

Patent Strength, Innovation, and CO₂ Emissions: Evidence of Non-Linear Environmental Impacts Across Economies

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Abstract

This study investigates the complex relationship between patent strength, innovation, and CO₂ emissions by exploring a pathway through which the strength of patents influences environmental sustainability. Utilizing Structural Equation Modelling (SEM), we examine data from a diverse set of OECD and non-OECD countries over the period 1998–2017. Our results reveal a non-linear, S-shaped relationship between patent stringency and CO₂ emissions, highlighting that while stronger patent protections can initially lead to increased emissions due to industrial activity, they may also encourage efficiency improvements and cleaner practices after reaching a certain threshold. However, excessively stringent patents may revive emissions by reducing competition and innovation. The findings emphasize the need for nuanced patent policies that consider both economic growth and environmental sustainability.

Keywords: Patents; Innovation; CO₂;

JEL codes: F21; L6; O33; O38

1. Introduction

Strong patent protection can serve as a catalyst for innovation by providing inventors with exclusive rights, hence encouraging investment in research and development (R&D). In the context of climate change, this can lead to the creation of green technologies aimed at reducing carbon emissions. However, excessively stringent patents might also stifle competition and slow the diffusion of eco-friendly innovations, limiting their widespread adoption.

The role of intellectual property in climate change mitigation is gaining traction amid ongoing discussions on addressing the severe impacts of climate change on environmental sustainability. According to Copenhagen Economics (2009), advancing green technologies and sustainable energy resources is essential to combat climate change's adverse effects. Given however the disparities in resource availability, economic development, and technological advancement, the transfer of technological knowledge from advanced nations to developing countries is critical (Ockwell et al. 2010).

In international business, evaluating the strength of patent systems across different nations is essential to understand how intellectual property is managed. The variation in legal frameworks worldwide indicates that the economic benefits of introducing new products or technologies depend significantly on the protection and enforcement of intellectual property rights (Alexiou 2023; Teece 1998). Consequently, the development of technology in different economies, alongside the differing robustness of patent systems, affects firms' strategic choices, particularly in emerging markets (Brander et al. 2017; Brandl et al. 2019; Lamin and Ramos 2016; Peng et al. 2017; Zhao 2006). The World Trade Organization (WTO) highlights that safeguarding Intellectual Property Rights (IPRs) is crucial as it fosters innovation and economic growth (Article 7 TRIPS Agreement).

Empirical studies generally support the role of patents in fostering innovation, although the impact varies across industries. According to OECD (2004) companies in certain sectors, particularly biotechnology, pharmaceuticals, chemicals, and to some extent, machinery and computers, regarded patents as highly significant for protecting their competitive advantage. However, firms in other industries viewed patents as less critical, often relying more on alternative strategies such as secrecy, market leadership, early entry, technological complexity, and control of complementary assets (Levin et al. 1987; Cohen et al. 2000).

Studies on the impact of Intellectual Property Rights (IPR) protection on climate change however, have yielded mixed results. Some research emphasizes that IPR protection is crucial in encouraging innovation and the adoption of clean energy technologies, while others argue that it may hinder access to these technologies in less developed countries due to higher costs (Kapur 2011; Alexiou 2023). The lack of agreement among scholars may be due to data constraints, differences in the data itself, or the methodological approaches used in the studies (Hascic et al. 2010).

Research on the relationship between IPR protection and innovation or transfer of clean technologies is still relatively new, with the preponderance of the extant literature based on legal analyses and case studies (Copenhagen Economics 2009; IRENA 2012). Therefore, given the lack of evidence on the direct or indirect – through innovation - effect of the strength of intellectual property rights on pollution, this study is the first to explore the pathway patent strength $\rightarrow$ innovation $\rightarrow$ CO₂ emissions in both OECD and non-OECD countries. It should be emphasized that these groups of countries exhibit contrasting developmental stages, industrial profiles, and environmental outcomes, which significantly influence how patent regimes affect CO₂ emissions.

In this direction utilizing a data set comprising 43 countries we adopt a Structural Equation Modelling (SEM) methodology to investigate the direct as well as the mediating

impact of the strength of patent systems via innovation on CO₂ emissions. Our analysis reveals a non-linear relationship between patent strength and CO₂ emissions, characterized by an S-shaped curve. Stronger patent protections initially lead to higher emissions, driven by increased industrial activity and production in carbon-intensive sectors. However, as firms mature and efficiency improves, emissions begin to decline. At very high levels of patent stringency, the relationship turns positive again, suggesting that excessively stringent patents might stifle competition and innovation, potentially leading to increased emissions. This dynamic is observed across both OECD and non-OECD countries, although the specific patterns differ, underscoring the importance of considering economic context when crafting patent and environmental policies.

The paper introduces several novel insights into the relationship between patent strength, innovation, and CO₂ emissions. More specifically it is the first study to analyze the non-linear (S-shaped) pathway of patent strength → innovation → CO₂ emissions using Structural Equation Modeling (SEM) across 43 countries by incorporating latent variables for innovation and distinguishes between OECD and non-OECD dynamics. Furthermore, it uncovers a non-linear, S-shaped impact of patent system strength on emissions, where stronger patents initially increase emissions due to industrial activity, then reduce them as innovation drives efficiency, but overly stringent protections lead to higher emissions again by stifling competition. The study employs Structural Equation Modeling (SEM) to capture both direct and indirect effects of patent strength, using two distinct indices—IPRA (patent protection) and IPRP (patent enforcement)—to assess these impacts. By differentiating between OECD and non-OECD countries, the paper reveals that the relationship between patents and emissions varies based on economic context, with an inverse S-shaped pattern in developing countries. A key finding is that innovation acts as a mediator, meaning the focus of innovation—clean or fossil fuel technologies—determines the environmental outcome. Additionally, the

study challenges assumptions that stronger patents always lead to greater renewable energy adoption and emphasizes the need for balanced patent policies to encourage green innovation without creating market monopolies. The use of latent variables to refine innovation measurement further enhances the robustness of these findings, offering important policy implications for aligning intellectual property rights with environmental goals.

The rest of the paper is organized as follows. Section 2 presents a literature overview which serves basis for the hypothesis development. Section 3 reveals the empirical strategy of the paper and the underlying data. Section 4 presents the results and offers a discussion. Section 5 concludes and offers some policy advice.

2. Relevant literature

Traditional economic analyses of patent law effectiveness have primarily examined the connection between these laws and their ability to promote innovation. Although views vary regarding how patent laws impact innovation, there is broad agreement that they offer incentives for private, economically efficient research and development (R&D), ultimately fostering innovation by enabling monopoly profits (Scotchmer, 1999; Budish et al. 2016; Nordhaus, 1969). Economic literature on patents however reveals that conclusions about the efficiency of R&D vary depending on the industry being analysed. The differences in these findings have become increasingly pronounced with the global expansion of patent systems.

Previous research has evaluated the role of technologies in reducing CO₂ emissions and numerous technologies have been created by industries, businesses, and individuals to address pollution-related challenges. Whilst environmental degradation is influenced by various factors, such as population growth and technological development (Ehrlich and Holdren, 1971; Cole and Elliott, 2003), it is also been suggested that patents

that are granted for new technologies may lead to the reduction of pollution (Albino et al. 2014). Even though ecological innovation is closely related with the development of green technologies, products aimed at promoting a greener environment should also be considered in the discourse of analysis. In this context, empirical research has revealed that innovations and patents for climate-related technologies are influenced by CO₂ emissions and other greenhouse gases (Su and Moaniba, 2017) and the level of these emissions impacts the invention and patenting of climate technologies.

In the empirical literature several channels through which innovation impacts emissions have been identified. A few of such mechanism work through productivity improvements, through developing and patenting new inventions, as well as the efficient utilization of scarce resources (Oyebanji et al. 2022). Linnenluecke et al. (2019) by investigating the influence of country-level economic factors, such as real GDP, market return, and turnover, as well as institutional variables on patent intensity found that cleantech patenting activity is encouraged by a supportive institutional environment, particularly through carbon pricing policies, public R&D spending, and human capital development, all of which promote innovation and low-carbon advancements. Additionally, the study extends the concept of 'path creation' by outlining various pathways for cleantech development at the country level within a real options framework and providing a valuation approach for cleantech patents. In a study by Zuo and Zhou (2023), it was found that: (1) the factors influencing green innovation efficiency in patent-intensive industries can be grouped into five categories: organizational, institutional, environmental, capital, and technical factors; (2) out of 24 specific sub-factors within these categories, key factors such as intellectual property protection, economic development level, trade openness, infrastructure development, foreign direct investment (FDI), outward FDI, and government support have the most significant impact on efficiency; (3) there are specific configuration paths that lead to high efficiency in green technology

R&D, green achievement transformation, and overall efficiency in patent-intensive industries.

On the impact of patent strength on CO₂ emission, Wang et al.'s (2012) study contributes to the theoretical understanding of energy technology innovation by offering insights for shaping energy technology policies. More specifically, by examining the impact of patent strength on CO₂ emissions in China found that domestic patents for fossil-fuel-based technologies do not significantly influence CO₂ emission reductions whilst patents for carbon-free energy technologies play a crucial role in reducing emissions, particularly in eastern China. This impact however is less significant at the central, western, and national levels.

Furthermore, Cheng et al. (2019) provided evidence suggesting that increasing the renewable energy supply reduces CO₂ emissions per capita, with the strongest effect observed at the 95th quantile. However, the development of environmental patents accelerates carbon emissions per capita, significantly impacting emissions only at the higher end of the conditional distribution. Additionally, GDP per capita was found to raise CO₂ emissions, with the most significant effect in the 5th quantile. Exports also increase emissions, following an asymmetric inverted U-shaped pattern (Cheng et al. 2019).

Using a more dynamic framework (Vector Error Correction model, Impulse Response Functions and Decomposition of Variance), Wang, Yang, & Zhang, (2012) looked at both the long and short-run. The results showed that only in the long-run an increase in energy technology patents helps to reduce CO₂ emissions intensity. Along the same lines, Wang et al. (2022) explored the short and long-

term effects of green innovation on carbon emission intensity in China from 1993 to 2020, using an ARDL methodology. The evidence suggests that green invention patents reduce carbon emission intensity in the short term but act as a barrier in the long term. In contrast, green utility model patents consistently suppress carbon emission intensity in both short and long terms. Additionally, it was found that adjusting the industrial structure by reducing the secondary sector and expanding the tertiary sector is most effective for short-term emission reductions. Furthermore, the impact of energy prices on reducing emissions is weaker than that of industrial restructuring whilst foreign direct investment (FDI) and non-fossil energy consumption increase carbon intensity in the short term, but increasing the proportion of non-fossil energy is critical for long-term emission reduction.

In a study exploring non-linearities Gierałtowska et al. (2022) using fixed effects regression and two-step system GMM, analysing World Bank data for 163 countries from 2000 to 2016 found that that urbanization has an inverted U-shaped relationship with CO₂ emissions, while renewable energy consumption reduces emissions. Additionally, GDP per capita is also found to follow an inverted U-shaped pattern, supporting the Environmental Kuznets Curve (EKC) whilst innovation, measured by residents' patents, exhibits a non-linear inverted U-shaped effect on emissions. In the same spirit, Mahmood et al. (2023) explored the effects of economic growth, patents, industrialization, and urbanization on CO₂ emissions in 17 Middle East and North Africa (MENA) economies using spatial econometrics. Their findings support the Environmental Kuznets Curve (EKC) both within individual economies and across the MENA region. Urbanization is

found to increase CO₂ emissions in local economies but reduces emissions in neighbouring countries, with its total effect found to be insignificant whilst industrialization has a positive impact on emissions both domestically and regionally. As for the impact of patents, while increasing emissions in domestic economies, they help however reduce CO₂ emissions in neighbouring countries and across the MENA region, hence, suggesting a beneficial regional environmental impact.

Additional evidence produced by Mehmet and Emrullah (2021) in a study investigating the impact of environmental technological innovations on CO₂ emissions in 18 OECD countries from 2005 to 2018, using the panel generalized method of moments (GMM) suggested that a 1% increase in patent applications aimed at preventing climate change reduced CO₂ emissions by 0.02%. Conversely, a 1% increase in energy consumption raised emissions by 0.56%, while a 1% increase in GDP growth caused a 0.002% increase in emissions.

Chui et al. (2024) using a QARDL approach they explored the impact of renewable energy consumption on CO₂ emissions in the USA, using data from January 2010 to May 2022. The long-term analysis reveals a negative relationship between renewable energy consumption and emissions, while short-term significance is only observed at lower quantile levels. When incorporating technological innovation (measured by patents), the study found a substantial reduction in emissions over time. However, renewable energy consumption, rather than technological innovation, had the most significant impact on reducing emissions at lower quantiles. Moreover, a study by Alexiou (2023) which is the first to use two alternative indices measuring differences in patent system

strength to investigate the relationship between intellectual property rights (IPRs) and renewable energy consumption, while controlling for other potential determinants found that stronger IPR protection has a negative impact on renewable energy consumption whilst a convex relationship emerges when non-linearities are considered.

Finally, Ductor and Grechyna (2015) highlight that a country's financial sector characteristics and its level of financial openness are critical to its economic performance, hence suggesting that financial development can positively influence environmental outcomes by facilitating the adoption of energy-saving technologies through improved financing options. Greater financial openness could also promote positive spillovers from foreign technological innovations. In the BRIC economies, Tamazian et al. (2009) found that financial development is linked to lower CO₂ emissions, while Tamazian and Rao (2010) reported that financial liberalization reduces emissions in European transitional economies. Conversely, You et al. (2015) found no relationship between financial openness and pollution.

In view of the extant literature, there is a) lack of empirical work on how patent strength indirectly affects emissions via innovation, especially using cross country data; b) prior studies focus on legal analysis or are country specific (e.g., China), not global SEM approaches; and c) no clear consensus in the literature on whether strong patents support or hinder clean innovation. As such, there is a valid justification of a study that explores and effectively provides a comprehensive empirical investigation of the direct as well as the mediating effect of IPR protection on the innovation-pollution nexus.

3. Empirical investigation

According to Nordhaus (1969), the promise of monopoly rents from patent protection provides firms with incentives to invest in research and development (R&D), thereby fostering technological innovation. Building on this, Scotchmer (1999) emphasizes that well-designed intellectual property rights (IPRs) can balance the trade-off between innovation incentives and the diffusion of knowledge. This innovation dynamic is then connected to environmental outcomes through the clean technology adoption channel. Specifically, stronger patent regimes can facilitate the development and dissemination of environmentally friendly technologies, as argued by Su and Moaniba (2017). Their work illustrates how intellectual property protection can reduce uncertainty for clean tech investments and encourage firms to shift toward lower-emission alternatives. Finally, the relationship between patent strength and emissions is theorized to follow an S-shaped curve, drawing on the logic of the Environmental Kuznets Curve (EKC) and its economic counterpart. Initially, patent strengthening may have little effect on emissions; as innovation gains traction, emissions decline more rapidly. However, diminishing returns or saturation effects may later flatten this trend. This non-linear trajectory addresses critiques regarding the absence of a well-articulated causal pathway and supports the empirical hypotheses with a clearer theoretical logic.

We therefore hypothesize that the patent strength affects innovation, which in turn influences CO₂ emissions. This framework aligns well with both economic theory and empirical findings expounded in the preceding section. Stronger patent systems can potentially encourage innovation by providing legal protection and economic incentives for firms to invest in research and development (R&D). This

protection enables firms to recover their R&D costs and profit from new technologies, which can lead to higher rates of innovation, including clean technology. However, overly stringent patents might also stifle innovation by increasing costs or limiting the spread of new technologies, particularly in developing countries (Kapur 2011; Alexiou 2023).

Innovation, particularly in clean technology, can lead to the development of more efficient, less carbon-intensive energy production and consumption processes. Thus, higher innovation in clean technology can reduce CO₂ emissions by replacing fossil fuels with renewable energy sources or improving energy efficiency. Conversely, if the innovation is focused on more efficient fossil fuel extraction or processing, it could potentially lead to an increase in CO₂ emissions, depending on the balance between clean and conventional energy technologies.

3.1. Methodology

To simultaneously examine the hypothesized pathway: patent strength $\rightarrow$ innovation $\rightarrow$ CO₂ emissions, we utilize a structural equation model (SEM), as we explore multiple relationships, including direct, indirect (mediating), and complex interactions among variables. SEM explicitly models measurement errors and latent variables, reducing issues related to endogeneity (Bollen and Paxton, 1998). In SEM methodology the direct effects are those of patent strength on CO₂ emissions, while indirect effects are mediated through innovation and renewable energy. We compare them based on the magnitude and statistical significance of standardized path coefficients. When innovation is modelled as a latent variable,

the indirect pathway becomes weaker due to the shared variance being absorbed into the latent construct, reducing observed mediation.

In this direction an econometric model is formulated and estimated for a dataset comprising a cluster of both OECD and non-OECD countries over the period 1998–2017 based on the availability and consistency of the IPRA and IPRP indices, which are central to our analysis. The 43 countries included were those for which complete and consistent data were available across all variables in our SEM framework. In exploring the link between the strength of patent enforcement and CO2 via the innovation channel additional control variables have also been used. The 43 countries used in the empirical analysis are listed in Table A1 in the Appendix.

We consider a SEM with three endogenous variables: innovation, renewable energy usage, and carbon dioxide emissions per capita. The model can be expressed with the following equations:

Innovation Equation:

$$Innovation_{it} = \beta_1 IPR_{it} + \beta_2 IPRsq_{it} + \beta_3 IPRcubed_{it} + \beta_4 RD_{it} + \beta_5 Trade_{it} + \beta_6 FD_{it} + \varepsilon_{1it} \quad (1)$$

Renewable Energy Usage Equation:

$$REU_{it} = \gamma_1 Innovation_{it} + \gamma_2 Trade_{it} + \gamma_3 FD_{it} + \varepsilon_{2it} \quad (2)$$

CO2 Emissions Per Capita Equation:

$$CO2pc_{it} = \delta_1 IPR_{it} + \delta_2 IPRsq_{it} + \delta_3 IPRcubed_{it} + \delta_4 Innovation_{it} + \delta_5 REU_{it} + \delta_6 EnergyUse_{it} + \delta_7 EnergyInt_{it} + \delta_8 Trade_{it} + \delta_9 FD_{it} + \varepsilon_{3it} \quad (3)$$

where $Innovation_{it}$ is the total patent applications in country i in time t ; IPR_{it} is an index that measures the strength of patent systems, coming in two forms IPRA and IPRP and are used in separate specifications; they do not form a composite index, but are meant to capture different dimensions of patent strength - legal provisions (IPRA) vs. enforcement dynamics (IPRP), (further explanation is provide below). We also include their squared and cubic terms, $IPRsq_{it}$ and

$IPRcubed_{it}$, to capture non-linear patterns. $CO2pc_{it}$ refers to the CO2 emissions in metric tons per capita. RD_{it} is the countries' spending on R&D as share of their GDP; $Trade_{it}$ is total import and export as share of GDP; FD_{it} is the share of credit in GDP. REU_{it} is the renewable energy consumption as share of total final energy consumption; $EnergyUse_{it}$ refers to the amount of energy consumed by countries in kilograms of oil equivalent per capita; $EnergyInt_{it}$ refers to the amount of energy consumed per unit of output or economic activity expressed in megajoules (\$2011 PPP GDP). ε_{1it} , ε_{2it} and ε_{3it} are the error terms assumed to be normally distributed and independent of the predictor variables. It should be noted that our innovation proxy captures total patent applications, and we acknowledge its limitation in distinguishing green from non-green innovation and emphasize that the observed S-shaped pattern partly reflects the aggregate mix of innovation, where cleaner innovation initially rises, but may eventually give way to strategic or non-green patenting under monopolization (see Chui et al., 2024).

3.2. The variables

The IPRA Index is developed by Papageorgiadis, Cross, and Alexiou (2014) and updated by Alexiou (2023) to cover 1998–2017. It captures the strength of patent protection across countries by focusing on aspects such as the legal framework, enforcement mechanisms, and duration of protection, with its score ranging from 0 to 10, where higher values indicate stronger patent systems. The IPRP Index is developed later by Papageorgiadis and Sofka (2020) and is similar to the IPRA but incorporates firm-level patent litigation data, which reflects how effectively patents are enforced at a granular level. This index also ranges from 0 to 10,

offering a measure of patent enforcement strength. The indices' design considers the volatility in patent enforcement costs, reflecting real-world legal and practical challenges companies face when protecting their innovations.

Conceptually, equation (1) postulates that stronger patent systems can encourage innovation by providing legal protection and economic incentives for firms to invest in research and development (R&D). This protection enables firms to recover their R&D costs and profit from new technologies, which can lead to higher rates of innovation, including clean technology. However, overly stringent patents might also stifle innovation by increasing costs or limiting the spread of new technologies, particularly in developing countries.

Equation (2) postulates that technological advances can lead to increased adoption of renewable energy technologies. By including renewable energy consumption as an outcome of innovation, we explore whether innovation is translating into tangible shifts towards cleaner energy sources. This pathway helps to explain part of the indirect effect of patent strength on CO₂ emissions: strong patent systems encourage innovation, which leads to greater adoption of renewable energy, thereby reducing carbon emissions.

Finally, equation (3) postulates that patent systems and innovation, particularly in clean technology, can lead to the development of more efficient, less carbon-intensive energy production and consumption processes. Thus, higher innovation in clean technology can reduce CO₂ emissions by replacing fossil fuels with renewable energy sources or improving energy efficiency. Conversely, if the innovation is focused on more efficient fossil fuel extraction or processing, it could

potentially lead to an increase in CO₂ emissions, depending on the balance between clean and conventional energy technologies.

It is critical to note that our key variable: patent strength index enters SEM in three forms: level, square and cube term. We are hypothesizing a specific type of nonlinear relationship characterized by what is known as an S-shaped (or cubic) response. We assume that at low levels of patent strength, increases lead to more innovation and/or lower CO₂ emissions, as firms feel secure enough to invest in developing new technologies. As patent strength increases, the effectiveness in driving further innovation or CO₂ reductions starts to wane due to potential negative effects, such as reduced collaboration and increased costs associated with navigating complex patent landscapes. At very high levels of patent strength, the relationship becomes positive again, indicating that strong patents might foster an environment conducive to advanced innovation and CO₂ reductions, possibly because firms have gained substantial market power and can further invest in cutting-edge technologies.

The inclusion of variables like renewable energy consumption, R&D investment, energy use, energy intensity, financial development in equation (3) is in line with the extant literature which enriches the model by providing a more comprehensive illustration of the relationships at hand. In particular, renewable energy consumption is directly related with pollution (Alexiou, 2023); R&D investment is a direct driver of innovation (Budish et al. 2016); Energy use intensity can help explain CO₂ emissions directly (Wang et al. 2022); for example, higher energy use (especially from non-renewable sources) would typically lead to higher CO₂ emissions, while energy intensity measures how efficiently energy is

used per unit of GDP; Financial development can influence environmental outcomes by facilitating the adoption of energy-saving technologies through improved financing options (Ductor and Grechyna, 2015).

The main data provider is the World Development Indicators database of the World Bank. Definition of variables is provided in Table A2 in the Appendix. Tables A3 and A4 also provide the summary statistics and the cross correlations of the variables used in the estimation.

The rationale of introducing the equations (1) to (3) in a SEM setup is to observe direct pathways, such as how stronger patent systems affects CO₂ emissions, or how innovation affects CO₂ emissions or renewable energy consumption; as well as the indirect effects, i.e. whether the effects of patent strength on CO₂ emissions are mediated through pathways like innovation and renewable energy consumption.

4. Results and discussion

4.1. Baseline results

Table 1 presents the baseline results, for the two patent strength indices: IPRA (columns 1-3) and IPRP (columns 4-6). Both measures of patent strength are hypothesized to be important factors for driving innovation when measured either through the IPRA index, or IPRP index. Albeit attempting to capture the same effect i.e. patent enforcement, it should be stressed that the IPRP index is more dynamic due to the inclusion of litigation data, hence, providing insights into the effectiveness of patent systems beyond just legal provisions, which could be the driver difference. Patent strength is found to be positively influencing innovation,

indicating that stronger patent protections are associated with increased innovative activities which is in line with Allred and Park (2007). This suggests that firms feel more secure in investing in research and development (R&D) when their inventions are well-protected. However, the negative coefficient of the squared patent strength index indicates diminishing returns; indicates; that is, the benefits to innovation rise at a decreasing rate and may even begin to decline at intermediate levels of patent strength. Furthermore, the positive coefficient for the cubic term, albeit marginally significant, implies that at very high levels of patent strength, the positive influence on innovation may be restored, suggesting a potential resurgence in innovative activity.

The second equation examines how innovation impacts renewable energy consumption. The significant negative coefficient for innovation indicates that higher levels of innovation are associated with lower renewable energy usage. This counterintuitive result (see Jafri and Liu, 2023) may suggest that innovation is occurring in sectors that do not prioritize renewable technologies, or that firms may be focusing on more profitable but less sustainable innovations. Additionally, unlike Thi et al. (2023) trade openness negatively affects renewable energy consumption, reinforcing concerns that increased trade may lead to reliance on cheaper, non-renewable energy sources rather than investing in renewables. Financial development shows a positive but not statistically significant relationship with renewable energy, suggesting that while it may contribute positively, the effect is not strong enough to draw definitive conclusions.

In the third equation, patent protection strength is relevant for CO₂ emissions when the two measures of patent strength are used. They provide

similar conclusions, although the relationships are less pronounced in the magnitude reflected by the respective coefficients when IPRP is used. Higher levels of patent strength are associated with increased CO₂ emissions per capita, implying that stronger patent protections could lead to an increase in industrial activity or production processes that rely on fossil fuels, resulting in higher emissions. However, after a certain threshold, stronger patent protections may lead to less additional CO₂ emissions, indicating that overly strong patents may encourage firms to seek efficiency improvements or engage in cleaner practices as they mature. At very high levels of patent strength, the effect on CO₂ emissions becomes positive again, restoring the initial pattern.

The non-linear relationship between patent strength and CO₂ emissions, characterized by the cubic pattern, can be explained by the interplay between incentives for innovation, market power dynamics, and the competitive environment. Initially, stronger patents lead to increased emissions due to industrial expansion. As firms mature, they may pursue efficiency improvements and cleaner practices, leading to reduced emissions. However, at very high levels of patent strength, the relationship between patent protection and CO₂ emissions turns positive again, likely due to increased market dominance and reduced competition. Strong patents can give a few firms significant control, reducing the pressure to innovate toward cleaner technologies. Instead, these firms may continue relying on existing, carbon-intensive processes that maximize short-term profits. Additionally, excessively strong patents can act as barriers to new entrants, restricting the diffusion of green technologies and hindering broader industry adoption of sustainable practices. Industries benefiting the most from

strong patents might also be inherently high-emission, further contributing to the rebound in CO2 levels.

The other explanatory variables in the third SEM equation reveal essential drivers of CO2 emissions. Innovation and renewable energy consumption are key factors in reducing emissions, while higher energy use and energy intensity contribute to increased emissions. Trade openness appears beneficial for lowering emissions, likely due to the diffusion of cleaner technologies, whereas financial development slightly increases emissions, indicating a need for green financing initiatives.

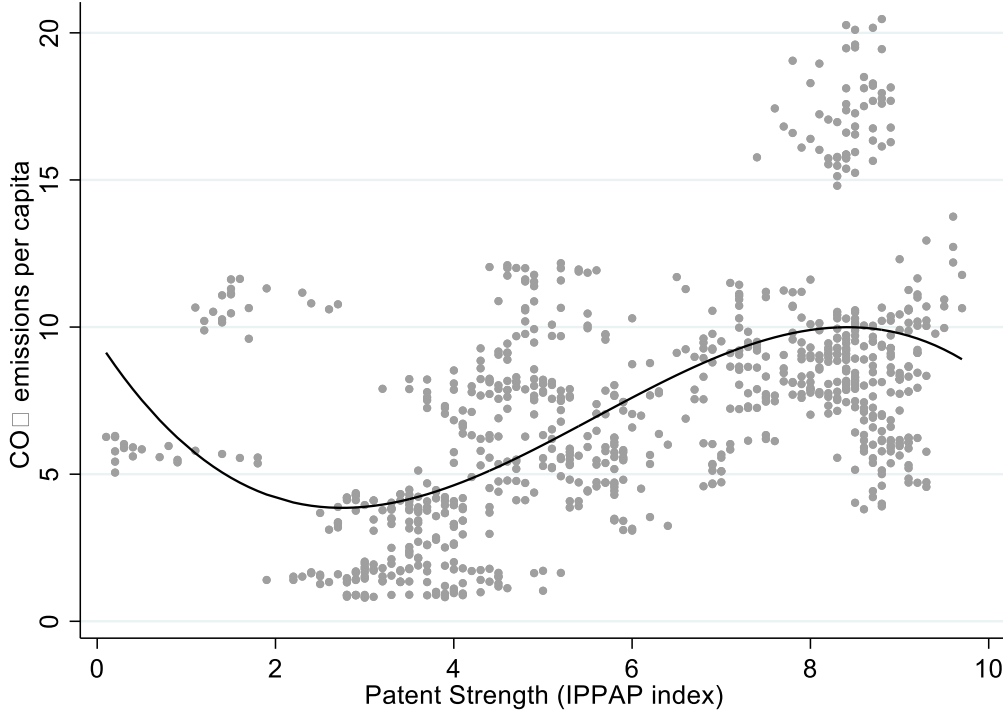
Table 1 – Baseline results

VARIABLES	IPRA index			IPRP index		
	Log of innovation	Renewable energy consumption	CO2 per capita	Log of innovation	Renewable energy consumption	CO2 per capita
	(1)	(2)	(3)	(4)	(5)	(6)
IPR	0.906		2.672**	0.752**		1.232***
	(1.026)		(1.092)	(0.345)		(0.368)
IPR square	-0.165		-0.414**	-0.174**		-0.249***
	(0.168)		(0.180)	(0.075)		(0.080)
IPR cube	0.00632		0.0203**	0.00868*		0.0154***
	(0.009)		(0.009)	(0.005)		(0.005)
Log of innovation		-2.575***	-0.177***		-2.575***	-0.188***
		(0.303)	(0.039)		(0.303)	(0.039)
R&D	1.132***			1.157***		
	(0.079)			(0.086)		
Trade	-0.00793***	-0.0790***	-0.0142***	-0.00822***	-0.0790***	-0.0148***
	(0.001)	(0.009)	(0.001)	(0.001)	(0.009)	(0.001)
Financial development	0.0166***	0.0191	0.00629***	0.0160***	0.0191	0.00564***
	(0.002)	(0.012)	(0.002)	(0.002)	(0.012)	(0.002)
Renewable energy consumption			-0.108***			-0.112***
			(0.005)			(0.005)
Energy use			0.00181***			0.00177***
			(0.000)			(0.000)
Energy intensity			0.159***			0.189***
			(0.041)			(0.039)
Constant	4.710**	41.66***	-1.059	5.233***	41.66***	2.708***
	(2.018)	(2.411)	(2.107)	(0.509)	(2.411)	(0.594)
Observations	631	631	631	631	631	631

The SEM results reveal distinct patterns in the direct and indirect effects of patent strength on CO₂ emissions per capita. Directly, stronger patent protections are associated with increased CO₂ emissions. This suggests that robust intellectual property rights can lead to more industrial activity and production, often in sectors that rely on carbon-intensive processes. The indirect effects of patent strength on CO₂ emissions are generally weaker, suggesting that the influence of patents primarily occurs through direct pathways rather than through other variables like innovation or renewable energy adoption. However, there are subtle indirect dynamics; for instance, stronger patents could initially encourage more innovation, which might not immediately translate into cleaner technologies. Additionally, when patent protections are overly stringent, they could indirectly stifle the spread of green technologies, as market barriers prevent new entrants and limit competition.

To further substantiate the cubic patterns estimated in **Table 1**, **Figure 1** provides a graphical depiction of the relationship between patent strength (IPPAP) and CO₂ emissions. The scatterplots with fitted cubic lines confirm the non-linear trajectories discussed above.

Figure 1 –S-shaped relationships between patent strength (IPPAP) and CO₂ emissions per capita



Source: Authors estimations.

4.2. Innovation as a latent process

In the next step, we incorporate measurement error explicitly by modelling constructs as latent variables. By treating innovation as a latent variable, we aim to capture its underlying dimensions more accurately (reference needed), including the effects of total patent applications, research and development (R&D) spending and the patent stringency index. Of the latter, we just use the level, to circumvent convergence problems; we normalize at the first variable of the vector. This approach allows us to address potential biases that arise when these constructs are treated as directly observable variables (Bollen and Paxton 1998). Specifically, a latent variable framework helps disentangle the true effects of innovation from measurement noise, providing a clearer picture of how patent strength influences CO2 emissions. Furthermore, by modelling innovation as a

latent construct, we can better understand the interplay between intellectual property rights, the intensity of innovation activities, and their environmental impact. This refinement in our methodology aims to reveal whether the observed relationships between patent strength and CO2 emissions are robust or if they shift when we account for the deeper, less visible aspects of innovation processes.

Results are provided in Table 2. Compared to Table 1, here we have both the log of innovation and the latent innovation. The former is included to demonstrate how it normalizes the distribution within the latent variable framework, while our focus in the interpretation is on the coefficient of the latter.

In general, these results corroborate our earlier findings. The positive coefficient for the patent strength in the characterization of the latent process framework (columns 1 and 4), suggests that robust intellectual property rights not only stimulate inventive activities but also contribute to economic growth by fostering an environment where innovation can thrive. Likewise, higher R&D spending is important to stir innovation, as expected. It is important to note that we document here a stronger association between the patent strength index and the innovation as latent process, compared to the case when innovation was captured only through the number of patent applications.

However, the influence of innovation on renewable energy consumption appears to be statistically insignificant, as opposed to our baseline finding. This raises important questions about the current trajectory of innovation efforts, indicating that while patents may enhance industrial productivity, they do not automatically lead to a transition toward cleaner technologies. In terms of trade and its relationship with renewable energy consumption, the results suggest that

increased openness to international markets correlates with a reduction in the use of renewable energy resources, as in the baseline results. On the other hand, the coefficient for financial development gains significance and is also negative, indicating that improved financial conditions do not necessarily promote the adoption of renewable energy technologies. Instead, they may facilitate investments in traditional energy sources, leading to a paradox where access to financial resources does not align with green energy adoption.

When examining CO2 emissions per capita, the results are fully aligned with the baseline results, with the same directions and similar magnitudes of the coefficients. The robustness analysis demonstrates that patent protection strength significantly influences CO2 emissions, with higher levels generally correlating with increased emissions per capita, as stronger protections can drive industrial activity reliant on fossil fuels. However, beyond a certain threshold, excessively strong patents may encourage firms to pursue efficiency improvements or cleaner practices, leading to reduced emissions. At very high levels of patent strength, the positive association with CO2 emissions re-emerges. The other variables in the SEM highlight that innovation (here modelled as a latent process) and renewable energy consumption are critical for reducing emissions, while higher energy use and energy intensity contribute to increased emissions.

Table 2 – Results when innovation is treated as a latent process

VARIABLES	IPRA index			IPRP index		
	Innovation as latent variable	Renewable energy consumption	CO2 per capita	Innovation as latent variable	Renewable energy consumption	CO2 per capita
	(1)	(2)	(3)	(4)	(5)	(6)
IPR	1.730***		2.247**	2.021***		0.973***
	(0.184)		(1.126)	(0.208)		(0.368)
IPR square			-0.352*			-0.201**
			(0.186)			(0.081)

IPR cube		0.0174*		0.0133***	
		(0.010)		(0.005)	
Log of innovation	1	1			
	0.000	0.000			
R&D	1.318***	1.241***			
	(0.127)	(0.127)			
Latent innovation	-1.328	-0.0367	2.021***	-0.274	-0.319***
	(0.844)	(0.118)	(0.208)	(0.740)	(0.119)
Trade	-0.0542***	-0.0119***		-0.0542***	-0.0132***
	(0.009)	(0.001)		(0.009)	(0.001)
Financial development	-0.0292**	0.00302*		-0.0299**	0.00313*
	(0.013)	(0.002)		(0.013)	(0.002)
Renewable energy consumption		-0.0999***			-0.108***
		(0.005)			(0.005)
Energy use		0.00174***			0.00174***
		(0.000)			(0.000)
Energy intensity		0.147***			0.147***
		(0.042)			(0.039)
Constant	6.558***	23.87***	-1.259	5.952***	23.83***
	(0.076)	(1.467)	(2.194)	(0.090)	(1.452)
Observations	631	631	631	631	631

*Source: Authors' estimations. *, ** and *** refer to a statistical significance at the 10%, 5% and 1% level, respectively.*

The SEM results when innovation is treated as a latent process validate that stronger patent protections are directly associated with increased CO2 emissions, while that the indirect effects are generally weaker or even non-existent.

4.3. Country heterogeneity

We delve into country heterogeneity, by referring to two groups of countries in our sample: OECD and non-OECD economies. Dividing the sample this way when analysing the relationship between patent strength and CO2 emissions helps capture key differences in industrial development, innovation capacity, and regulatory environments. OECD countries, with more established and diversified

economies, stricter environmental regulations, and greater access to green technologies (reference), may see stronger patents drive innovation in cleaner processes, potentially reducing emissions. In contrast, non-OECD countries, which often rely on traditional, carbon-intensive industries and have less stringent regulations, may experience increased emissions as patent strength drives industrial growth without necessarily prioritizing sustainability. Additionally, stronger patents in non-OECD economies could limit access to advanced green technologies, further affecting their ability to reduce emissions. This distinction enables a clearer understanding of how patent policies impact emissions across diverse economic contexts.

Table 3 reveals the results. The findings for the OECD countries are almost akin to the overall findings (Table 1). They suggest that patent strength protection is relevant for the CO₂ emissions through the S-shaped pattern we discussed earlier: first, higher patent stringency increases the CO₂ emissions, then this is reversed, but when patent stringency becomes stifled, the effect resumes again. Yet, the latter is only significant at the 10% level, which may indicate that the resuming effect in the developed world rather does not happen. The results however for the non-OECD countries are display an opposite pattern. This is an interesting finding, hence, suggesting that with patent stringency CO₂ emissions are first reduced, after a turning point they start increasing, while for the highest stringency, the effect is reducing again.

The opposite pattern observed in non-OECD countries could be explained by the different stages of economic development and the varying industrial structures between developed and developing economies. In non-OECD countries,

stronger patent protection might initially lead to the adoption of cleaner technologies, as firms are incentivized to innovate and invest in modern, efficient equipment that reduces emissions. This could explain the initial reduction in CO2 emissions with increasing patent stringency.

However, as patent protection becomes more robust, it might lead to increased industrial activity and production, especially in sectors where these countries are developing new capabilities. This growth phase can lead to a rise in CO2 emissions as industries expand and scale up operations, potentially using more energy-intensive processes despite the innovations. This explains the turning point where emissions start to rise after an initial reduction.

Finally, when patent stringency reaches very high levels, it may encourage further technological advancements focused specifically on efficiency and sustainability, leading to a reduction in CO2 emissions once again. This S-shaped pattern, though opposite to that of developed economies, highlights the dynamic interplay between innovation incentives, industrial growth, and environmental impacts in developing countries, suggesting that the stage of development and the nature of economic activities play critical roles in how patent policies influence CO2 emissions.

Results further confirm that stronger patent protections are directly associated with increased CO2 emissions, while that the indirect effects are generally weaker or even non-existent; this conclusion being valid for both OECD and non-OECD members.

Table 3 – Developed versus developing world (IPRP index)

VARIABLES	OECD countries			Non-OECD countries		
	Log of innovation	Renewable energy consumption	CO2 per capita	Log of innovation	Renewable energy consumption	CO2 per capita

	(1)	(2)	(3)	(4)	(5)	(6)
IPR	0.158		2.508**	1.617***		-1.374***
	(1.487)		(1.766)	(0.325)		(0.220)
IPR square	0.0666		-0.47**	-0.334***		0.330***
	(0.244)		(0.290)	(0.089)		(0.057)
IPR cube	-0.00905		0.0269*	0.00854		-0.0210***
	(0.013)		(0.015)	(0.007)		(0.004)
Log of innovation		-4.143***	-0.531***			0.23
		(0.346)	(0.059)		(0.513)	(0.025)
R&D	0.866***			4.435***		
	(0.086)			(0.191)		
Trade	-0.0194***	-0.0524***	-0.0275***	0.00199	-0.0673***	-0.00795***
	(0.002)	(0.018)	(0.003)	(0.002)	(0.012)	(0.001)
Financial development	0.0129***	0.0875***	0.00826***	0.00254	-0.0586**	0.00708***
	(0.002)	(0.014)	(0.003)	(0.002)	(0.025)	(0.002)
Renewable energy consumption			-0.156***			
			(0.007)			(0.005)
Energy use			0.00211***			
			(0.000)			(0.000)
Energy intensity			0.0929			0.135***
			(0.097)			(0.029)
Constant	5.698**	44.47***	3.839	2.580***	28.12***	2.885***
	(2.805)	(3.206)	(3.276)	(0.383)	(3.955)	(0.361)
Observations	451	451	451	180	180	180

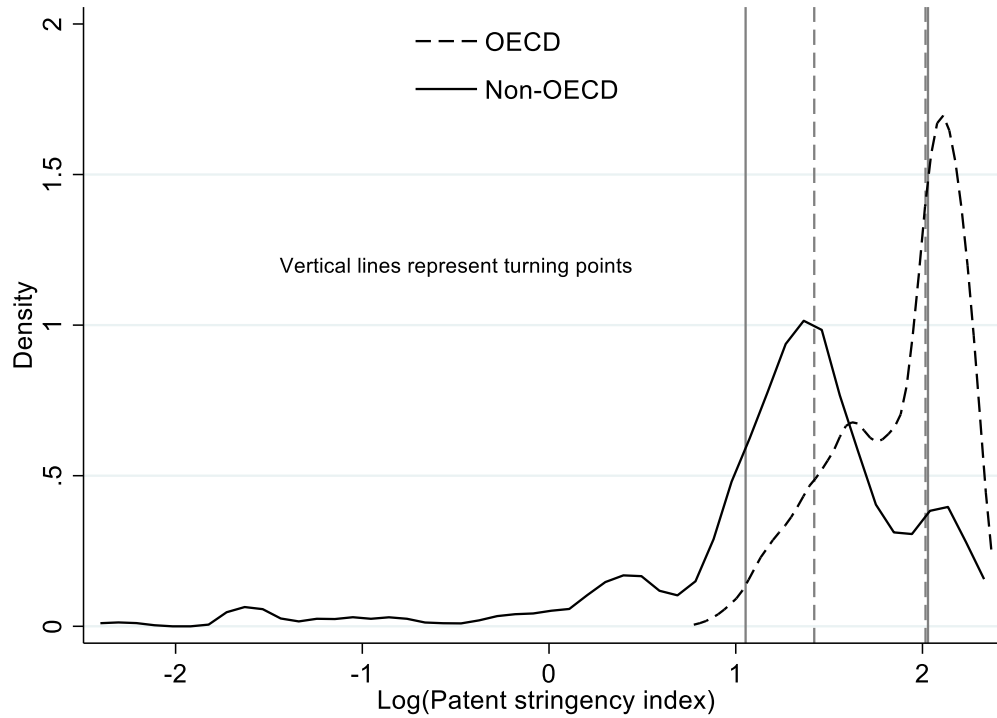
*Source: Authors' estimations. *, ** and *** refer to a statistical significance at the 10%, 5% and 1% level, respectively.*

In providing a more comprehensive picture of the country-heterogenous results we introduce Figure 2 which presents the kernel distribution of the (log of) the patent stringency index for both OECD and non-OECD countries, along the turning points calculated from the results in Table 3. For non-OECD countries, we observe that a significant portion of the data points fall between the two turning points (and that the lower turning point is earlier than in the OECD), indicating that higher patent stringency in these nations is generally associated with increasing CO2 emissions. In other words, the first turning point typically reflects the transition from positive effects of patents (incentives for innovation) to diminishing or negative returns (e.g., restricted diffusion). The second turning

point captures potential rebound effects—where overly strong patents reduce innovation or favor emissions-intensive incumbents. This phenomenon can be attributed to the fact that in many developing countries, stringent patent protections may incentivize industrial expansion, often in carbon-intensive sectors, without necessarily leading to significant investments in cleaner technologies.

In contrast, most OECD countries are located beyond the third turning point (which is almost identical for the two groups), where the relationship between patent strength and CO₂ emissions continues to hold, albeit with a more complex distribution pattern. The double-humped nature of this distribution suggests that while higher patent stringency is linked to increased CO₂ emissions in some contexts, there is also a period where it correlates with lower emissions. This smaller hump between the turning points indicates that, in certain OECD countries during specific timeframes, stronger patent protections may lead to innovations and efficiencies that reduce emissions, illustrating a transition towards greener technologies.

Figure 2 – Patent stringency index distribution and turning points



Source: Authors estimations.

Overall, these findings allow us to assert that the relationship between stronger patent systems and CO2 emissions is largely positive for most country-period observations in our sample, but with significant variability based on economic development levels. This underscores the importance of considering country-specific contexts when analysing the impacts of patent policies on environmental outcomes. In practical terms, policymakers should recognize that while robust intellectual property rights can drive economic growth, they may also need to implement complementary measures to ensure that these protections do not hinder the adoption of sustainable practices, particularly in non-OECD countries.

5. Concluding remarks

This study aimed to explore the complex interplay between patent strength, innovation, and CO2 emissions. Our primary objective was to determine how the

strength of intellectual property rights impacts environmental outcomes, specifically focusing on whether stronger patent protections encourage innovation that leads to cleaner technologies or inadvertently promote carbon-intensive industrial activities. The motivation behind this inquiry stems from the growing global focus on sustainable development and the need to understand how policy mechanisms, such as patent protections, can be aligned with environmental goals.

To achieve this objective, we employed Structural Equation Modelling (SEM), which allows for a comprehensive examination of both direct and indirect effects of patent strength on CO₂ emissions. The SEM approach enabled us to account for latent variables, such as innovation, which are not directly observable but play a crucial role in the analysis. Our dataset comprised panel data from a sample of 43 countries, both OECD and non-OECD, spanning the period from 1998 to 2017. By differentiating between developed and developing economies, we were able to uncover unique patterns and better understand how the economic context influences the relationship between patent strength and environmental impact.

The study's findings indicate a complex, non-linear relationship between patent strength and CO₂ emissions, characterized by an S-shaped pattern. Initially, stronger patent protections tend to increase CO₂ emissions, primarily due to the stimulation of industrial activity and production processes that are often carbon-intensive. This phase reflects how robust intellectual property rights can drive economic growth by encouraging firms to invest in production, even if these activities lead to higher emissions. However, as the level of patent stringency increases, there appears to be a turning point where firms begin to innovate toward more efficient, cleaner practices, leading to a reduction in emissions. Yet,

at very high levels of patent protection, the relationship reverses again, with CO₂ emissions rising, likely due to the consolidation of market power among a few firms, which stifles competition and slows the diffusion of green technologies. Robustness checks, including the treatment of innovation as a latent variable in the SEM framework, support these findings by confirming that the observed effects are consistent across different model specifications. This indicates that while patent protections can drive innovation, the type and impact of this innovation vary depending on the competitive and regulatory environment.

The analysis of OECD and non-OECD countries reveals interesting distinctions in the relationship between patent strength and CO₂ emissions. For OECD economies, the results mirror the overall S-shaped pattern. Conversely, the findings for non-OECD economies show an inverse pattern. In these developing countries, stronger patent protections initially correlate with a reduction in CO₂ emissions, potentially reflecting an early adoption of cleaner technologies as firms innovate or, better, immitate to compete on the global stage. However, after reaching a turning point, the relationship reverses, with emissions increasing as industrial activities expand. Yet, unlike in the OECD, at very high levels of patent protection, emissions tend to decline again, suggesting that the innovation fostered in these regions may eventually lead to more widespread adoption of green practices. Furthermore, for OECD countries, patent strength becomes counterproductive at extreme values due to monopolization and innovation suppression whilst in non-OECD countries, intermediate levels show increased emissions - likely due to industrial expansion.

The policy implications of these findings are significant. Policymakers need to recognize that while strengthening patent protections can stimulate innovation, there must be a balance to prevent market monopolization that could stifle technological advancement, particularly in the field of green technologies. For developed economies, the key may lie in fostering competitive markets where innovation thrives without overly restrictive patent laws. For developing economies, there is an opportunity to leverage moderate patent protections to encourage the adoption of cleaner technologies early in the industrialization process. Policymakers should also consider complementary measures, such as subsidies for green technology and investment in renewable energy infrastructure, to ensure that the environmental benefits of innovation are realized. In a nutshell, OECD countries should ensure that patent strength does not create monopolies and encourage green innovation through competition policies whilst non-OECD countries should maintain moderate patent protections and supplement with tech-transfer incentives and green subsidies.

Looking ahead, future research could delve deeper into the sector-specific impacts of patent strength, as the relationship between innovation and emissions can vary significantly across different industries. For instance, sectors like renewable energy and automotive may exhibit different dynamics compared to heavy manufacturing. Additionally, examining the role of international trade and cross-border intellectual property agreements could provide further insights into how global frameworks influence domestic environmental outcomes. Longitudinal studies that track changes over a longer period could also help in understanding how the evolution of patent regimes impacts sustainability goals. Moreover, future

research could benefit from incorporating data on actual patent applications and technology types, allowing for a more nuanced view of which innovations are driving changes in emissions. Finally, while we cite market power as a theoretical mechanism for the non-linear effects, we did not include direct competition or concentration indicators due to data constraints across the sample. This might be another factor to be taken into account as a direction for future work.

In conclusion, this study highlights the dual-edged nature of patent strength as a policy tool. While it can drive economic growth and innovation, there is a risk that overly stringent protections may hinder progress toward sustainability. As the world continues to grapple with the challenges of climate change, striking the right balance between encouraging innovation and promoting green technology diffusion will be crucial. By taking into account the specific economic contexts and ensuring a supportive ecosystem for innovation, policymakers can craft intellectual property frameworks that not only drive economic growth but also contribute to a cleaner, more sustainable future.

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Appendix – Sample, variables and descriptives

Table A1 – Countries in this paper

Argentina	Non-OECD
Australia	OECD
Austria	OECD
Belgium	OECD
Brazil	Non-OECD
Canada	OECD
Chile	OECD
China	Non-OECD
Colombia	OECD
Czech Republic	OECD
Denmark	OECD
Finland	OECD
France	OECD
Germany	OECD
Greece	OECD
Hong Kong	Non-OECD
Hungary	OECD
India	Non-OECD
Indonesia	Non-OECD
Ireland	OECD
Israel	OECD
Italy	OECD
Japan	OECD
Malaysia	Non-OECD
Mexico	OECD
Netherlands	OECD
New Zealand	OECD
Norway	OECD
Philippines	Non-OECD
Poland	OECD
Portugal	OECD
Russia	Non-OECD
Singapore	Non-OECD
South Africa	Non-OECD
Korea, Rep.	Non-OECD
Spain	OECD
Sweden	OECD
Switzerland	OECD

Thailand	Non-OECD
Turkey	OECD
United Kingdom	OECD
USA	OECD
Venezuela, RB	Non-OECD

Table A2 – Variables descriptions

	Definition	Source
CO2 emissions per capita	Metric tons of CO2 emitted per person in a country.	World Development Indicators
Log of innovation	The logarithmic transformation of the total number of patent applications in a country.	World Development Indicators
IPRA	Index capturing the strength of patent protection, scored from 0 to 10.	Papageorgiadis, Cross, & Alexiou (2014); updated to cover 1998-2017
IPRP	Index capturing patent enforcement strength, incorporating firm-level patent litigation data, scored 0 to 10.	Papageorgiadis & Sofka (2020).
Renewable energy consumption	Share of renewable energy in total final energy consumption.	World Development Indicators
R&D	Country's spending on research and development (R&D) as a percentage of GDP.	World Development Indicators
Trade	Total imports and exports as a share of GDP.	World Development Indicators
Financial development	Measured as the share of credit in GDP, indicating the development of financial markets.	World Development Indicators
Energy use	Energy consumption in kilograms of oil equivalent per capita.	World Development Indicators
Energy intensity	Energy consumed per unit of output, measured in megajoules per \$2011 PPP GDP.	World Development Indicators

Table A3 – Descriptive statistics

	Mean	Standard deviation	Minimum	maximum	Lowest percentile	Median	Highest percentile	Skewness	Kurtosis
CO2 emissions per capita	7.35	4.01	0.81	20.47	0.89	7.45	19.06	0.75	3.78
Log of innovation	7.71	2.03	3.47	14.04	4.01	7.39	12.87	0.82	3.47
IPRA	6.58	1.98	2.10	9.90	2.90	6.80	9.60	(0.12)	1.69
IPRP	6.02	2.34	0.10	9.70	0.40	5.90	9.40	(0.29)	1.98
Renewable energy consumption	17.02	14.34	0.10	61.11	0.15	12.11	58.49	1.03	3.33
R&D	1.51	1.03	0.05	4.82	0.07	1.26	4.16	0.67	2.67
Trade	87.47	71.69	16.44	442.62	21.38	64.39	401.52	2.77	11.56
Financial development	92.77	50.16	8.91	233.21	11.21	94.65	207.90	0.21	2.18
Energy use	3,336.26	1,839.07	399.50	8,455.55	425.52	3,042.43	8,107.52	0.59	2.91
Energy intensity	5.06	1.94	1.49	13.99	1.86	4.61	11.04	1.23	4.81

Table A4 – Cross correlations

	CO2 emissions per capita	Log of innovation	IPRA	IPRP	Renewable energy consumption	R&D	Trade	Financial development	Energy use	Energy intensity
CO2 emissions per capita	1									
Log of innovation	0.4195*	1								
IPRA	0.5322*	0.1753*	1							
IPRP	0.5350*	0.2470*	0.9698*	1						
Renewable energy consumption	-0.4553*	-0.2203*	-0.0191	-0.0441	1					
R&D	0.5068*	0.5220*	0.6341*	0.6830*	-0.0815*	1				
Trade	0.0772*	-0.3000*	0.2968*	0.2973*	-0.3110*	0.0255	1			
Financial development	0.4089*	0.3666*	0.5870*	0.6037*	-0.1593*	0.4266*	0.2110*	1		
Energy use	0.8552*	0.3918*	0.6826*	0.6742*	-0.1424*	0.6386*	0.0808*	0.3753*	1	
Energy intensity	0.3536*	0.3161*	-0.1648*	-0.1631*	-0.0594	0.0515	-0.2743*	-0.0909*	0.3201*	1



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Patent strength, innovation, and CO2 emissions: evidence of nonlinear environmental impacts across economies

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