*	−0.250***	1					
trd	−0.152***	0.131**	−0.091**	−0.271**	−0.271***	1				
gdppc	0.093	0.031	−0.032**	−0.127**	−0.029**	0.196***	1			
findev	0.142**	0.320**	−0.356***	−0.017	0.457***	−0.006	−0.210***	1		
fdi	−0.018	0.119	−0.158***	−0.264***	−0.184***	0.592*	0.266***	−0.001	1	
urban	0.212***	0.340***	−0.168***	−0.195***	0.073	0.383***	0.010	0.196***	0.208***	1
Panel B. Developing economies										
CO ₂	1									
ipra	0.077	1								
iprasqr	0.161*	0.465***	1							
renew	−0.792***	−0.002	−0.001	1						
loginnov	0.174***	−0.051**	−0.094***	−0.109**	1					
trd	0.198***	0.315***	0.111**	−0.338***	−0.092**	1				
gdppc	0.044***	0.042	−0.087***	0.007***	0.196	0.031	1			
findev	0.288***	0.514*	0.183**	−0.153**	0.325**	0.472**	0.124	1		
fdi	0.035	0.557	0.432**	−0.009	−0.025	0.121**	0.081***	0.153**	1	
urban	0.267***	0.071***	0.383***	−0.327***	−0.110***	−0.221***	−0.274***	−0.280***	0.269***	1

Note: Author's calculations. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

TABLE A3 | Summary statistics.

Panel A. Developed economies					
Variable	Obs.	Mean	Standard deviation	Min	Max
CO ₂	560	9.172579	3.526158	3.811011	20.47193
ipra	553	7.751386	1.363289	4.078484	9.9
iprasqr	553	1.854094	2.165965	0.556268	13.4902
renew	560	14.76418	14.27633	0.0958	61.111
loginnov	560	8.083374	1.955492	3.73767	12.86712
trd	560	101.6418	82.30599	18.12563	442.62
gdppc	560	1.578739	0.109116	−10.0139	12.51916
findev	507	111.6961	43.51272	23.37688	233.211
urban	560	79.85007	10.94246	53.086	100
fdi	560	6.763556	11.01539	−15.74502	86.58909
Panel B. Developing economies					
Variable	Obs.	Mean	Standard deviation	Min	Max
CO ₂	360	4.375675	2.772048	0.8056783	11.63994
ipra	352	4.599038	1.064033	2.1	7.6
iprasqr	352	1.130088	1.892336	9.26E-07	9.005775
renew	360	20.82774	13.6412	1.9554	52.71226
loginnov	360	7.095919	2.01432	3.465736	14.03522
trd	360	63.56542	38.49522	16.43858	220.4068
gdppc	360	2.843505	0.228965	−14.8762	16.26195
findev	336	60.46955	43.92746	8.906126	160.1248
urban	360	65.34335	18.47982	27.24	91.749
fdi	360	2.729343	1.952848	−2.75744	11.74302

Note: Author's calculations.

TABLE A4 | Panel unit root tests.

Variables	Unit root test method			Test results
	Results	IPS test	HT test	
CO ₂	Statistic	−4.728	0.581	<i>I</i> (0)
	<i>p</i>	0.000	0.008	
ipra	Statistic	−6.471	0.596	<i>I</i> (0)
	<i>p</i>	0.000	0.025	
iprasqr	Statistic	−3.883	0.876	<i>I</i> (0)
	<i>p</i>	0.000	0.001	
d.renew	Statistic	−6.793	0.582	<i>I</i> (1)
	<i>p</i>	0.000	0.028	
d.loginnov	Statistic	−9.762	−1.913	<i>I</i> (1)
	<i>p</i>	0.000	0.035	
d.gdppc	Statistic	−14.854	−0.427	<i>I</i> (1)
	<i>p</i>	0.000	0.000	
d.dtr	Statistic	−13.659	0.638	<i>I</i> (1)
	<i>p</i>	0.000	0.000	
d.findev	Statistic	−3.154	0.478	<i>I</i> (1)
	<i>p</i>	0.000	0.031	
d.urban	Statistic	−9.473	0.932	<i>I</i> (1)
	<i>p</i>	0.00	0.001	
	<i>p</i>	0.000	0.003	
fdi	Statistic	−4.690	0.833	<i>I</i> (0)
	<i>p</i>	0.000	0.003	

Note: *P*-values < 0.05 denote significance at the 5% level of significance i.e., rejecting the Null Hypothesis of Unit roots in the series, in other words all series are non-stationary; *I*(0) and *I*(1) denote the order of integration, i.e., the number of times you need to difference the series to make it stationary; the prefix d denotes differencing the series. Source: Author's estimations.

TABLE A5 | Countries used in the estimation.

Argentina	Developing
Australia	Developed
Austria	Developed
Belgium	Developed
Brazil	Developing
Canada	Developed
Chile	Developing
China	Developing
Colombia	Developing
Czech Republic	Developing
Denmark	Developed
Finland	Developed
France	Developed
Germany	Developed
Greece	Developed
Hong Kong	Developed
Hungary	Developed
Iceland	Developed
India	Developing
Indonesia	Developing
Israel	Developed
Italy	Developed
Japan	Developed
Korea, Rep.	Developed
Malaysia	Developing
Mexico	Developing
Netherlands	Developed
New Zealand	Developed
Norway	Developed
Philippines	Developing
Poland	Developing
Portugal	Developed
Romania	Developing
Russia	Developing
Singapore	Developed
Slovakia	Developed
South Africa	Developing
Spain	Developed
Sweden	Developed
Switzerland	Developed
Taiwan	Developed
Thailand	Developing
Turkey	Developing
United Kingdom	Developed
USA	Developed
Venezuela, RB	Developing

Note: This classification aligns with Alexiou (2023) as well as with how institutions like the IMF, World Bank, UNCTAD defined them during the period 1998–2017.

TABLE A6 | Variance inflation factors (VIF).

Full dataset			Developed economies			Developing economies		
Variable	VIF	1/VIF	Variable	VIF	1/VIF	Variable	VIF	1/VIF
ipra	2.50	0.399531	ipra	2.31	0.432812	ipra	2.66	0.376276
findev	2.13	0.470035	loginnov	2.04	0.490098	urban	2.31	0.432550
urban	1.75	0.570965	trd	1.83	0.545355	iprasqr	2.29	0.436361
loginnov	1.71	0.584982	findev	1.73	0.577207	trd	2.13	0.469131
trd	1.65	0.604507	renew	1.73	0.578255	findev	2.02	0.495693
renew	1.64	0.608603	iprasqr	1.72	0.583041	renew	1.97	0.507328
fdi	1.34	0.748220	urban	1.50	0.665301	loginnov	1.85	0.541599
gdppc	1.19	0.842440	fdi	1.39	0.718566	fdi	1.79	0.559369
iprasqr	1.16	0.864799	gdppc	1.17	0.858077	gdppc	1.15	0.873311
Mean VIF	1.67		Mean VIF	1.71		Mean VIF	2.02	

Note: Author's estimations.



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