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Original Article

Assessing the Impact of Climate Change on Green Innovations: A Comparative Analysis of Developed and Developing Countries

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ABSTRACT

This study investigates the interaction effect of high-income and low-income green innovation on climate change from 2000–2023. The study employs a System Generalized Method of Moments (SGMM) estimator to explore the effect of different types of GHG emissions namely total CO_2, electricity, gaseous fuels, liquid fuels, and solid fuels on green innovation, which is proxied by the natural logarithm of patents in force. Results show that total CO_2 emissions and from the consumption of electricity and solid fuels drive worldwide innovation, whereas liquid fuels emissions negatively impact patent output. We find marked differences between developed and developing countries: while total CO_2 and gaseous fuel emission increase induce innovation responses in developed countries, the apparent innovation response for developing countries appears too limited to be significant, with marked effects on the innovation response phase concerning fundamental CO_2. R&D expenditure and GDP growth also serve as consistent positive drivers of innovation, regardless of context, while demographic factors have a stronger effect on innovation in more developed economies. The study highlights the challenges for policy, recommending boosted R&D funding in developed countries and investing in developing countries to build their capacity to innovate to meet climate change challenges. These insights add to the increasing literature around sustainable innovation, providing sets of suggestions to influence the unique interaction of climate and innovation in varied economic environments.

Introduction

The rapid acceleration of climate change is one of the most daunting challenges facing humankind today in the 21st century. Scientific and policy communities are now one on the idea that the cost of climate change is not centuries away, but is happening now and needs to be addressed. This urgency is demonstrated by landmark agreements including the 2015 Paris Agreement which centred around the UN Framework Convention on Climate Change (UNFCCC). In December of 2015, almost all the countries in the world signed the Paris Agreement, committing to keeping the increase in global average temperature to well below 2°C above pre-industrial levels, which has been determined to be essential for the planet (UNFCCC 2015). According to the latest report from the Intergovernmental Panel on Climate Change (IPCC, 2023), the decarbonization associated with this goal requires levels never before accomplished with a global carbon intensity of Gross Domestic Product (GDP) needing to decline by about 60% by 2050 in order to plateau emissions, let alone decrease them. And similar lofty aspirations can be heard in the United Nations Sustainable Development Goals (SDG 13 (Climate Action), SDG 7 (Affordable and Clean Energy), and SDG 6 (Clean Water and Sanitation) which all refer to the need for environmental sustainability to allow the planet to be liveable for generations to come.

Transformational changes in energy production and consumption are a necessity to achieve these global climate goals. Getting there, though, will take massive innovation investments — especially in R&D of climate-friendly technologies. Innovation is one of the clear choices made by the IPCC and the rest of the world. Investment in clean energy and technologies that enable decarbonization not only eases the transition to low-carbon economies but also lowers the cost of climate policy (Dechezleprêtre et al., 2023). There are innovations in natural gas technology to eliminate coal in the United Kingdom and the Netherlands and the ambitious German Ever greened program, showing the potential for transformative energy transitions (Hake et al., 2024). But for developing economies that face the challenges of scarce resources, poor policies and institutional rigidity, the road to these innovations is perilous.

According to the latest report from the International Energy Agency (IEA, 2024), solutions to accelerate innovation for climate change must be system-oriented and context-specific, covering all stages of the innovation chain from generation of ideas to their commercialization and global diffusion. At the opening of the IEA Technology and Collaboration Programme meeting having 2024, Executive Director Dr Fatih Birol emphasized the importance of integrated, multi-stakeholder approaches to energy innovation and called for collaboration between multiple stakeholders across borders to ensure a sustainable energy future. These appeals have not changed the reality of the divide between the capacities of developed markets versus developing nations to innovate in the name of climate. For example, Su and Moanib (2023) note that while developed nations typically enjoy the benefit of strong institutional structures, finance and established research ecosystems, developing countries often find themselves at the wrong end of systemic issues, such as lack of access to finance and a shortage of technical capacity. Such differences leave a big question in the air about how far the climate change factor has influenced innovation in countries with differing levels of development.

The body of literature on the topic of innovation and climate change has expanded substantially in the past two decades. Initial research was primarily geared towards examining the ways linear technological change can curb climate change through diminishing greenhouse gas emissions, sustainable economic development, and better environmental quality (Nino 2023, Grimsley 2024). Often, this body of research frames a one-way or linear relationship proposing that innovation mitigates climate change through the improvement and adoption of low-carbon or cleans technologies (Aghion & Howitt, 2008; Acemoglu et al, 2012). Recent research, however, has since turned towards testing the inverse causality, asking how climate change per se drives innovation. Su and Moanib (2023) examined greenhouse gas emissions and how it relates to climate technology development; they determined that carbon emissions arising from liquid fuels promote innovation while carbon emissions from coal hamper it. Although a reversal of perspective, it illustrates the complex dynamism of climate-innovation interactions from which broader principles could emerge, emphasizing the importance of context-sensitive analyses.

Incorporating these insights, this paper explores how the impact of climate change on innovation varies between developed and developing economies from 2000 to 2023. This study is unique comparing to previous studies which bring the data together and do not notice the country group, showing the dis-aggregation on the farther studies. Using a panel dynamic System Generalized Method of Moments (SGMM) estimation technique, this work assess how climate stressors differently shape innovation across diverse economic and policy contexts. Developed nations, with more sophisticated technology and financial markets are expected to react more strongly to innovation pressures from climate change compared to developing nations where institutions and financial constraints may limit innovation capacity.

Before discussing those examples, there is some preliminary evidence to suggest that the climate-change–innovation nexus may be highly context-specific, especially for developed compared to developing countries. In developed countries, it seems that climate change drives innovation in some sectors (e.g. liquid fuel technologies) but emissions from other sources act as impediments to innovation. On the other hand, this overall measure indicates a muted or negligible effect of climate change on innovation in developing countries, reflecting the structural and resource-related obstacles of these economies. This suggests that policy responses must be differentiated between the country groups where they are implemented due to the different forces at play and the different responsiveness to policy challenges.

Our paper fills in some of the gaps on the literature of environmental innovation and climate by understanding why the effects of climate on innovation vary across stages of development. Through a comparison, it underlines that policies that work for global innovation cannot be one size fits all, there will have to be a degree of contextualisation and adjustment. In addition, by discussing how climate challenges can be turned into opportunities for technological innovation, it contributes a multi-sectoral lens to existing literature on climate challenges in developing countries, where innovation is often limited.

The rest of the paper is organized as follows: Section II provides a literature review on climate change and innovation. In Section III, we discuss the methods of analysis and the data. Section IV elaborates the results of the quantitative analysis presented in this paper whilst Section V concludes the study with policy implications aimed at stimulating this process in industrialised and developing economies.

Theoretical Framework

Over the past few years, the link between innovation and environmental sustainability has received considerable attention in the academic literature. An increasing number of literature focuses on the potential for technology to reduce environmental harm at the same time as it stimulates economic and industrial development. At the heart of this narrative lies green innovation, this enhances carbon reduction and sustainable activity. In particular, advances in carbon capture and storage (CCS) technologies have become essential in reducing greenhouse gases (Huaman & Tian, 2014). Likewise, studies focusing on Japanese manufacturing industries show that eco-innovation and green R&D investment can lower carbon intensity and increase corporate value simultaneously (Lee & Min, 2015; Asghar et al., 2024; Iram et al., 2024; Khan et al., 2024). Such promising progress reinforces the role of deliberate innovation strategies in responding to climate challenges.

Broad studies, covering a certain geographical region including many firms also deliver implications on the macroeconomic impacts of green innovation apart from firm level studies. For example, Zhang et al., (2017) used system SGMM method to estimate panel data of 30 Chinese provinces from 2000 to 2013. The results bolster existing studies that have found that a variety of proxies for environmental innovation (patents, technology adoption, etc) are correlated with substantial reductions in carbon emissions. These results imply that adoption and diffusion of clean technologies have great impact on sustainability, particularly in fast developing economies.

Adding even historical perspectives expands the theoretical foundation of this subject. Elliott and Pye (1998) for example claim that the promotion of technology innovation policies by government will support the development of industry energy efficiency. According to them, carbon and energy savings resulting from these types of strategies can be as high as 12% in the short-term and more than 30% as we get to 2030. Expanding on this argument, Smithers and Blay-Palmer (2000) underscore the importance of strategic foresight and pro-active technology adoption to climatic challenges and argue for the necessity of integrated, long-term approaches.

Now, again, recent studies have also pointed out the non-linearity between the relationship of renewable energy technological innovation (RETI) and climate change. Using information from China for the time span 2000–2015, Lin and Zhu (2019) showed that CO_2 emissions are diminished significantly by RETI, but its impact is sensitive to energy mix. In particular, RETI becomes more beneficial with less coal in the energy mix and more renewable energy. These findings highlight how making transitions towards more carbon-free energy systems will make green technologies of almost any type much more effective.

The theoretical background of this study is the Sustainable-Innovative Growth (SIG) model with its integrated important drivers of sustainable growth, encompassing innovation, economic development and climate change (Su & Moanib, 2017). The framework underlines the fact that environment is imbibed into every stage of the growth process and reflects the inextricable link between innovation, environmental resources, and various policy interventions. Working within this framework, the present research seeks to make a complementary contribution to the innovation literature by examining heterogeneity in the relationship between climate change and innovation between developed and developing countries. The analysis takes into account varying values of R&D spending, population and income levels by type of outputs to represent the complexity of the relationship.

In such studies, innovation is usually proxied by patent-based indicators, such as patent applications or patents granted (Dosi et al., 2015; Josheski & Koteski, 2022). These metrics are useful to know, but I don't think we can take them for face value in terms of how this usually translates to societal adoption and commercialization. By contrast, this study provides a broader perspective by conceptualizing "patents in force" as a reflection of effective usage and influence of technological advancement (Popp, 2003). This index dovetails with the concept that for innovation to impact the environment or the economy, it must be integrated into larger processes within society.

While prior research has broadened our understanding of the innovation–climate nexus, we still face gaps. To start with, most of the literature analyses assembles at an aggregate level that are not disaggregated by background economic conditions. By investigating how the direct effect of climate change on innovation differs between developed and developing countries, this study overcomes this limitation. Second, although the literature cites the key role of innovation in addressing climate change, fewer studies have examined the opposite mechanism—namely the extent to which climate pressures stimulates innovation. This research fills these gaps, adding to the burgeoning literature on the interactive evolution of technological development and environmental challenges.

The present study also considers current developments in the area, providing a theoretically sound basis by integrating literatures up to 2023 and 2024 horizons. For instance, new research highlights the importance of transnational engagement in promoting maladaptive emissions reduction responses, thus calling for distinct approaches according to the specific strengths and limitations of developed and developing countries (Linnenluecke et al., 2023). New metrics to assess the effectiveness of environmental policies and innovations (e.g., the Green Innovation Index (GII)) also provide new angles to measure progress toward environmental sustainability (Dechezleprêtre et al., 2023). This renewed understanding strengthens the implications for theory behind the study and its relevance to current policy and academic discussions.

Methodology

This section specifies the sampling strategy and empirical approach used in this research. It begins with an overview of the sample composition and data sources, then describe the summary statistics and the correlation matrix. The following section explores the econometric method, model specification and variable definitions.

Sample

This paper studies the heterogeneous reaction of innovation types to climate change across developed and developing countries. In the beginning, it included 132 countries around the world. However, to maintain continuity of data and reliability, some countries were thrown out because in these countries there are no data or only partial data on such essential variables as patents and climate change. This meant, for example, eliminating countries with less than five years of data on patents or GHG emissions from the analysis. Following these refinements, our final sample comprised 71 countries (37 high-income and 34 low- income economies).

This study is covering from the year 2000 to 2023 to provide a complete analysis. This period was selected because data on patents as well as GHG emissions is relatively consistent during this time frame. The former subsample consists of developed countries and the latter developing countries. This distinction enables a more nuanced insight as to how economic and structural (1) divergences regarding both climate change and innovation ultimately affect their linkage.

We measured green innovation using patents in force, a more robust indicator than common proxies such as patent counts or patent applications, because it reflects the application and penetration of innovations in society. The data on patents in force comes from the World Intellectual Property Organization (WIPO), which provides consistent and comprehensive records for the time horizon considered. In contrast to patent applications or grants, patents in force provide a measure of active innovations with associated economic and environmental impacts.

As climate change measurements, the study used five indicators of greenhouse gas emissions including total carbon dioxide emissions (CO_2), CO_2 emissions from electricity generation (CO_2EL), CO_2 emissions from gaseous-fuel combustion (CO_2GF), CO_2 emissions from liquid-fuel combustion (CO_2LF), and CO_2 emissions from solid-fuel combustion (CO_2SF) [19]. These indicators were selected to reflect the complexity of climate change; no single metric can comprehensively measure the impacts of climate change. The data on these variables were obtained from World Development Indicators (WDI) database that provides credible statistics on global environmental and economic indicators.

Econometric Approach, Model Specification, and Variable Definitions

Using a System Generalized Method of Moments estimator, this study examines the dynamic link between climate change and innovation across developed and developing countries. It is able to deal with endogeneity, unobserved heterogeneity, and omitted variable bias, which are typical issues in panel data and are common challenges of are usual panel data analyses. The SGMM method adopts a general method of moment technique that uses both level and differenced variables as instruments which results to a more efficient and consistent parameter estimates as compared to Difference Generalized Method of Moments (DGMM). This is particularly well-suited for data with a smaller time dimension but a greater cross-sectional dimension, as is the case here. The SGMM approach also takes into account possible autocorrelation and measurement errors, allowing for robustness in estimation. The Sargan test and Arellano-Bond test, for this model reliability was tested with done diagnostic tests. In addition, the Sargan test indicated that instruments were valid, i.e. over-identifying restrictions were satisfied, and the Arellano-Bond test confirmed that there was no second-order autocorrelation in the residuals.

The empirical strategy is two steps. Step one is an aggregate-level analysis of the full sample of 71 countries, providing a general overview of climate change impacts on green innovation. Second, the sample is disaggregated into two groups (high-income (37) and low-income (34)) to examine if and how the relationship between climates change concern and innovation differs with economic development level. This method allows a comparative view and can detail the specific interaction that exists inside of each subgroup.

The econometric model is specified as follows:

$$GINVO_{i,t} = \beta_1 GINVO_{i,(t-1)} + \beta_2 CLICH_{i,t} + \beta_3 GDP_{i,t} + \beta_4 R\&D_{i,t} + \beta_4 POP_{i,t} + \varepsilon_{i.t}$$

Wherein GINOV, the dependent variable, is the log of the number of patents in force per year as the green innovations, data is from the World Intellectual Property Organization (WIPO) for the years 2000–2023. Patents in force are distinct from other common metrics like patent applications or grants because they show active forms of innovation embodied in the economy and society and hence reflect innovation in practice. The green innovation is dynamic and persistent and is captured by including a lagged dependent variable L.GINVOi,t

The principal independent variable which is climate change (CLICH) is proxied through five different measures of CO_2 emissions (total), CO_2 emissions from electricity and heat production, CO_2 emissions from gaseous fuel consumption, CO_2 emissions from liquid fuel consumption and CO_2 emissions from solid fuel consumption. Every one of those indicators is analyzed by itself to provide a finer-grained picture of how sources of emissions driving innovation. Data were taken from the World Development Indicators (WDI), 2000–2023.

The model also included several control variables that accounted for other influences on innovation. We included GDP growth (GDP) to represent economic conditions for research and development activities. We included research and development expenditure (R&D) as part of GDP to take into account investment levels in innovation, also a key factor underlying technological progress. Paper 1 took into account population growth (POP), since demographic dynamics may affect demand for innovation as well as climate-related challenges. The variables which we used to analyse and their definitions are listed in the Table 1.

Table 1: Variables Definition

Variable	Definition	Source
GINOV	Logarithmic number of patents in force per year	WIPO
GDP	GDP per capita growth (annual %)	WDI
R&D	Research and development expenditure (% of GDP)	WDI
POP	Population growth (annual %)	WDI
CO_2	Total CO_2 emissions (metric tons per capita)	WDI
CO_2EL	CO_2 emissions from electricity and heat production (%)	WDI
CO_2GF	CO_2 emissions from gaseous fuel consumption (%)	WDI
CO_2LF	CO_2 emissions from liquid fuel consumption (%)	WDI
CO_2SF	CO_2 emissions from solid fuel consumption (%)	WDI

Results and Interpretation

Table 2 presents the descriptive statistics for the full sample of 71 countries, and allows us to examine the dynamics of innovation, climate change indicators, and macroeconomic variables for the entire sample over the study period (2000–2023). Table 2 shows the mean, S.D, min. and max value, which reflects the differences and disparities among the countries studies.

The mean value for innovation (proxied by the log of patents in force) is 9.312, indicating an approximate figure of 11,100 per annum. The minimum value observed is 4.350 (approximately 78 patents), and the maximum is 14.620 (more than 2.3 million patents) consistent with the extent of the heterogeneous innovative activity in the sample. As anticipated, advanced economies have more innovation output due to greater R&D investment and robust institutions.

In the case of climate change proxies, the average value of the total CO_2 emissions per capita is 5.982 metric tons with a value interval from 0.090 to 21.879 metric tons. Average share 39.874% for emissions from electricity and heat production (CO_2EL), 22.659% for gaseous fuels (CO_2GA), 43.228% for liquid fuels (CO_2LF), and 28.019% for solid fuels (CO_2SF). The data shows a marked difference between developed and developing countries' energy use and emissions, with developed countries producing most their emissions from liquid fuels and electricity, whereas developing countries produce more from solid fuels, owing to their energy infrastructure limitations.

R&D expenditure, a fundamental innovation input, displays an average of 1.103% of GDP across the sample, with developed nations accounting for high growth relative to their developing peers. The maximum R&D allocation so far is at 4.213% of GDP, reflecting the pledge of certain high-income countries to promote technological development. GDP growth has a mean of 1.521% and ranges between −13.932% and 12.837%, reflecting the economic instability faced by certain nations in the time span observed. POP is 0.842% per year, with a more prominent contribution from developing countries because of demographics and their higher fertility rates.

Table 3 shows the correlation matrix of all the variables used, indicating the relationships among innovation, climate change indicators, and other macroeconomic variables. The results which confirm the correlation levels among most variables are weak, enabling the absence of multicollinearity and necessary for robustness of econometric model.

Table 2: Descriptive Statistics for the Full Sample (71 Countries)

Variable	Obser	Mean	S.Dev	Min	Max
GINVO	392	9.31	2.11	4.35	14.62
CO_2	420	5.98	4.32	0.09	21.78
CO_2EL	414	39.87	17.40	0.01	79.54
CO_2GA	399	22.65	16.34	0.00	82.36
CO_2LF	413	43.22	20.34	4.09	91.93
CO_2SF	413	28.01	21.94	0.00	87.64
R&D	363	1.103	0.88	0.02	4.21
GDP	420	1.52	3.48	-13.93	12.83
POP	419	0.84	1.08	-2.15	5.13

Based on the above table, the highest correlations is seen on CO_2SF and CO_2EL with the value of correlation coefficient 0.5892. This suggests a close relationship which is not surprising since both of these variables originate from overlapping industrial and energy-related activities. But since these variables are used in separate tests in the econometric models, the correlation is not perceived as a limitation for the estimation of the model. GINVO and R&D, other variables shows a average level of positive correlation (0.4128), as expected are closely related. Notably, the independent variables, in particular the climate change indicators, are weakly nor not correlated with each other, alleviating multicollinearity concerns in the regression models.

Table 3: Correlation Matrix

Variables	**GINVO**	**CO_2**	**CO_2EL**	**CO_2GA**	**CO_2LF**	**CO_2SF**	**R&D**	**GDP**	**POP**
GINVO	1								
CO_2	0.401	1							
CO_2EL	0.067	0.329	1						
CO_2GA	0.034	0.021	-0.072	1					
CO_2LF	-0.220	-0.194	-0.453	-0.371	1				
CO_2SF	0.215	0.262	0.589	-0.325	-0.699	1			
R&D	0.412	0.434	0.062	-0.058	0.027	0.068	1		
GD	-0.059	-0.141	0.001	0.060	-0.231	0.124	-0.127	1	
POP	-0.117	-0.020	-0.174	-0.152	0.375	-0.310	0.012	-0.014	1

Table 4 shows the estimation results by using the SGMM for the group of the full sample of 71 countries. The results underscore the time-varying nature of the impact of green innovation on different climate change variables. The lagged dependent variable L.GINVO has a positive and highly significant coefficient at the 1% level in all five models, indicating a noticeable impact of recent patenting activity on subsequent patenting. Our results suggest a path-dependent innovation process, with patent outputs substantially driven by past efforts. These findings are in line with previous research highlighting the path-dependent process of technology development (Aghion et al, 2021; Popp et al, 2023).

Climate change indicators have variable effects across models, suggesting complex climate innovation interrelationships. Total CO_2 emissions and CO_2EL positively and significantly affect patents, indicating that threats to the environment associated with emissions create demand for cleaner technologies. This also backs up the idea that the international priority of reducing emissions from these large polluting industries creates a space for innovation as countries seek to lessen negative environmental invasions. By the same token, emissions from CO_2SF also show a large significant positive effect, representing the more recent regulatory push for emissions reductions from high-polluting energy sources, especially in developing countries that rely on solid fuels (Linnenluecke et al., 2024). Instead, CO_2 emissions from liquid fuels (CO_2LF) negatively affect patents substantially, suggesting that the responses of innovation to liquid fuel emissions are restricted by structural barriers or weak policy incentives. Co2ga emissions (from gaseous fuels) have no significant effect on patents, which likely captures the fact that emissions from these sources are given less priority in global environmental policy regimes.

Across all models, investment in R&D is the significant positive driver of innovation with high significance coefficients. Such developments confirm the prominent influence that research and development (R&D) expenditure has on the advancement of technology, as scholars such as Griliches (1984) and Inglesi-Lotz and Pouris (2021) have previously reported. This drives R&D development that prepares countries to patent, innovate, and build cleaner technologies to face the environmental challenges that are growing through the decades.

The first two models show a positive and statistically significant coefficient for economic growth, suggesting that countries that have higher GDP growth rates are also those where more resources are allocated to research and technological development. This supports the case that economic growth catalyzes an innovation friendly environment by providing improved infrastructure, education and greater access to R&D funds. Nevertheless, the GDP growth effect becomes instead insignificant for the other models implying that other factors might moderate the growth-innovation nexus (i.e., institutional quality and policy frameworks) (Su et al., 2022). Conversely, demographic growth has a stable negative and statistically insignificant association with patens, meaning that the quantity of people in their respective counties, by itself, is not enough to spur innovation.

The robustness of the SGMM estimations is confirmed with the diagnostic tests. Results are robust over use of a dynamic panel to account for endogeneity as suggested by the low Arellano-Bond AR (1) and AR(2) tests that there is second order autocorrelation in the residuals, and Sargan test to support the validity of the instrumental variables. These results confirm the suitability of SGMM for our analysis of the dynamic innovation-climate change nexus.

Table 4: Impact of Climate change on green innovation

Variable	Model 1 (CO_2)	Model 2 (CO_2EL)	Model 3 (CO_2GA)	Model 4 (CO_2LF)	Model 5 (CO_2SF)
L.GINVO	0.675***	0.692***	0.627***	0.363***	0.533***
	(33.49)	(28.93)	(24.73)	(18.61)	(15.34)
CO_2	5.170***				
	(3.91)				
CO_2EL		1.968***			
		(5.77)			
CO_2GA			0.140		
			(0.54)		
CO_2LF				-1.962***	
				(-3.94)	
CO_2SF					1.672***
					(3.92)
R&D	3.260***	4.309***	4.914***	5.044***	5.689***
	(3.86)	(4.71)	(4.66)	(8.06)	(8.68)
GDP	0.525**	0.747***	0.717	0.081	0.402
	(2.28)	(3.15)	(3.63)	(0.26)	(1.34)
POP	-4.882	-1.096	-4.176	-4.585	-6.746
	(-1.13)	(-0.27)	(-1.03)	(-1.05)	(-1.72)
Constant	2.576***	1.756***	3.233***	6.291***	3.350***
	(4.03)	(4.58)	(8.33)	(8.52)	(8.15)
Sargan Test	26.197	22.772	29.421	22.140	20.274
p-value	(0.124)	(0.247)	(0.089)	(0.277)	(0.378)
AR(1)	-2.071	-2.106	-2.050	-1.952	-2.061
p-value	(0.038)	(0.035)	(0.040)	(0.050)	(0.039)
AR(2)	1.720	1.723	1.655	1.398	1.585
p-value	(0.085)	(0.084)	(0.097)	(0.162)	(0.113)
No of Obs	352	352	352	352	352

Disaggregated Analysis for high income and low-income Countries

Results of the SGMM estimations for developed countries are given on Table 5, where we see that the responses of innovation to climate change indicators are differentiated. The results show that emissions in developed countries have both positive and negative effects of varying degree on innovation activities, and that this is particularly true when distinguishing between different types of CO_2 emissions.

The results for the developed country group show that total CO_2 and CO_2GA also have positive and statistically significantly results for patents. Collectively, these results suggest that the innovation response to climate change in the developed world is driven mainly by global CO_2 concentrations and by emissions embodied in gaseous fuel consumption. The positive coefficients suggest that an increase in these emissions leads the developed countries to become more active in innovating, which is likely motivated by their international frameworks to realize the reduction of carbon emission and better sustainability. This result is consistent with recent research that underscores the proactive efforts by the developed world in its innovation efforts to adapt to climate change (Popp et al., 2023; Aghion et al., 2021).

In the opposite direction, CO2 emissions from electricity and heat production (CO2EL), CO2 emissions from liquid fuels (CO2LF), and CO2 emissions from solid fuels (CO2SF) have negative and statistically significant effects on patents. Such results indicate that innovation activities in developed countries do not react positively to raises in these particular emissions. The absence of meaningful innovation responses to these emissions may indicate the structural dependence of developed economies on these fuels, which constrains incentives for the development of specific mitigation technologies. To close this gap, governments in the developed world must make much larger investments in so-called R&D to drive down emissions from electricity, liquid fuels, and solid fuels.

Table 5: Impact of Climate change on green innovation for High-income Countries

Variable	**Model 1 (CO_2)**	**Model 2 (CO_2EL)**	**Model 3 (CO_2GA)**	**Model 4 (CO_2LF)**	**Model 5 (CO_2SF)**
L.GINVO	0.816***	0.840***	0.614***	0.651***	0.799***
	(58.84)	(96.75)	(14.20)	(53.94)	(67.01)
CO_2	0.093***				
	(8.85)				
CO_2EL		-0.033***			
		(-14.12)			
CO_2GA			0.016***		
			(12.92)		
CO_2LF				-0.018***	
				(-11.12)	
CO_2SF					-0.012***
					(-5.41)
R&D	0.435***	0.215***	0.182***	0.610***	0.530***
	(9.32)	(5.07)	(8.94)	(15.89)	(14.74)
GDPpc	0.004	-0.003	0.009***	0.005*	0.008***
	(1.34)	(-0.08)	(9.26)	(1.58)	(10.11)
POP	-0.003	-0.050***	0.029***	0.087***	0.056***
	(-0.35)	(-3.81)	(2.41)	(3.37)	(2.72)
Constant	0.682***	2.530***	3.300***	3.470***	1.200***
	(5.10)	(19.84)	(11.12)	(20.47)	(15.91)
Sargan Test	20.102	29.845	24.674	25.840	23.761
p-value	(0.351)	(0.055)	(0.155)	(0.128)	(0.191)

AR(1)	-1.578	-1.665	-1.288	-1.540	-1.579
p-value	(0.092)	(0.083)	(0.209)	(0.108)	(0.098)
AR(2)	1.056	1.012	0.390	0.850	0.910
p-value	(0.289)	(0.320)	(0.690)	(0.393)	(0.360)
Observations	182	180	176	179	181

The share of R&D expenditure on GDP is still the primary determinant of innovation, with positive and statistically significant signs across all specifications. Investing Output And Our Novel Results This work highlights the importance of continued R&D investment for technological innovation and tackling climate change. In a different vein, GDP growth composes a positive correlation with patents in some specifications, suggesting that economic growth is a driver of innovation by enlarging the resource base for productivity-enhancing research and development activities.

An idiosyncratic result for the developed country group is that population growth also positively and significantly impacts on patents, contrary to the full sample. This indicates that for the case of developed countries the larger population may positively contribute to innovation through the expansion of the human capital pool and greater demand for new technologies. And, indeed, it has been noted that (link resides outside) countries with many people (in addition to high-performing research-and-development ecosystems), such as the United States and Germany, turn out higher levels of innovation then do less populous nations. This result aligns with arguments made by more recent literature regarding a positive association between size of population, and quantity and quality of research output (Linnenluecke et al., 2024; Inglesi-Lotz & Pouris, 2021).

The diagnostic tests prove the strength of SGMM models. The checks agree that we find no second order autocorrelation according to the Arellano-Bond AR (1) and AR (2) tests; and the Sargan test shows that at least the instruments used instrumental variables are consistent.

Group of developing countries: Climate change vs innovation – Table 6 The findings demonstrate that climate change indicators have a very weaker innovation response with only total CO_2 showing a significant return on patents in the positive sense. Their findings suggest that in developing countries, innovators and policy makers respond to aggregate CO_2 emissions as a more general indicator of environmental distress, and that this response strengthens innovation efforts. On the other hand, emissions from electricity (CO_2EL), gaseous (CO_2GA), liquid (CO_2LF), and solid fuels (CO_2SF) make no significant difference in innovation. Such slowness perhaps indicates that these countries lack the structural element or resources to use new technologies to alleviate emissions from specific source sectors.

Strikingly, the coefficient for total CO_2 emissions is much greater for developing nations than for their developed peers. The result shows that innovation in developing countries is less tolerant of overall environmental pressures, which seems reasonable since many of these countries are far more vulnerable to the effects of climate change. On the one hand, the higher sensitivity from these countries could imply an immediate need for sustainable practices and technologies in these nations (Linnenluecke et al., 2024; Popp et al., 2023).

In all models, the lagged variable of GINVO is significant and with a positive sign, suggesting that innovation is a cumulative process over time, which coincides with the results found using the full sample and for developed countries. R&D maintains a strong and positive effect on patents in all models, highlighting that the increasing commitment to R&D remains an important determinant of technological development and innovation in the developing world. Furthermore, in some specifications, GDP growth has a positive effect on patents, indicating that economic growth promotes innovation through the provision of resources and technical infrastructure for research activities (Inglesi-Lotz & Pouris, 2021).

Population growth has no significant effect on innovation in developing countries and this is different from the results for full sample and developed countries. This finding could be an indication that there are significant obstacles to translating population growth into economically productive innovation behavior in these countries, including poor quality education, lack of proper research infrastructure, and weak institutional frameworks.

Table 6: Impact of Climate Change on green innovation for Low income Countries

Variable	**Model 1 (CO_2)**	**Model 2 (CO_2EL)**	**Model 3 (CO_2GA)**	**Model 4 (CO_2LF)**	**Model 5 (CO_2SF)**
L.GINVO	0.275***	0.195***	0.365***	0.224***	0.222***
	(12.21)	(4.93)	(10.20)	(9.36)	(5.18)
CO_2	2.318***				
	(6.15)				
CO_2EL		-0.145			
		(-0.16)			
CO_2GA			1.555		
			(1.24)		
CO_2LF				-0.917	
				(-0.86)	
CO_2SF					-0.867
					(-1.51)
R&D	2.644***	3.673***	3.625***	2.517***	3.500***
	(10.31)	(15.05)	(15.51)	(14.66)	(17.23)
GDP	-0.025	1.452***	0.894***	0.753	0.989
	(-0.05)	(2.47)	(2.82)	(1.28)	(1.22)
POP	1.874	1.350	-1.220	0.452	0.223
	(0.70)	(0.51)	(-0.64)	(0.16)	(0.28)
Constant	3.970***	4.826***	3.314***	5.263***	4.751***
	(12.77)	(5.25)	(7.59)	(11.47)	(7.82)
Sargan Test	11.309	12.431	8.980	12.674	11.872
p-value	(0.913)	(0.866)	(0.973)	(0.854)	(0.891)
AR(1)	-1.389	-1.465	-1.329	-1.445	-1.624
p-value	(0.164)	(0.142)	(0.183)	(0.148)	(0.104)
AR(2)	1.490	1.641	1.493	1.590	1.133

p-value	(0.136)	(0.101)	(0.135)	(0.111)	(0.156)
Observations	170	167	170	169	169

Conclusion and Policy Recommendations

It expands the premise that innovation reacts to changes in environmental trends, specifically CO_2 emissions (Su and Moanib, 2017), by applying the idea of climate change stochastic processes to the realm of technological innovation. Su and Moanib highlighted the global nature of their results, while within our own paper, we provide a juxtaposition between the effects of climate change on innovative activity in a developed versus a developing country.

We find marked differences in the innovation response to climate change across country groups. Evidence presented in Table 1 indicates that total CO_2 emissions and emissions from electricity and solid fuel consumption are strong indicators of innovation, measured by patenting activity for the full sample of 71 countries. On the contrary, emission from use of liquid fuels indicates a negative impact, indicating the emission sources is not consistent with innovation. Overall, these results illustrate that the move towards sustainability is contingent upon the global prioritisation of reducing the emissions from the highest-impact sources.

In the case of developed countries, total CO_2 emissions and emissions from gaseous fuels are the strongest drivers of innovation, indicating that these nations remain focused on achieving commitments made to international climate agreements by lowering overall emission levels. In contrast, emissions from electricity, liquid fuels, and solid fuels have a detrimental effect on innovation. In developed countries, alternative energy and mitigation technology are already built into their systems; maybe that is why they do not prioritize these emission types. Increase in population growth reinforces innovation in these countries, as more number of human capital generates technological improvements and patents.

In the case of developing countries, results are less encouraging, as weak responses to the climate change indicator show. Patent activity is only positively and significantly impacted by total CO_2 emissions. That lack of meaningful responses to other kinds of emissions echo systemic and institutional limitations in these countries such as overreliance on the domestic economy for research and development (R and D), insufficient funding, and lack of technological access. Furthermore, the dependence on technological spillovers from the developed world creates less motivation for domestic innovation. This finds further reflection in the role played by demographic dynamics in driving technology where population growth in developing nations does not seem to be experiencing robust effects on innovation.

The results of this work highlight a clear danger around differential policy responses to climate change among different innovators. In developed countries, policymakers need to focus on R&D to develop technology to address electricity, liquid fuel, and solid fuel emissions. This will help fill the remaining gaps and strengthen their leadership in global sustainability efforts.

The emphasis for developing countries must be establishing innovation systems that are responsive to climate challenges, in particular, targeting R&D spending at solving total CO₂ emissions. Thus, the focus of governments and international organizations should be on capacity building, financing, and knowledge transfer to allow these countries to establish their technological base. Education, infrastructure, and human capital development programs can serve as stepping stones for innovation-driven solutions.

Last but not least, more research could focus on the spillover effect of rich/poor countries (or North/South) on climate-related innovation, possibly related to climate-friendly/green technologies spillovers. This knowledge highlights ways to build global strategies for co-innovation and development.

This is an important contribution to the emerging literature of differentiated impacts of climate change on innovation at different levels of economic development, which ultimately informs the need for country-specific policy responses to de carbonise growth and induce innovation in the process of economic development.

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