The Role of Targeted Innovation in Explaining Cross-Country Differences in CO_2 Emissions

CO_2 Emissions Dataset and Innovation metric Dataset

1. Introduction

Climate change, driven by rising carbon dioxide (CO_2) emissions, is a global challenge requiring urgent solutions (IPCC, 2021). While industrial growth boosts economies, it also increases environmental degradation (World Bank, 2020). Many believe that innovation—through new technologies and better policies—can help reduce emissions while maintaining economic growth (Schumpeter, 1942). Clean energy, energy efficiency, and industrial improvements are key to making this shift (OECD, 2019).

Using data from the Global Innovation Index and the Global Carbon Budget (Friedlingstein et al., 2022), alongside income classifications from the World Bank (2020), this study compares how innovation relates to emissions outcomes across countries. Wealthier nations often lead in green technology but still record high emissions due to industrial activity and consumption (IEA, 2021). Conversely, poorer nations depend on older, carbon-intensive energy sources, limiting their ability to adopt cleaner alternatives (Sachs et al., 2021).

Previous studies support the relevance of innovation to climate policy. Popp (2012) and Acemoglu et al. (2014) argue that investment in research and development (R&D), particularly in green sectors, can reduce emissions over time. However, others like Nordhaus (2019) and Frontiers in Environmental Science (2022) emphasize that without supportive policy environments—such as carbon pricing, green subsidies, and knowledge diffusion—innovation’s potential remains underutilized. Literature also suggests that innovation's impact may be nonlinear: early stages of growth may drive emissions up before technological efficiency begins to reduce them (EKC theory).

This paper contributes to the literature by combining cross-sectional emissions and innovation data and controlling for income levels, enabling a richer understanding of whether and when innovation helps mitigate emissions. Unlike most studies that focus on high-income nations or isolated policy effects, this analysis integrates innovation metrics, energy efficiency, and income across 130+ countries, offering a more inclusive global view. To analyze these relationships, the paper applies a combination of OLS regression models**, a** regression tree to uncover nonlinear and threshold effects, and a web-scraped green patent dataset to explore the quality and direction of innovation efforts. These methods allow us to evaluate not only whether innovation reduces emissions, but under what conditions and through which channels it becomes most effective.

The findings could help policymakers assess whether investments in innovation alone are sufficient, or whether they must be complemented by systemic economic and governance reforms. Understanding this dynamic is vital as we collectively strive for sustainable growth.

2. Data

This project draws on two primary datasets to analyse the relationship between innovation and CO_2 emissions: the Global Carbon Budget 2022 dataset and the Global Innovation Index (GII). Both datasets were merged to form a comprehensive panel capturing emissions, innovation performance, and economic indicators across countries.

After cleaning and merging, the final dataset includes over 130 countries with observations covering emissions data (2000–2020) and innovation indicators (2011–2020). For cross-sectional analysis, we selected data from 2010-2020, the most recent year with complete observations across both datasets. By combining environmental performance with innovation and economic indicators, the dataset enables a detailed investigation of whether higher innovation correlates with lower emissions—and under what economic conditions that relationship holds.

2.1 CO_2 Emissions Dataset (Global Carbon Budget 2022)

This dataset was sourced from the Global Carbon Project (Friedlingstein et al., 2022). It contains annual CO_2 emissions data from 2000 to 2020, broken down by source: coal, oil, gas, cement production, and gas flaring. Each row represents a country-year pair, allowing for cross-country and time-series comparisons. To standardize comparisons, we focused on Total CO_2 Emissions per capita as the primary outcome variable. This variable accounts for population size and reflects the average environmental impact of individuals in each country.

2.2 Global Innovation Index (GII)

The Global Innovation Index (GII), compiled by WIPO, measures a country's innovation capacity and performance across areas like institutions, education, infrastructure, and technology output. A higher GII score reflects stronger innovation systems and greater investment in R&D. For this project, the GII is used as a key explanatory variable, along with related metrics such as the Innovation Efficiency Ratio, R&D spending, high-tech imports, and the share of high-tech manufacturing. These indicators help assess how different dimensions of innovation relate to CO_2 emissions across countries.

2.3 World Bank Income Classification

To control for differences in economic development, we merged in World Bank income group classifications, categorizing countries as high, upper-middle, lower-middle, or low-income. This allows us to examine whether innovation plays a different role in emissions mitigation depending on a country's stage of development.

3. Summary statistic

With the datasets prepared and key variables defined, we now turn to the descriptive statistics that help contextualize the patterns in emissions and innovation across countries. The summary statistics provide a foundational understanding of long-term emissions trends, levels of innovation, and how these factors vary by country and decade. These insights serve as a bridge between the raw data and the deeper analysis performed in the regression models that follow.

Table 1: Summary of total, per capital and decadal CO2 Emissions by country (2000- 2020)

Country	Total Emissions	Total Per Capita Emissions	Mean Emissions over 20 years	Total Emissions 2000-2009	Total Emissions 2010-2020
Afghanistan	134.716516	4.279085	6.415072	23.749169	110.967347
Albania	95.202807	32.295674	4.533467	39.398730	55.804077
Algeria	2655.136465	71.876520	126.435070	978.604375	1676.532090
Andorra	10.645796	144.730713	0.506943	5.389744	5.256052
Angola	455.129260	19.056985	21.672822	178.610861	276.518399

This table is essential for understanding long-term emission trends at both the country and per capita levels. It provides a comprehensive summary of total CO_2 emissions, emissions per capita, and how those emissions have evolved over two distinct decades (2000–2009 and 2010–

2020). These comparisons allow us to assess whether emission levels are decreasing, stabilizing, or accelerating—especially in innovation-driven countries.

For example, Algeria's total emissions increased significantly between decades (from ~978 $MtCO_2$ to ~1676 $MtCO_2$) despite moderate innovation levels, while Andorra maintained stable emissions with very high per capita values, likely due to consumption-heavy economic patterns. This reflects the core insight of your research: innovation alone is not sufficient to drive down emissions unless it's coupled with structural changes in energy consumption and industrial behaviour.

This table strengthens the regression and visualization analysis by providing real-world context. It helps illustrate whether countries with high innovation have actually reduced emissions over time. Some still show rising emissions, highlighting that innovation's impact depends on its application and is not inherently linked to lower emissions.

Building on the emissions data, the next stage of analysis incorporates a broader set of innovation and technology indicators to assess how countries' innovation capacities align with their environmental and industrial performance.

Table 2: Global Innovation Metrics and Environmental and Technological Indicators by Country

Country	Global Innovation Index	Innovation Efficiency Ratio	Gdp Per Unit of Energy Use	ISO 14001 Certificates	R\&D	High-tech Imports	High-tech and Medium High-tech Mfg. \%
Albania	27.1	0.4	44.1	29.9	0.0	1.7	2.8
Algeria	19.5	0.3	29.7	1.2	5.1	28.1	4.6
Argentina	28.3	0.5	27.8	11.9	28.1	29.0	0.0
Armenia	32.6	0.7	21.4	0.6	1.2	19.5	4.2
Australia	48.4	0.5	26.2	16.0	59.4	34.0	33.7

Table 2 offers a multidimensional snapshot of each country's innovation landscape and environmental performance. It merges key indicators—such as the Global Innovation Index (GII), innovation efficiency, R&D investment, tech imports, high-tech manufacturing, and GDP per unit of energy use—into a single framework. This integration allows you to evaluate how innovation manifests across different countries and whether it aligns with environmental outcomes.

What makes this table powerful is that it connects inputs (R&D, manufacturing share, imports) with outcomes (energy efficiency, emissions per capita), enabling a more nuanced analysis. For instance, Australia shows high scores across most innovation indicators, including a strong R&D sector and efficient energy use. However, as seen in other tables and figures, its CO_2 emissions remain significant, suggesting that innovation success must be interpreted within broader economic and policy contexts.

This table directly feeds into my regression models and the figures, which explore the relationship between these variables and emissions. It reinforces the core argument: innovation must be efficiently translated into green outputs—especially in countries with high industrial activity—for it to impact emissions meaningfully.

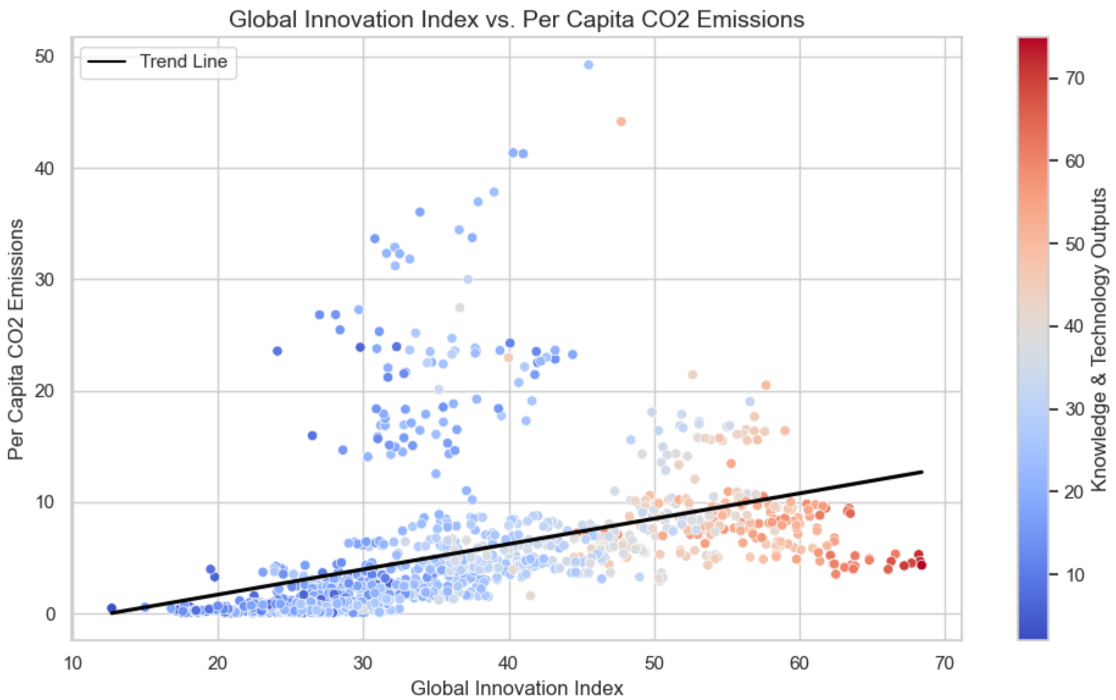
It supports the claim that innovation must be contextualized within income levels, governance, and infrastructure strength, rather than assumed to be universally effective.

4. Visualisations and Maps

While the summary statistics provided a foundational understanding of emissions trends and innovation levels, visualizations allow us to explore these relationships more intuitively—revealing patterns, anomalies, and non-linear dynamics that raw numbers alone may not capture.

4.1 Using Primary and Secondary Dataset

Figure 1: Global Innovation Index Vs Per Capita CO2 Emissions



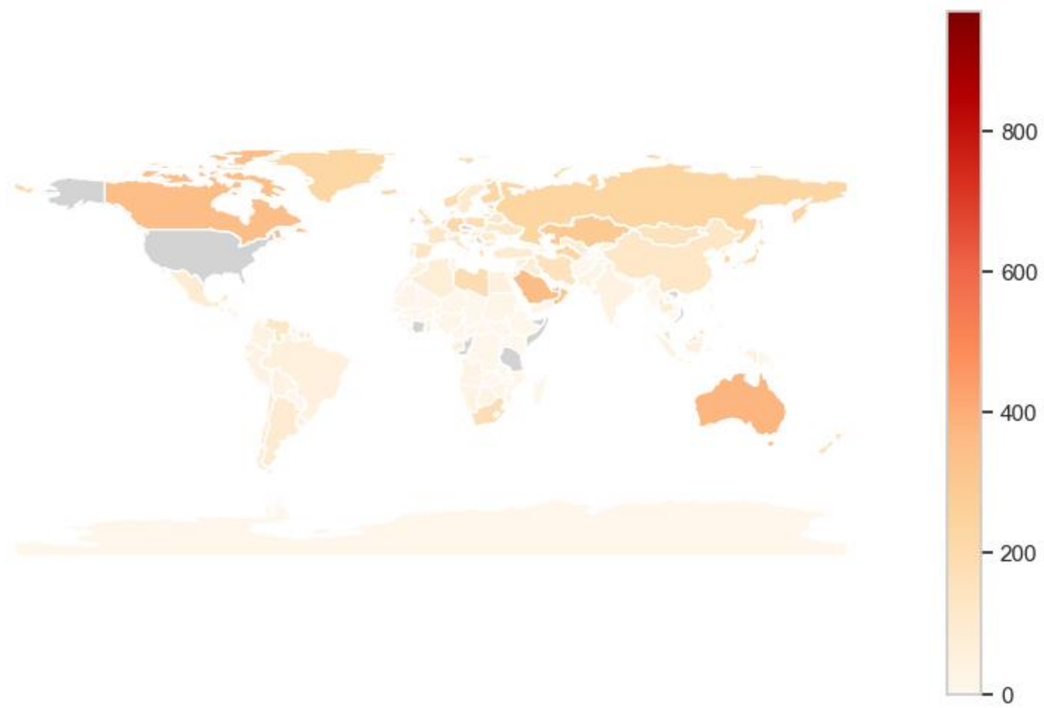
The scatter plot above (Figure 1) shows the relationship between a country's Global Innovation Index (GII) and its per capita CO_2 emissions, with colour representing Knowledge and Technology Outputs. The trend line reveals a mild positive correlation—countries with higher innovation scores often have higher emissions. However, this relationship is not consistent.

While some highly innovative countries have low emissions, others do not, suggesting that innovation alone does not guarantee sustainability.

While some correlation exists between innovation and emissions, it becomes clear that not all innovation is "green" innovation. Countries may rank highly in innovation due to advances in fields like AI, finance, or telecom, while still contributing significantly to emissions. This reveals a gap between innovation capacity and environmental action.

Moreover, the choropleth map below (Figure 2) visualizes per capita CO_2 emissions by country in 2020. Countries with darker shades emit more CO_2 per person. The map reveals that high-income, energy-intensive nations like the United States, Australia, and several Gulf states have some of the highest per capita emissions globally. Meanwhile, Sub-Saharan Africa and parts of Asia show much lower emissions per capita, reflecting lower energy use and industrial output.

Figure 2: Global Map of CO_2 Emissions Per Capita (2020)

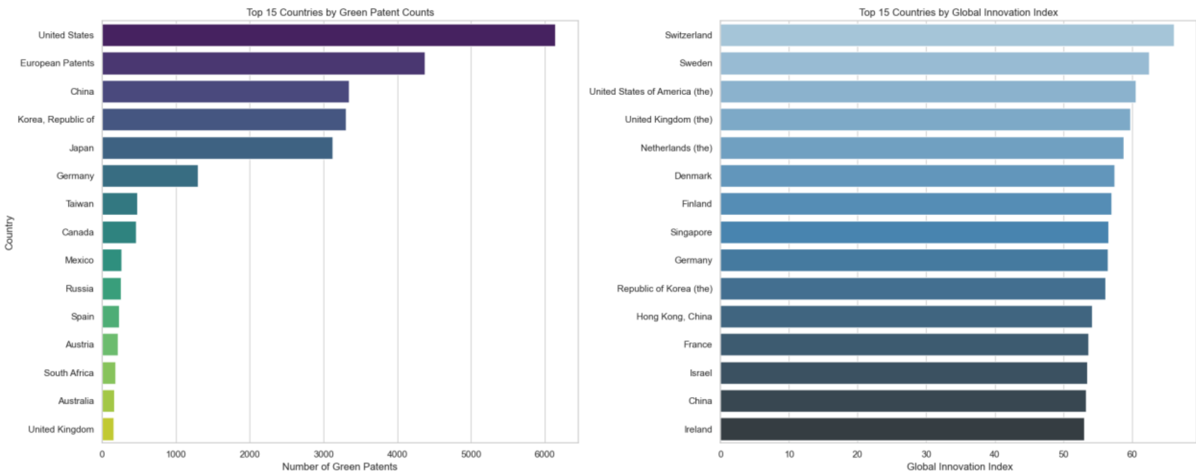


Some countries appear unshaded due to missing data in the emissions dataset or discrepancies in country naming between datasets. This includes smaller nations, disputed territories, and regions with inconsistent reporting. Despite these gaps, the map adds a geographic dimension to the analysis and helps contextualize the scatter plot in Figure 1 by illustrating the global spread of emissions. It supports the core claim of the paper: **innovation must be directed and supported by policy to meaningfully reduce emissions**, especially in high-output regions.

4.2 Using Web scraped data – Green patents

Therefore, the visual below (Figure 2) reinforces the importance of looking beyond general innovation indicators. By focusing specifically on green patent activity—as captured through my scraped dataset—the aim is to assess whether a country's innovation efforts are environmentally aligned. This graph supports using green patents as a more targeted proxy for sustainable innovation and highlights why general innovation scores may not fully capture a country's climate contribution.

Figure 2: Comparing Innovation index and Focus on Green Patents by country



The left panel is based on a scraped dataset, compiled using public patent data sources, which specifically captures green technology-related patent filings. This required custom data collection and processing using Python web scraping techniques. The right panel uses data from the Global Innovation Index, a widely recognized measure of innovation output, including technological, institutional, and infrastructural dimensions.

This dual-panel comparison provides a deeper look into the focus of national innovation systems. While countries like South Korea and the United States rank highly in both innovation and green patent activity, others like China dominate green patent filings but rank lower in the innovation index. Conversely, Switzerland and Sweden are global innovation leaders but have relatively lower counts of green patents, indicating broader innovation priorities rather than a specific focus on green technology.

The research investigates the relationship between innovation output and environmental sustainability, with a specific focus on whether countries with higher innovation rankings are also driving green technological change. This chart is central to this investigation—it helps identify not just the quantity of innovation (via GII), but also the quality or direction of that innovation (via green patent focus).

This distinction matters: a country may rank high on the innovation index due to advances in pharmaceuticals or AI, but may lag in contributing to climate-related technological solutions. The graph suggests that innovation leadership does not necessarily imply environmental leadership, underscoring the importance of aligning innovation policy with sustainability goals.

5. Regression Results

While the visualizations reveal broad patterns between innovation and emissions, the regression models that follow allow for a more rigorous, statistical assessment of these relationships—controlling for multiple variables and testing their significance

5.1 OLS Regression table

The regression analysis conducted in this project provides meaningful insights into how different components of innovation influence per capita CO_2 emissions across countries. Drawing on the full OLS model presented in Regression Table 1: Influence of Economic Factors on the Relationship Between Innovation and CO_2 Emissions, we find that innovation, as measured by the Global Innovation Index (GII), has a statistically significant positive association with CO_2 emissions. This suggests that countries investing heavily in innovation may experience rising emissions, potentially due to the industrial activity and energy consumption that often accompany economic and technological growth.

However, this relationship becomes more nuanced when we disaggregate innovation into its sub-pillars. Human Capital and Research and Infrastructure both show strong positive effects on emissions, indicating that innovation through educational and physical capital investments—often associated with development and production capacity—can elevate environmental pressure. In contrast, Knowledge and Technology Outputs exhibit a statistically significant negative relationship with emissions. This implies that countries that are not only innovating but effectively transforming that innovation into technological advancement—particularly clean and efficient technologies—tend to experience reduced emissions. From a performance standpoint, the model's adjusted R^2 increases from 0.163 in the base model to

0.254 in the full specification, confirming that accounting for the multidimensional nature of innovation improves our ability to explain variations in emissions.

Regression Table: Dependent Variable - Per Capita CO2 Emissions

	(1)	(2)	(3)	(4)
Global Innovation Index	0.227***	0.026	0.298***	0.154**
	(0.015)	(0.032)	(0.045)	(0.054)
Human capital and research		0.175***	0.144***	0.144***
		(0.024)	(0.024)	(0.024)
Infrastructure			0.104***	0.104***
			(0.022)	(0.022)
Knowledge and technology outputs			-0.231***	-0.186***
			(0.028)	(0.030)
const	-2.852***	-1.313***	-3.995***	-4.070***
	(0.572)	(0.600)	(0.669)	(0.663)
Observations	1192	1192	1192	1192
R^2	0.164	0.199	0.242	0.256
Adjusted R^2	0.163	0.198	0.240	0.254
Residual Std. Error	5.942 (df=1190)	5.819 (df=1189)	5.663 (df=1188)	5.612 (df=1187)
F Statistic	233.634*** (df=1; 1190)	147.819*** (df=2; 1189)	126.421*** (df=3; 1188)	102.320*** (df=4; 1187)

Note: *p<0.1; **p<0.05; ***p<0.01

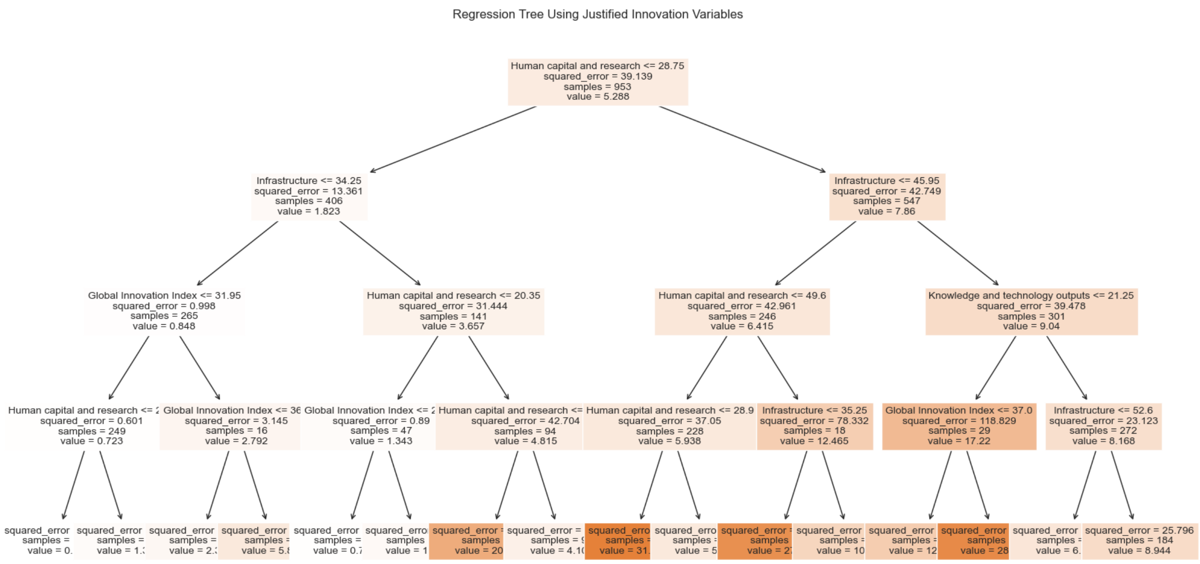
5.2 Regression Tree

To complement and extend these linear findings, a regression tree model was developed and is visualized in Regression Tree 1: Using Justified Innovation Variables. This tree offers a non-linear and threshold-sensitive understanding of the relationship between innovation and emissions. It identifies Human Capital and Research as the most critical splitting variable, reaffirming its central role in shaping emissions outcomes. Further splits along variables like Infrastructure, Knowledge and Technology Outputs, and the Global Innovation Index reveal distinct pathways.

For example, countries with high levels of human capital and infrastructure often fall into high-emission branches of the tree. Conversely, those with strong knowledge and technology outputs—regardless of their infrastructure scale—tend to appear in lower-emission nodes.

The regression tree yields a test Mean Squared Error (MSE) of 50.11, providing a complementary performance measure that captures the complexity of interactions and non-linear thresholds missed by the OLS model. This difference in structure highlights a key strength of the regression tree: its ability to model conditional relationships, such as the notion that innovation only begins to reduce emissions after a certain level of technological advancement or educational investment has been reached.

Regression Tree 1:



From an economic perspective, these results align well with the logic of the Environmental Kuznets Curve (EKC). Innovation, like income, may initially drive emissions upward as countries industrialize and expand. However, as innovation matures—especially when channelled into knowledge diffusion and clean technologies—it can become a tool for emissions reduction. This transition reinforces the importance of innovation quality and direction, not just quantity. Economic development supported by education, research, and green innovation can thus decouple growth from environmental harm.

In comparing the two models, both the OLS regression and the regression tree identify Human Capital, Infrastructure, and Knowledge & Technology Outputs as the most influential factors, providing strong consistency in key findings. However, their interpretive approaches differ: the OLS model provides a clean and interpretable summary of average trends, while the regression tree uncovers conditional logic and non-linear dynamics that offer deeper insights into how innovation must be structured to achieve environmental benefits. Taken together, they paint a robust and coherent picture: innovation can either exacerbate or alleviate emissions, depending on its form, application, and policy context.

Ultimately, these findings emphasize that innovation policy should not simply aim to boost national innovation scores but should also prioritize innovation that is environmentally conscious and efficiently translated into practical outcomes. For policymakers, this means investing not just in more innovation, but in the right kinds of innovation—particularly those rooted in knowledge creation, human capital development, and clean technology adoption.

5. Conclusion

This paper explored the economic question: Does innovation reduce CO_2 emissions, and under what conditions is it most effective across countries at different income levels? While innovation is often seen as a solution to environmental problems, this study finds that its impact on emissions depends greatly on the type and focus of the innovation.

The results contribute to the existing literature in several important ways. First, using Regression Table 1, we find that not all forms of innovation reduce emissions.

Components such as Human Capital and Infrastructure are positively associated with emissions, likely because they support industrial activity and economic growth. In contrast, Knowledge and Technology Outputs show a significant negative relationship with emissions, suggesting that innovation that leads to clean and productive technologies can help reduce environmental impact. Second, the regression tree model (Regression Tree 1) reveals that the effects of innovation are nonlinear—innovation only reduces emissions after certain thresholds are met. For example, countries with strong Knowledge Outputs tend to fall into lower-emission categories, even if other innovation indicators are high. This shows that how innovation is applied matters just as much as how much innovation exists.

This project adds a new perspective by combining traditional regression analysis with machine learning techniques, offering a more complete view of the innovation-emissions relationship. Unlike many previous studies, it looks across more than 130 countries and includes several dimensions of innovation, rather than relying on a single index. It also considers how these effects vary across income groups, making the analysis more inclusive and globally relevant.

There are still areas for future research. This study uses data from a single year (2020), so future work could look at how these relationships change over time. In addition, other factors such as government policies, environmental regulations, or institutional quality were not included but likely play an important role. Lastly, deeper analysis of green patent activity could help identify which types of innovation are most directly tied to emissions reductions.

In conclusion, this research shows that innovation alone is not enough to reduce emissions. Its effectiveness depends on its direction, focus, and the broader economic and policy environment. For innovation to support climate goals, it must be strategically guided toward sustainable technologies, supported by education, research, and the right institutional frameworks.

Word count: 2898

6. References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2014). The environment and directed technical change. American Economic Review, 102(1), 131-166. https://doi.org/10.1257/aer.102.1.131

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., et al. (2022). Global carbon budget 2022. Earth System Science Data, 14(8), 4653-4723. https://doi.org/10.5194/essd-14-4653-2022

Frontiers in Environmental Science. (2022). The impact of innovation on CO_2 emissions: The threshold effect of financial development. Frontiers in Environmental Science. Retrieved from https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2022.980267/full

Free Policy Briefs. (2024). The impact of technological innovations and economic growth on CO_2 emissions in different countries. Free Policy Briefs. Retrieved from https://freepolicybriefs.org/2024/04/08/economic-growth-co2-emissions/

International Energy Agency (IEA). (2021). Energy efficiency 2021: A global analysis of energy efficiency trends and policies. IEA Publications. Retrieved from https://www.iea.org/reports/energy-efficiency-2021

Intergovernmental Panel on Climate Change (IPCC). (2021). Climate change 2021: The physical science basis.Cambridge University Press. Retrieved from https://www.ipcc.ch/report/ar6/wg1/

National Center for Biotechnology Information (NCBI). (2021). A comparative analysis of the relationship between innovation and carbon emissions in the transportation sector. NCBI. Retrieved from https://pmc.ncbi.nlm.nih.gov/articles/PMC8055480/

National Center for Biotechnology Information (NCBI). (2023). Revisiting R&D intensity and CO_2 emissions link in the USA using time-varying Granger causality. NCBI. Retrieved from https://pmc.ncbi.nlm.nih.gov/articles/PMC10520821/

Nordhaus, W. D. (2019). Climate change: The ultimate challenge for economics. American Economic Review, 109(6), 1991-2014. https://doi.org/10.1257/aer.109.6.1991

Organisation for Economic Co-operation and Development (OECD). (2019). Innovation and environmental sustainability: Policy insights. OECD Publishing. https://doi.org/10.1787/9789264307438-en

Organisation for Economic Co-operation and Development (OECD). (2019). Measuring innovation in energy technologies. OECD Publishing. https://doi.org/10.1787/9789264311992-en

Popp, D. (2012). The role of technological change in green growth. Energy Economics, 34(1), S63-S74. https://doi.org/10.1016/j.eneco.2012.08.052

Sachs, J. D., Schmidt-Traub, G., Kroll, C., Lafortune, G., & Fuller, G. (2021). The decade of action for the Sustainable Development Goals: Sustainable Development Report 2021. Cambridge University Press. https://doi.org/10.1017/9781009106559

Schumpeter, J. A. (1942). Capitalism, socialism, and democracy. Harper & Brothers.

Stern, N. (2007). The economics of climate change: The Stern Review. Cambridge University Press. https://doi.org/10.1017/CBO9780511817434

Taylor & Francis Online. (2020). Income inequality, innovation, and carbon emission. Taylor & Francis Online. Retrieved from https://www.tandfonline.com/doi/full/10.1080/1331677X.2020.1734855

Taylor & Francis Online. (2024). The interrelationships between carbon dioxide emissions and technological innovation. Taylor & Francis Online. Retrieved from https://www.tandfonline.com/doi/full/10.1080/14786451.2024.2352515

World Bank. (2020). World development indicators 2020. World Bank Group. Retrieved from https://databank.worldbank.org/source/world-development-indicators