The Complementary Role of Human Capital in Innovation-Driven Decarbonization

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Abstract

Achieving net-zero emissions requires a strategic alignment of human capital development and technological innovation. This study examines how education enhances the impact of R&D in reducing carbon emissions, using fixed effects and Difference-in-Differences methods. The findings confirm that while education and R&D independently influence emissions, their interaction significantly accelerates decarbonization, with evidence showing that countries with higher education and R&D achieve a 7% emissions reduction. Mechanism analysis reveals that this interaction strengthens environmental policy enforcement, fosters the diffusion of green technologies, and improves energy efficiency. These results highlight the need for policies that integrate education and innovation to maximize environmental benefits, accelerate the transition to net zero, and support long-term carbon reduction.

Keywords: Human capital, Innovation, Carbon Emissions, Environmental Policy

JEL Codes: Q55, Q58, O31, O44

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1 Introduction

Addressing climate change requires a fundamental shift in how economies grow while reducing carbon emissions. The global challenge of decarbonization has sparked significant policy efforts, particularly in advanced economies, to balance economic expansion with environmental sustainability (Stern, 2008; Fankhauser and Jotzo, 2018). Traditional economic models suggest that as countries develop, emissions initially rise due to industrialization but eventually decline as economies transition toward cleaner energy and advanced technologies (Grossman and Krueger, 1995). However, this pattern is not uniform across countries, and a growing body of research emphasizes that factors beyond economic growth, such as education and technological innovation, play a crucial role in shaping emissions trajectories (Heil and Selden, 2001).

The relationship between economic growth and carbon emissions has been extensively analyzed within the Environmental Kuznets Curve (EKC) framework. Early studies suggest that emissions initially rise with economic development before declining as economies transition toward cleaner industries and adopt more sustainable production methods (Agras and Chapman, 1999; Heil and Selden, 2001). However, subsequent research challenges the notion that economic growth alone leads to emissions reductions, emphasizing the role of technological advancements, institutional quality, and policy interventions in shaping emissions trajectories (Stern, 2018; Friedrichs and Inderwildi, 2013; Vollebergh et al., 2009).

Among these factors, human capital and R&D investment stand out as key drivers of decarbonization. Education enhances a society's capacity to develop and absorb new knowledge, while R&D fosters the creation of green technologies (Balaguer and Cantavella, 2018; Shahbaz et al., 2016). Yet, the effectiveness of R&D in mitigating emissions likely depends on the availability of a highly skilled workforce that can translate innovation into widespread application. Empirical studies confirm that R&D plays a crucial role in improving energy efficiency and fostering the development of low-carbon technologies (Sadorsky, 2018; Shahbaz et al., 2016). However, renewable energy investments alone do not necessarily lead to long-term emissions reductions unless accompanied by technological advancements (Al-Mulali et al., 2015; Pata, 2018). Green R&D is, therefore, essential for breaking the link between energy consumption and emissions (Wang et al., 2011; Zhang and Cheng, 2009). Despite the intuitive link between education, innovation, and environmental outcomes, the extent to which education amplifies the emissions-reducing effects of R&D and whether this relationship holds across different economic contexts remains an empirical open question.

This study tests the hypothesis that education amplifies the impact of R&D on carbon emissions reduction, enhancing an economy's ability to translate innovation into effective decarbonization. It focuses on answering a main question: Does R&D investment alone lead to significant reductions in carbon emissions, or does its effectiveness depend on the presence of a highly skilled workforce? Additionally, how do different income-level countries benefit from education and R&D investments in decarbonization? What are the mechanisms through which education and R&D contribute to emissions reductions?

Beyond these baseline findings, the analysis shows that R&D investments alone reduce emissions by 4.9% but become significantly more effective when combined with education, amplifying the effect to 6.4%, a 30.6% stronger decarbonization impact. This pattern holds across the full sample and is particularly strong in middle-income countries, where the education-R&D interaction doubles its reduction in emissions. However, this interaction effect weakens in the highest-emission economies, where structural constraints in hard-to-abate sectors limit the extent to which education-driven innovation can accelerate decarbonization. This suggests that while human capital enhances the effectiveness of R&D investments, additional policy mechanisms may be necessary to overcome sectoral barriers in heavily industrialized, high-emission countries.

To further validate the main findings, a Difference-in-Differences (DiD) approach exploits the EU 2020 policy as a quasi-experimental setting, confirming that the interaction between education and R&D plays a significant role in post-policy emissions reductions. Specifically, the EU 2020 policy led to an immediate 15% reduction in CO_2 emissions in treated countries, stabilizing at 6% in the longer term. Furthermore, in high-education, high-R&D economies, the policy impact was stronger, reducing emissions by 7% due to an additional 1 percentage point effect from human capital and innovation investments.

This research also explores the mechanisms driving these results. The channels considered are the development and diffusion of green patents, institutional capacity, and energy efficiency improvements. the study finds that green patent development alone does not immediately lead to emissions reductions. However, the diffusion of both inventions and technologies plays a crucial role in emissions reductions. These results indicate that fostering the development of green patents must be complemented by policies that enhance their diffusion. The findings also confirm that nations with stronger education and R&D systems enforce more stringent environmental policies, suggesting that human capital and innovation not only drive technological change but also enhance institutional capacity for climate governance. The last mechanism shown by reductions in carbon intensity confirms that emissions decline primarily through efficiency gains rather than economic contraction. Lastly, while education and R&D contribute to the expansion of green jobs, employment shifts alone do not necessarily drive emissions reductions. Instead, the key factor in decarbonization is the extent to which R&D investments are directed toward green technologies and effectively implemented.

This study contributes to the literature by providing novel evidence on the role of human capital in amplifying the effectiveness of R&D in achieving long-term emissions reductions. While previous research has examined the independent effects of education and R&D on environmental sustainability, this analysis is the first to systematically test their interaction and the pathways through which it influences carbon emissions. The findings suggest that policies aimed at accelerating decarbonization should not only promote technological innovation but also invest in education to enhance the workforce's ability to implement and scale low-carbon solutions. By highlighting the importance of absorptive capacity and institutional quality in translating innovation into environmental benefits, this research offers new insights into how economies can navigate the transition to sustainability more effectively.

The remainder of the paper is organized as follows. The empirical methods and data are presented in 2. Section 3 reports the main results of the analysis, Section 4 provides robustness checks, and Section 5 explains the mechanisms driving the results. Lastly, Section 6 concludes the analysis.

2 Empirical Strategy

This section outlines the econometric strategy used to estimate the Environmental Kuznets Curve while incorporating the role of human capital and innovation. The analysis proceeds in two stages. First, a baseline fixed effects model is estimated to assess how education and R&D influence emissions across countries over time. Second, a Difference-in-Differences (DiD) framework is employed to evaluate the impact of the EU 2020 policy using a Two-Way Fixed Effects (TWFE) approach. To assess the impact of education and R&D on the EKC, we estimate the following fixed effects model:

$$\begin{aligned} \log\ \text{CO}_{2it} = {} & \beta_1 \log\ \text{GDPpc}_{it} + \beta_2 \log\ \text{GDPpc}_{2it} + \beta_3 \log\ \text{Educ}_{it} + \beta_4 \log\ \text{Educ}_{2it} \\ & + \beta_5 \log\ \text{R\&D}_{it} + \beta_6 \log\ \text{R\&D}_{2it} + \beta_7 (\log\ \text{Educ}_{it} \times \log\ \text{R\&D}_{it}) \\ & + \beta_8 X_{it} + \alpha_i + \delta_t + \varepsilon_{it} \end{aligned} \tag{1}$$

where $\log(\text{CO}_2)_{it}$ captures the natural logarithm of carbon emissions in country i at time t. Economic growth is modeled through $\log(\text{GDPpc})_{it}$ and its squared term, capturing the potential nonlinear relationship implied by the EKC. Education effects are introduced via $\log(\text{Education})_{it}$ and its squared term, allowing for diminishing or nonlinear impacts of human capital on emissions. Similarly, $\log(\text{R\&D})_{it}$ and its squared term assess the role of research and development in influencing emissions, with potential nonlinearities. The interaction term $\log(\text{Education})_{it} \times \log(\text{R\&D})_{it}$ examines whether higher education levels enhance the emissions-reducing effect of R&D investment. The control variables, X_{it}, capturing additional structural and economic determinants such as energy use, trade openness, and disposable income inequality measured by the Gini Coefficient. The model includes country-fixed effects (α_i), time-fixed effects (δ_t) and the error term ε_{it} captures unobserved factors affecting emissions.

2.1 Data

The dataset covers a balanced panel of 91 countries over a 25-year period from 1995 to 2019. The dependent variable, CO_2 emissions per capita, is sourced from the Our World in Data database. Income inequality data, measured by the disposable Gini coefficient, is obtained from the Standardized World Income Inequality Database (SWIID). Additional variables, including GDP per capita, tertiary education enrollment, R&D expenditures, energy use, and trade openness, come from the World Bank's World Development Indicators (WDI). Countries are classified as high-, middle-, or low-income economies following the World Bank's income classification. Table 12 lists the countries in the analysis and table 13 classifies countries by income levels in the Appendix.

Summary statistics and a correlation matrix are presented in Tables 9 and 10 in the Appendix. CO_2 emissions per capita vary across countries, reflecting differences in economic structures and energy consumption patterns. These differences are also appreciated in table 11 that presents summary statistics by income classification. As expected, CO_2 emissions per capita are significantly higher in high-income countries compared to middle- and low-income economies. This aligns with greater industrialization and energy consumption in wealthier nations, driven by manufacturing, transportation, and energy-intensive industries. GDP per capita also exhibits stark differences, with high-income countries outpacing middle- and low-income economies, underscoring productivity gaps, technological disparities, and differences in capital accumulation. While middle-income countries show notable economic growth, they remain well below the income levels of high-income nations.

R&D investment is another key differentiator across income groups. High-income countries allocate significantly more resources to research and innovation, fostering technological advancements and high-value industries. Middle-income countries are increasing R&D spending but still lag in absolute investment and intensity relative to GDP. Low-income countries invest the least in R&D, constrained by limited funding, fewer research institutions, and weaker incentives for private-sector innovation. These patterns underscore the role of human capital and innovation capacity in shaping economic and environmental trajectories.

3 Results

Table 1 presents the regression results examining the relationship between economic growth, tertiary education, R&D expenditures, and CO_2 emissions per capita. In column (1), the coefficient for the log of GDP per capita is positive and statistically significant, while its squared term is negative and highly significant. This confirms the Environmental Kuznets Curve (EKC) hypothesis, suggesting that CO_2 emissions initially rise with economic growth but decline beyond a certain income threshold.

Column (2) introduces tertiary education enrollment. The coefficient is positive and significant, while its squared term is negative and significant. These results indicate a nonlinear relationship: initially, higher tertiary education enrollment is associated with increased CO_2 emissions, likely due to industrial expansion and knowledge-driven economic activity. However, as education levels rise further, emissions decline, suggesting that human capital fosters environmental awareness and supports green innovation. Column (3) incorporates R&D expenditures and their squared term, revealing also a nonlinear effect on emissions. The negative linear coefficient suggests that R&D generally reduces emissions by 4.9%, and the negative squared term implies that the decarbonization effect accelerates at higher levels of investment.

Column (4) introduces the interaction term between tertiary education and R&D. While the standalone coefficient for R&D turns positive, the interaction term remains negative and highly significant. This suggests that the emissions-reducing effect of R&D is conditional on human capital levels. Specifically, in economies with a more educated workforce, R&D investments are more effectively directed toward clean technologies, accelerating emissions reductions.

Quantitatively, the results indicate that R&D alone reduces carbon emissions by 4.9%, as shown in column 3, while the interaction with tertiary education leads to an amplified reduction of 6.4%. This 1.5 percentage point increase represents a 30.6% stronger decarbonization effect, underscoring the role of human capital in maximizing the environmental impact of innovation. The interaction effect implies that without a sufficiently skilled workforce, the full potential of R&D in reducing emissions may remain unrealized.[1]

Across all models, energy use remains a strong positive predictor of CO_2 emissions. Trade openness has a small and marginally significant negative effect, suggesting that higher trade

[1]Additional results to confirm the robustness of these findings using instrumental variables estimation are presented in table 14 in Appendix B.

Table 1: Impact of Education and R&D on CO_2 Emissions

	(1)	(2)	(3)	(4)
Log GDP p.c	2.523***	1.797***	1.324***	1.176***
	(0.090)	(0.100)	(0.143)	(0.145)
Log GDP p.c Sq.	-0.142***	-0.098***	-0.071***	-0.062***
	(0.005)	(0.006)	(0.009)	(0.009)
Log Tertiary Enrollment		0.213***	0.172***	0.090*
		(0.020)	(0.049)	(0.051)
Log Tertiary Enrollment Sq.		-0.034***	-0.032***	-0.026***
		(0.004)	(0.007)	(0.007)
Log R&D Exp.			-0.049***	0.204***
			(0.017)	(0.053)
Log R&D Exp. Sq.			-0.010**	0.003
			(0.005)	(0.005)
Log Tertiary Enrollment × Log R&D				-0.064***
				(0.013)
Log Energy Use	0.766***	0.861***	0.976***	0.955***
	(0.023)	(0.023)	(0.031)	(0.031)
Log Trade	0.083***	-0.006	-0.037*	-0.022
	(0.016)	(0.016)	(0.021)	(0.021)
Income Inequality	-0.002	-0.005***	-0.001	-0.001
	(0.002)	(0.002)	(0.002)	(0.002)
Observations	2,471	1,793	984	984
Adjusted R^2	0.56	0.70	0.69	0.70

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is log CO_2 per capita. Column (1) includes only economic growth variables, column (2) adds education, column (3) introduces R&D, and column (4) examines the interaction between education and R&D.

integration may be associated with efficiency improvements or technology diffusion that lowers emissions. Income inequality, measured by the Gini coefficient, exhibits a small but statistically significant negative effect in some models, potentially reflecting redistributive policies or structural economic shifts linked to lower emissions.

3.1 Heterogeneous Effects by Income Level

Table 2 presents regression results estimated separately for high-, middle-, and low-income countries, highlighting key differences in the relationship between economic development, education, R&D, and CO_2 emissions. The EKC hypothesis holds for high- and middle-income countries, where emissions initially rise with GDP but decline beyond a threshold. High-income countries reach this turning point earlier, likely due to advanced regulations and cleaner technologies. In contrast, middle-income nations require higher GDP levels to experience emissions reductions, suggesting structural constraints in their energy transitions. For low-income countries, GDP has no significant nonlinear effect, implying that economic growth alone is insufficient to drive emissions reductions.

Table 2: Impact of Education and R&D on CO_2 Emissions by Income Level

	High Income (1)	Middle Income (2)	Low Income (3)
Log GDP p.c	1.250***	2.417***	0.971*
	(0.370)	(0.393)	(0.529)
Log GDP p.c Sq.	-0.065***	-0.139***	-0.052
	(0.019)	(0.024)	(0.034)
Log Tertiary Enrollment	0.321**	-0.335**	0.125
	(0.135)	(0.161)	(0.081)
Log Tertiary Enrollment Sq.	-0.061***	0.031	-0.019
	(0.018)	(0.022)	(0.017)
Log R&D Exp.	0.250**	0.443***	-0.085
	(0.106)	(0.152)	(0.104)
Log R&D Exp. Sq.	0.017*	0.002	-0.033*
	(0.009)	(0.019)	(0.017)
Log Tertiary Enrollment × Log R&D	-0.062**	-0.139***	-0.037
	(0.026)	(0.033)	(0.032)
Observations	488	296	145
Adjusted R^2	0.70	0.77	0.68

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is log CO_2 per capita. Columns (1), (2), and (3) correspond to high-income, middle-income, and low-income countries, respectively. Control variables include log of energy use, trade and income inequality.

Tertiary education impacts emissions differently across income groups. In high-income countries, education shows similar non-linear behavior discussed previously. In middle-income countries, tertiary education has a negative effect on emissions, indicating that factors such as improved energy efficiency, technological spillovers, or policy shifts contribute to decarbonization as education levels rise. In low-income countries, education's effect remains weak, indicating that education alone may not yet play a decisive role in shaping emissions trajectories in less developed economies.

The relationship between R&D expenditures and carbon emissions varies significantly by income level, reflecting differences in innovation capacity and the ability to translate technological advancements into environmental benefits. In high-income countries, R&D investment is associated with higher emissions, as indicated by the positive and significant coefficients for R&D expenditures and its squared term. However, the negative and statistically significant interaction between R&D and tertiary education indicates that the emissions-increasing effect of R&D is moderated in economies with a more skilled workforce. This interaction reduces by 6.2% carbon emissions per capita. This implies that education plays a crucial role in redirecting R&D toward green innovation. In other words, without sufficient human capital, R&D alone may not be enough to drive decarbonization in high-income economies.

R&D expenditures in middle-income economies exhibit a stronger effect. The coefficient on R&D is larger, but also the interaction term with tertiary education. The interaction effect reduces carbon emissions per capita by 14%, more than double the effect found in high-income countries. This suggests that middle-income countries are in a phase where investments in knowledge and technological innovation are particularly effective at reducing emissions, likely because these economies are undergoing structural transitions toward cleaner production methods. In low-income countries, neither R&D expenditures nor their interaction with tertiary education significantly influences emissions reductions. The coefficient for R&D is negative but not statistically significant, while the squared term suggests that any potential benefits from R&D may only materialize at higher levels of investment. This suggests that, in lower-income settings, constraints such as limited technology transfer mechanisms, or insufficient absorptive capacity may prevent R&D investments from translating into effective emissions reductions.

3.2 Quantile Regression

This section presents the results of the quantile regression analysis, which examines the heterogeneous effects of education and R&D on carbon emissions across different levels of emissions. Table 15 reported in section C in the appendix, reports the estimates for the 25th, 50th, 75th, and 90th percentiles of the emissions distribution.

The estimates for log GDP per capita are positive and significant across all quantiles, indicating that economic growth is associated with higher emissions. The squared term is negative and significant, confirming the Environmental Kuznets Curve hypothesis. Similar results are confirmed also for education. The coefficients for R&D expenditure indicate that investments in R&D contribute to emissions reductions. The squared term is also negative, confirming that higher levels of R&D investment accelerate emissions reductions.

The interaction term between tertiary education and R&D expenditure is negative and significant at the 25th, 50th, and 75th percentiles but not at the 90th percentile. This suggests that education enhances the emissions-reducing effect of R&D, particularly in low- to mid-high-emission economies. The magnitude of the interaction effect is largest at the median, where a one percent increase in both education and R&D leads to an additional 14.5% reduction in emissions. At the 25th and 75th percentiles, the effect is 9.4% and 12.4%, respectively.

For the highest-emission countries (90th percentile), however, the interaction is not significant. This could be due to structural factors that make decarbonization particularly difficult in these economies. Many high-emission countries have a large share of industries such as steel, cement, and chemicals, which rely on carbon-intensive processes that are difficult to replace even with technological advancements.

4 Difference-in-Differences Approach

The European Union (EU) has long been at the forefront of climate policy, implementing ambitious frameworks to reduce carbon emissions while fostering economic growth. In 2010, the EU introduced the Europe 2020 Strategy, a comprehensive plan designed to promote smart, sustainable, and inclusive growth. One of the key components of this strategy was the EU 2020 Climate and Energy Package, which set legally binding targets for all member states. These targets aimed to reduce greenhouse gas (GHG) emissions by 20% compared to 1990 levels, increase the share of renewable energy in total final energy consumption to 20%, and improve energy efficiency by 20%.

Beyond direct regulatory mandates, the EU 2020 Strategy placed significant emphasis on education and innovation as key enablers of long-term decarbonization. Recognizing that achieving emissions reductions required structural economic transformations, the EU complemented its climate targets with policies designed to stimulate technological progress, human capital formation, and industrial transition. The Innovation Union initiative, launched under the Europe 2020 framework, sought to strengthen the role of R&D in fostering sustainable economic growth. The policy aimed to increase public and private R&D investment to at least 3% of GDP, enhance the capacity of higher education institutions to support technological advancements, and promote university-industry collaboration to accelerate the commercialization of clean energy technologies.

This study evaluates whether education enhances the emissions-reducing effects of R&D investment, testing the hypothesis that a highly educated workforce strengthens the role of innovation in decarbonization. A Difference-in-Differences (DiD) approach within a Two-Way Fixed Effects framework is used, comparing emissions trends between EU member states (treated group) and advanced non-EU economies (control group). The model is specified as:

$$\log(\text{CO}_{2it}) = \beta_1 \text{Post}_t + \beta_2 \text{Treated}_i + \beta_3 (\text{Post}_t \times \text{Treated}_i) + \beta_4 X_{it} + \alpha_i + \delta_t + \varepsilon_{it} \qquad (2)$$

where $\log(\text{CO}_{2it})$ represents per capita carbon emissions, Post_t is a binary indicator for years after 2010, and Treated_i is a binary variable for EU membership. The interaction term captures the policy's effect, and the model controls for GDP per capita, tertiary education enrollment, R&D expenditures (including squared terms), their interaction, energy use, trade, and income inequality.

Table 3 presents the results, showing a significant reduction in emissions for treated countries. The negative and significant coefficient for the Post $\times$ Treated interaction in column (1) indicates that the EU 2020 policy led to an immediate 15% reduction in CO_2

emissions among EU member states. However, as seen in column (2), this effect moderates to a 6% reduction in the longer term when accounting for a two-period lag.

The impact of education and R&D on emissions reduction emerges with a delay. This term suggests that in countries with higher levels of tertiary education and R&D investment, emissions decline an additional 1 percentage point, bringing the total long-term policy effect to 7% in these economies, similar to the results found previously. This suggests that innovation and human capital play a growing role over time, likely through technology adoption and structural adjustments. The results for GDP per capita and its squared term align with the EKC, indicating that emissions initially rise with economic growth before declining at higher income levels.[2]

Table 3: Difference-in-Differences Estimation of EU 2020 Policy Impact

	(1)	(2)
Post × Treated	-0.15***	-0.06***
	(0.06)	(0.02)
Post-Treated Education × R&D	0.00	
	(0.01)	
L2.Post-Treated Education × R&D		-0.01***
		(0.00)
Log GDP p.c	0.84*	1.21**
	(0.47)	(0.60)
Log GDP p.c Sq.	-0.05*	-0.06*
	(0.03)	(0.03)
Observations	236	191
Adjusted R^2	0.87	0.92

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is log CO_2 per capita. Column (1) estimates the immediate impact of the EU 2020 policy, while column (2) includes a two-period lag to assess delayed effects. The key interaction term (Post × Treated) captures the effect of the EU 2020 policy on emissions. Control variables include the log enrollment in tertiary education, log R&D, log R&D squared, log of energy use, trade, and income inequality.

5 Mechanisms

To better understand the main results, this section explores several potential mechanisms through which the interaction of human capital and innovation contribute to decarbonization. We investigate whether emissions reductions occur through the development and diffusion of green inventions, the adoption of low-carbon technologies, the role of environmental reg-

[2]Conditional parallel trends are presented in figure 2 in the Appendix.

ulations, improvements in energy efficiency, and shifts in green employment. Each of these pathways provides insight into how education and R&D investments translate into tangible environmental benefits, helping to clarify the channels through which innovation fosters sustainability.

5.1 Development of Inventions

This subsection examines whether green inventions mediate the relationship between the interaction of tertiary education and R&D investment and CO_2 emissions. Column (1) of table 18 in the Appendix, indicates that the interaction term has a positive and significant effect on the development of environment-related inventions, suggesting that education enhances the impact of R&D in fostering green innovation. However, column (2) shows that the share of newly developed green inventions does not significantly affect CO_2 emissions. Similarly, column (3) finds that the interaction between tertiary education and R&D remains non-significant in reducing emissions through green inventions. This implies that while education boosts innovation capacity, it does not directly translate into emissions reductions.

Several factors may explain this result. First, green inventions must be widely adopted and integrated into production systems to impact emissions. If technologies remain in the patent stage or face commercialization barriers, their environmental benefits remain limited. Second, many green technologies require time for scaling, regulatory approval, and industry adoption, delaying their impact on emissions. Third, weak incentives for firms and insufficient environmental policies may hinder the adoption of low-carbon technologies. Lastly, competition with established high-carbon technologies may limit diffusion, preventing immediate emissions reductions. These findings are consistent with prior research showing that despite a surge in climate change mitigation technology patents, diffusion, and commercialization remain key bottlenecks (Probst et al., 2021). These findings suggest that while education and R&D investments expand the frontier of green innovation, their environmental benefits depend on complementary policies that ensure the adoption and scaling of these technologies.

5.2 Diffusion of Inventions

While the development of green inventions expands the technological frontier, their diffusion may be more relevant for emissions reductions, as it ensures adoption and integration into industries and economies. This subsection examines whether the diffusion of green inventions mediates the interaction term and CO_2 emissions. The results are presented in table 4. Column (1) results show that the interaction between tertiary education and R&D has a positive and significant effect on the diffusion of environment-related inventions. This suggests that education enhances a country's ability to absorb, adapt, and distribute green innovations, leading to increased patent citations, licensing activity, and international collaborations.

Column (2) indicates that diffusion has a significant negative impact on CO_2 emissions, implying that as green technologies spread, emissions decline. This highlights the role of knowledge diffusion in accelerating clean technology adoption. Lastly, column (3) confirms that the interaction between tertiary education and R&D indirectly reduces CO_2 emissions through diffusion. While the development of new inventions is essential, their environmental benefits can only materialize when they are widely disseminated and utilized. These results reinforce the idea that green invention development alone is insufficient—diffusion must be prioritized to fully realize the potential of environmental technologies.

Table 4: Mediation Analysis: Diffusion of Inventions

	Dependent Variable:		
	Diff. Inventions	Log CO_2 p.c.	
	(1)	(2)	(3)
Diffusion Inventions		-0.002***	-0.002**
		(0.00)	(0.00)
Log Tertiary Enrollment × Log R&D	1.36***		-0.06***
	(0.48)		(0.01)
Log GDP p.c	11.83**	1.68***	1.13***
	(5.00)	(0.08)	(0.14)
Log GDP p.c Sq.	-0.60**	-0.10***	-0.06***
	(0.29)	(0.00)	(0.01)
Log Tertiary Enrollment	23.56***		0.14*
	(2.60)		(0.08)
Log Tertiary Enrollment Sq.	-3.05***		-0.04***
	(0.35)		(0.01)
Log R&D Expenditure	-3.26*		0.19***
	(1.98)		(0.05)
Log R&D Expenditure Sq.	0.41**		-0.00
	(0.18)		(0.01)
Observations	852	1,659	852
Adjusted R^2	0.26	0.73	0.77

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Column (1) estimates the effect of education and R&D on Diffusion Innovation, column (2) estimates the impact of Diffusion Innovation on CO_2 emissions, and column (3) includes both direct and mediated effects. Additional control variables include the log of trade, energy use, and income inequality.

5.3 Diffusion of Technology

While invention diffusion facilitates knowledge transfer, technology diffusion is key to ensuring that green innovations are implemented in industries and firms. This section examines whether the diffusion of environment-related technologies mediates the relationship between tertiary education, R&D investment, and CO_2 emissions. Column (1) of table 5 shows that the interaction between tertiary education and R&D has a positive and significant effect on technology diffusion. This suggests that education strengthens a country's ability to integrate green technologies into production and energy systems, increasing firm-level adoption of low-carbon solutions.

Table 5: Mediation Analysis: Diffusion of Technology

	Dependent Variable:		
	Diff. Technology	Log CO_2 p.c.	
	(1)	(2)	(3)
Diffusion Technology		-0.00**	-0.00***
		(0.00)	(0.00)
Log Tertiary Enrollment × Log R&D	1.99**		-0.06***
	(0.92)		(0.01)
Log GDP p.c	-32.58***	1.62***	1.06***
	(9.72)	(0.08)	(0.14)
Log GDP p.c Sq.	2.12***	-0.09***	-0.05***
	(0.56)	(0.00)	(0.01)
Log Tertiary Enrollment	2.53		0.09
	(5.04)		(0.07)
Log Tertiary Enrollment Sq.	-0.05		-0.03***
	(0.68)		(0.01)
Log R&D Expenditure	-5.50		0.19***
	(3.84)		(0.05)
Log R&D Expenditure Sq.	-0.53		-0.00
	(0.35)		(0.01)
Observations	852	1,659	852
Adjusted R^2	0.07	0.73	0.77

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of education and R&D on Diffusion Innovation, Model (2) estimates the impact of Diffusion Innovation on CO_2 emissions, and Model (3) includes both direct and mediated effects. Additional control variables include the log of trade, energy use, and income inequality.

Column (2) indicates that technology diffusion has a significant negative impact on CO_2 emissions, implying that as green technologies become more widely adopted, emissions decline. Column (3) confirms that the interaction between tertiary education and R&D indirectly reduces CO_2 emissions through technology diffusion. Unlike invention diffusion, which focuses on knowledge sharing, technology diffusion directly affects emissions by replacing high-carbon production methods with low-carbon alternatives. These findings reinforce that R&D-driven innovation alone is not sufficient; education and policy interventions are essential for ensuring the large-scale implementation of green technologies. By fostering an environment where technology adoption is prioritized, policymakers can maximize the environmental benefits of innovation and accelerate the transition to a low-carbon economy.

5.4 Environmental Regulations

This section examines whether education and R&D indirectly reduce CO_2 emissions through stronger environmental regulations. The intuition would be that countries with strong education and R&D capacity enforce stricter environmental policies because a more informed population increases public demand for climate action, while research institutions provide the expertise needed to design and implement effective regulations. These policies then drive emissions reductions by incentivizing cleaner industrial practices and penalizing pollution-intensive activities. The Environmental Policy Stringency Index (EPSI) serves as a proxy for regulatory effectiveness.

Table 6: Mediation Analysis: Environmental Policy Stringency Index

	Dependent Variable:		
	EPSI	Log CO_2 p.c.	
	(1)	(2)	(3)
EPSI		-0.04***	-0.04***
		(0.00)	(0.01)
Log Tertiary Enrollment × Log R&D	0.83***		-0.06**
	(0.21)		(0.03)
Log GDP p.c	-0.38	1.22***	1.44***
	(2.00)	(0.08)	(0.24)
Log GDP p.c Sq.	0.21**	-0.06***	-0.07***
	(0.10)	(0.01)	(0.01)
Log Tertiary Enrollment	-0.94		-0.10
	(0.85)		(0.10)
Log Tertiary Enrollment Sq.	0.26**		0.00
	(0.11)		(0.01)
Log R&D Expenditure	-2.66***		0.21**
	(0.80)		(0.10)
Log R&D Expenditure Sq.	-0.34**		0.04**
	(0.15)		(0.02)
Observations	495	916	495
Adjusted R^2	0.69	0.83	0.82

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Column (1) estimates the effect of education and R&D on the Environmental Policy Stringency Index (EPSI), column (2) estimates the impact of EPSI on CO_2 emissions, and column (3) includes both direct and mediated effects. Additional control variables include the log of trade, energy use, and income inequality.

Table 6 presents the mediation analysis results. Column (1) shows that the interaction between tertiary education and R&D positively influences environmental policy stringency, suggesting that countries with stronger human capital and innovation capabilities implement more stringent regulations. This supports the idea that education and innovation enhance governance and regulatory effectiveness. Column (2) confirms that stricter environmental policies significantly reduce CO_2 emissions and column (3) includes both direct and mediated effects, showing that while education and R&D still have a direct impact on emissions, part of their effect is channeled through environmental policies. The reduction in magnitude of the interaction term suggests that regulatory improvements account for a portion of the emissions decline, but additional unexplored pathways may also contribute. Strengthening regulatory frameworks can enhance the impact of education and innovation on climate outcomes, ensuring that technological advancements translate into real environmental benefits.

5.5 Energy Efficiency

Another key channel through which the interaction between education and R&D may amplify emissions reductions is energy efficiency improvements. Education enhances the diffusion and application of research-driven innovations, while R&D investments foster technological progress. When combined, these factors facilitate the development and large-scale adoption of cleaner production methods, renewable energy technologies, and energy-saving practices. If this mechanism is at play, we expect that countries with stronger education and R&D investment show lower carbon intensity, meaning they generate less CO_2 per unit of economic output. Carbon intensity of GDP—measuring emissions per dollar of GDP captures this dynamic, helping to explain whether the interaction between education and R&D primarily drives emissions reductions via efficiency gains rather than simply output contraction.

Table 7 presents the results of this mediation analysis. Column (1) estimates whether the interaction between education and R&D affects carbon intensity. The results indicate that countries with higher education levels and greater R&D investment exhibit significantly lower carbon intensity, supporting the hypothesis that economies with stronger human capital and innovation capacity are more effective in adopting clean technologies and improving energy efficiency.

Column (2) examines the link between carbon intensity and per capita CO_2 emissions. The coefficient for carbon intensity is positive and statistically significant, implying that economies with a higher carbon intensity tend to have greater per capita emissions, as expected. Column (3) incorporates both direct and mediated effects. The interaction term between education and R&D remains negative and statistically significant, though attenuated compared to the baseline model without the mediator. This suggests that a portion of the emissions reduction effect associated with education and R&D operates through improvements in energy efficiency, but that other mechanisms, such as changes in industrial composition or shifts in energy sources, may also play a role.

Table 7: Mediation Analysis: Carbon Intensity

	Dependent Variable:		
	Carbon Int. GDP	Log CO_2 p.c.	
	(1)	(2)	(3)
Carbon Int. GDP		0.28***	0.12***
		(0.01)	(0.02)
Log Tertiary Enrollment × Log R&D	-0.13***		-0.05***
	(0.02)		(0.01)
Log GDP p.c	-4.09***	2.91***	1.67***
	(0.24)	(0.09)	(0.16)
Log GDP p.c Sq.	0.18***	-0.15***	-0.08***
	(0.01)	(0.01)	(0.01)
Log Tertiary Enrollment	0.60***		0.02
	(0.08)		(0.05)
Log Tertiary Enrollment Sq.	-0.10***		-0.02**
	(0.01)		(0.01)
Log R&D Expenditure	0.65***		0.15***
	(0.09)		(0.05)
Log R&D Expenditure Sq.	0.05***		0.00
	(0.01)		(0.01)
Observations	978	2451	978
Adjusted R^2	0.61	0.62	0.72

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of education and R&D on Carbon Intensity (Carbon Int. GDP), Model (2) estimates the impact of Carbon Intensity on CO_2 emissions, and Model (3) includes both direct and mediated effects. Additional control variables include the log of trade, energy use, and income inequality.

5.6 Green Employment

This section examines whether green job creation mediates the relationship between education, R&D, and carbon emissions. Green employment is measured in full-time equivalent jobs engaged in environmental goods and services production, capturing the labor market's transition toward sustainability.

Table 19 in the Appendix presents the mediation analysis results. Column (1) shows that the interaction between tertiary education and R&D is positively associated with green job creation, indicating that economies with skilled workforces and strong innovation capacity generate more sustainability-related employment. However, Column (2) finds that green jobs do not significantly reduce CO_2 emissions, as the coefficient is negative but statistically insignificant. Column (3), which includes both direct and mediated effects, also finds no significant role for green jobs in emissions reductions.

The lack of a strong link between green jobs and emissions reductions may suggest that employment shifts alone do not necessarily lead to lower emissions unless tied to green R&D and technological advancements. However, a key limitation is the smaller sample size for green employment data compared to other macroeconomic indicators. The unbalanced panel dataset, with limited years of reported green job figures, may introduce bias due to missing observations. These findings suggest that while green employment reflects structural economic shifts, emissions reductions depend more on targeted R&D investments in low-carbon technologies.

6 Conclusions

R&D and green climate technologies are key to reducing carbon emissions, but understanding the factors that amplify their effects is essential for designing effective climate policies. While economic growth, education, and innovation all influence emissions, their interactions remain underexplored. This study provides empirical evidence that human capital enhances the effectiveness of R&D in reducing carbon emissions, reinforcing that technological progress alone is insufficient for decarbonization, an educated workforce is crucial for translating innovation into environmental benefits.

The findings confirm an inverted-U relationship between GDP per capita and emissions, as well as a similar non-linear pattern with education. While R&D investment alone reduces carbon emissions by 4.9%, its impact becomes significantly stronger when paired with a highly skilled workforce, amplifying the reduction to 6.4%. This 30.6% stronger decarbonization effect underscores the role of human capital in maximizing the environmental benefits of innovation. This interaction is particularly significant in middle-income countries but less so in the highest-emission economies, where structural barriers may limit the effectiveness of education-driven technological change. The Difference-in-Differences analysis further suggests that while the EU 2020 policy led to an immediate 15% decline in emissions for treated countries, its full impact materialized gradually in knowledge-intensive economies. This aligns with the idea that structural shifts driven by education and technological innovation take time before significantly lowering carbon intensity.

Examining the mechanisms behind these effects, the study identifies several key pathways. First, the study finds that green patent development alone does not immediately lead to emissions reductions, as new technologies require widespread diffusion and industry adoption to generate environmental benefits. However, the diffusion of both inventions and technologies plays a crucial role in emissions reductions, emphasizing the importance of knowledge spillovers and large-scale implementation of green innovations. These results indicate that fostering the development of green patents must be complemented by policies that enhance their diffusion to maximize environmental benefits. Second, nations with stronger education and R&D systems enforce more stringent environmental policies, suggesting that human capital and innovation not only drive technological change but also enhance institutional capacity for climate governance. Third, reductions in carbon intensity confirm that emissions decline primarily through efficiency gains rather than economic contraction. Fourth, while education and R&D foster the expansion of green jobs, these employment shifts alone do not directly translate into emissions reductions. The key factor in decarbonization is not the growth of sustainability-related employment per se but rather the extent to which R&D investments are directed toward green technologies.

These findings highlight the need for policies that integrate human capital development with innovation strategies to maximize environmental benefits. Investments in education should complement R&D spending, particularly by fostering green innovation and ensuring the widespread diffusion of sustainable technologies. Without targeted efforts to direct R&D toward low-carbon solutions and promote their adoption, economic transitions alone will be insufficient to achieve long-term climate goals. The findings also suggest targeted policy interventions—such as sector-specific decarbonization strategies and industrial policy support—may be necessary for the highest-emission countries. Future research should also explore the labor market implications of R&D-driven innovation, particularly its potential to exacerbate inequality. While education enhances the effectiveness of innovation in reducing CO_2 emissions, lower-educated populations may struggle to transition into green jobs. Investigating policies that facilitate reskilling and workforce adaptation will be crucial to ensuring that the green transition is both effective and equitable.

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Appendix

A Appendix: Additional Empirical Information

Table 8: Variable Definitions and Sources

Variable	**Definition**
CO_2 p.c.	CO_2 emissions per capita (metric tons). Source: Our World in Data
GDP p.c	GDP per capita (constant 2015 US$). Source: World Bank WDI
Tertiary Enrollment	Tertiary education enrollment (gross %). Source: World Bank WDI
R&D Exp.	Gross domestic expenditure on research and development (public and private) as a percentage of GDP, covering business, government, higher education, and private non-profits. Source: World Bank WDI
Energy Use	Energy use (kg of oil equivalent per capita). Source: World Bank WDI
Trade	Trade openness ((Exports + Imports)/GDP). Source: World Bank WDI
Income Inequality	Gini coefficient (0-100 scale). Source: SWIID Data

Table 9: Summary Statistics

Variable	Observations	Mean	Std. Dev.	Min	Max
Log CO_2 p.c	578	2.27	0.38	1.24	3.06
Log GDP p.c.	578	10.39	0.48	8.46	11.10
Log GDP p.c. Sq.	578	108.11	9.65	71.62	123.11
Log Tertiary Enrollment	477	4.13	0.36	2.66	4.79
Log Tertiary Enrollment Sq.	477	17.17	2.80	7.06	22.90
Log R&D Exp.	426	0.72	0.45	-0.62	1.60
Log R&D Exp. Sq.	426	0.71	0.53	0.00	2.55
Education × R&D	354	2.95	2.08	-2.54	7.35
Log Energy Use	442	8.38	0.33	7.68	9.04
Log Trade	573	4.19	0.52	2.76	5.26
Income Inequality	523	29.38	3.81	20.90	42.70

Note: Summary statistics include key variables used in the regression analysis. The sources of the variables are detailed in section 2.

Table 10: Correlation Matrix

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Log CO_2 p.c.	1.00	0.11	-0.01	0.06	0.03	0.67	-0.27	0.22
(2) Log GDP p.c.	0.11	1.00	0.51	0.69	0.69	0.56	-0.05	-0.05
(3) Log Tertiary Enrollment	-0.01	0.51	1.00	0.51	0.55	0.33	0.19	0.21
(4) Log R&D Exp.	0.06	0.69	0.51	1.00	1.00	0.55	-0.04	-0.20
(5) Education × R&D	0.03	0.69	0.55	1.00	1.00	0.62	0.08	-0.26
(6) Log Energy Use	0.67	0.56	0.33	0.55	0.62	1.00	-0.02	-0.00
(7) Log Trade	-0.27	-0.05	0.19	-0.04	0.08	-0.02	1.00	-0.53
(8) Income Inequality	0.22	-0.05	0.21	-0.20	-0.26	-0.00	-0.53	1.00

Note: The table presents the correlation coefficients between key variables in the analysis. All values are rounded to two decimal places. Squared terms have been excluded for clarity.

Table 11: Summary Statistics by Income Level

	N	Mean	St.Dev.	Min	Max
Log CO_2 p.c.					
High-Income	1496	2.20	0.63	0.29	5.90
Middle-Income	1393	0.98	0.87	-1.45	3.39
Low-Income	1696	-0.85	1.19	-3.83	2.61
Log GDP p.c.					
High-Income	1496	10.24	0.65	8.25	11.63
Middle-Income	1384	8.56	0.65	6.81	10.14
Low-Income	1635	7.11	0.76	5.12	10.05
Log Tertiary Ed.					
High-Income	1167	3.84	0.65	1.23	4.78
Middle-Income	896	3.39	0.75	-1.55	5.12
Low-Income	970	2.00	1.27	-2.44	4.45
Log R&D					
High-Income	931	0.20	0.97	-3.48	1.74
Middle-Income	570	-1.11	0.85	-3.77	0.89
Low-Income	313	-1.61	1.08	-5.21	0.18
Log Energy Use					
High-Income	1084	8.30	0.61	6.44	10.00
Middle-Income	867	7.08	0.70	4.96	9.44
Low-Income	791	6.12	0.74	2.27	8.48
Log Trade					
High-Income	1362	4.43	0.59	2.62	6.08
Middle-Income	1265	4.33	0.46	2.72	5.40
Low-Income	1362	4.06	0.53	0.91	5.85
Income Inequality					
High-Income	1260	31.82	5.96	20.90	50.80
Middle-Income	1140	40.88	8.34	20.40	65.20
Low-Income	1173	42.26	5.61	24.40	54.80

Note: The construction of this dataset and the definitions of the variables are discussed in section 2.

A.1 List of Countries

Table 12: List of Countries

Country	ISO Code	Country	ISO Code
Argentina	ARG	Armenia	ARM
Australia	AUS	Austria	AUT
Azerbaijan	AZE	Belgium	BEL
Bulgaria	BGR	Bahrain	BHR
Bosnia and Herzegovina	BIH	Belarus	BLR
Brazil	BRA	Botswana	BWA
Canada	CAN	Switzerland	CHE
Chile	CHL	China	CHN
Colombia	COL	Costa Rica	CRI
Cyprus	CYP	Germany	DEU
Denmark	DNK	Algeria	DZA
Ecuador	ECU	Spain	ESP
Estonia	EST	Finland	FIN
France	FRA	United Kingdom	GBR
Georgia	GEO	Ghana	GHA
Greece	GRC	Guatemala	GTM
Honduras	HND	Croatia	HRV
Hungary	HUN	Indonesia	IDN
India	IND	Ireland	IRL
Iceland	ISL	Israel	ISR
Italy	ITA	Jamaica	JAM
Jordan	JOR	Japan	JPN
Kazakhstan	KAZ	Cambodia	KHM
South Korea	KOR	Kuwait	KWT
Lithuania	LTU	Luxembourg	LUX
Latvia	LVA	Morocco	MAR
Moldova	MDA	Mexico	MEX
North Macedonia	MKD	Malta	MLT
Montenegro	MNE	Mongolia	MNG
Mozambique	MOZ	Mauritius	MUS
Malaysia	MYS	Namibia	NAM
Netherlands	NLD	Norway	NOR
Nepal	NPL	New Zealand	NZL
Pakistan	PAK	Panama	PAN
Peru	PER	Philippines	PHL
Poland	POL	Portugal	PRT
Paraguay	PRY	Qatar	QAT
Romania	ROU	Saudi Arabia	SAU
Sudan	SDN	Senegal	SEN
El Salvador	SLV	Slovenia	SVN
Sweden	SWE	Togo	TGO
Thailand	THA	Tajikistan	TJK
Tunisia	TUN	Tanzania	TZA
Ukraine	UKR	Uruguay	URY
United States	USA	Uzbekistan	UZB
South Africa	ZAF		

Note: This table lists the countries with ISO codes from the World Bank.

Table 13: Low, Middle, and High-Income Countries

Low-Income		Middle-Income		High-Income	
Country	**ISO Code**	**Country**	**ISO Code**	**Country**	**ISO Code**
Armenia	ARM	Argentina	ARG	Austria	AUT
Bosnia	BIH	Azerbaijan	AZE	Belgium	BEL
Bulgaria	BGR	Bahrain	BHR	Canada	CAN
Ghana	GHA	Belarus	BLR	Switzerland	CHE
Honduras	HND	Brazil	BRA	Chile	CHL
India	IND	China	CHN	Germany	DEU
Senegal	SEN	Colombia	COL	Spain	ESP
El Salvador	SLV	Costa Rica	CRI	Finland	FIN
Sudan	SDN	Ecuador	ECU	France	FRA
Cambodia	KHM	Georgia	GEO	United Kingdom	GBR
Morocco	MAR	Greece	GRC	Hungary	HUN
Mozambique	MOZ	Indonesia	IDN	Ireland	IRL
Tanzania	TZA	Jamaica	JAM	Israel	ISR
Ukraine	UKR	Jordan	JOR	Italy	ITA
		Kazakhstan	KAZ	Japan	JPN
		Malaysia	MYS	South Korea	KOR
		Mexico	MEX	Luxembourg	LUX
		Moldova	MDA	Netherlands	NLD
		Montenegro	MNE	Norway	NOR
		North Macedonia	MKD	Portugal	PRT
		Paraguay	PRY	Sweden	SWE
		Peru	PER	United States	USA
		Philippines	PHL		
		Poland	POL		
		Romania	ROU		
		Slovenia	SVN		
		South Africa	ZAF		
		Thailand	THA		
		Tunisia	TUN		
		Uruguay	URY		
		Uzbekistan	UZB		

Note: This table categorizes countries into low-income, middle-income, and high-income groups based on World Bank criteria.

B Instrumental Variables Analysis

Given concerns about potential endogeneity bias, where higher education levels might be influenced by factors also shaping CO_2 emissions, an instrumental variables (IV) approach is proposed as a complementary robustness check. The instrument is compulsory schooling laws, which proxy for a country's long-term commitment to human capital development. While they directly affect basic education, they also reflect broader educational policies that shape higher education accessibility and the quality of labor markets, ultimately influencing innovation potential.

The first-stage results in columns (1) and (2) of table 14 confirm that compulsory education significantly predicts tertiary enrollment, while its interaction with R&D strongly predicts the interaction term. The second-stage results indicate that while some individual effects lose significance, the interaction term remains negative and highly significant, reducing carbon emissions per capita by 7.7%, supporting the idea that education amplifies the impact of innovation on decarbonization. Diagnostic tests show that the instrument for the interaction term is strong, while the instrument for tertiary enrollment alone is weaker, justifying the focus on the interaction effect.

Table 14: Instrumental Variables Regression

	First Stage		Second Stage
	(1)	(2)	(3)
Compulsory Education	0.04***		
	(0.01)		
Comp. Education × Log R&D		0.05***	
		(0.01)	
Log Tertiary Enrollment			-0.88
			(0.61)
Log Tertiary Enrollment × Log R&D			-0.77***
			(0.20)
Log R&D Expenditure	0.08**	3.41***	3.11***
	(0.03)	(0.09)	(0.83)
Log R&D Expenditure Sq.	-0.01	0.16***	0.15**
	(0.01)	(0.01)	(0.05)
Observations	877	877	867
Adjusted R^2	0.55	0.96	0.79
F-statistic	121.65***	2186.73***	392.00***
Weak IV Test (Tertiary)			1.93
Weak IV Test (Interaction)			15.79***

Notes: Standard errors are in parentheses. Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the first-stage relationship between compulsory education and tertiary enrollment, Model (2) estimates the first-stage regression for the interaction term, and Model (3) estimates the second-stage IV regression for CO_2 emissions. Additional variables included are GDP per capita, GDP per capita squared, energy use, trade and income inequality.

C Quantile-quantile Regression

Table 15: Quantile Regression Results

	Q25	Q50	Q75	Q90
Log GDP p.c	1.069***	0.631***	0.648***	0.642***
	(0.192)	(0.160)	(0.134)	(0.139)
Log GDP p.c Sq.	-0.050***	-0.027***	-0.030***	-0.034***
	(0.011)	(0.010)	(0.008)	(0.009)
Log Tertiary Enrollment	0.187**	0.051	0.180***	0.226***
	(0.085)	(0.031)	(0.026)	(0.078)
Log Tertiary Enrollment Sq.	-0.028**	-0.018***	-0.033***	-0.031***
	(0.012)	(0.005)	(0.005)	(0.011)
Log R&D Exp.	-0.028	-0.071***	-0.041**	-0.045**
	(0.021)	(0.020)	(0.017)	(0.018)
Log R&D Exp. Sq.	-0.010**	-0.025***	-0.020***	-0.029***
	(0.004)	(0.005)	(0.003)	(0.005)
Log Tertiary Enrollment × Log R&D	-0.094**	-0.145***	-0.124***	-0.023
	(0.038)	(0.031)	(0.020)	(0.042)
Log Energy Use	0.685***	0.790***	0.850***	0.882***
	(0.033)	(0.027)	(0.035)	(0.027)
Log Trade	-0.077***	-0.087***	-0.100***	-0.025
	(0.024)	(0.022)	(0.019)	(0.022)
Income Inequality	-0.016***	-0.013***	-0.006***	-0.011***
	(0.003)	(0.002)	(0.002)	(0.002)
Constant	-0.057***	0.016***	0.070***	0.113***
	(0.005)	(0.004)	(0.004)	(0.004)
Observations	984	984	984	984

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is log CO_2 per capita. Column Q25 estimates the 25th percentile, Q50 the median, Q75 the 75th percentile, and Q90 the 90th percentile effects of education and R&D on emissions.

D Appendix: Difference in Differences

D.1 Average Carbon Emissions over Time

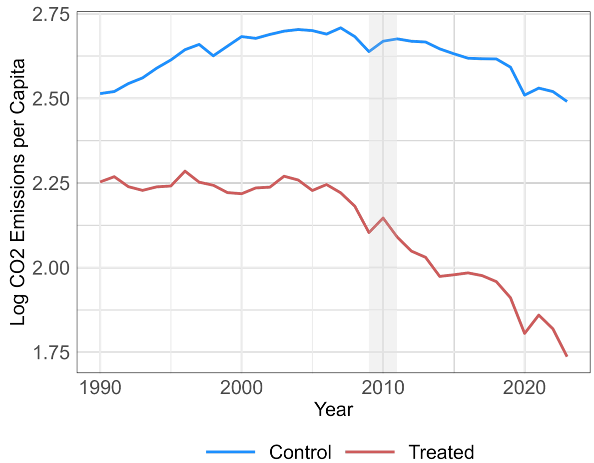

Figure 1: Average CO_2 Emissions Over Time

D.2 List of Countries: DiD

Table 16: Countries in the DiD Analysis

Treated		Control	
Country	**ISO Code**	**Country**	**ISO Code**
Germany	DEU	USA	USA
France	FRA	Canada	CAN
Italy	ITA	Japan	JPN
Spain	ESP	South Korea	KOR
Netherlands	NLD	Australia	AUS
Belgium	BEL		
Austria	AUT		
Sweden	SWE		
Finland	FIN		
Denmark	DNK		
Poland	POL		
Czech Republic	CZE		

Note: This table lists countries used in the DiD analysis by treated and control countries.

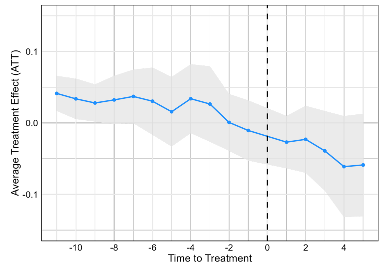

Figure 2: Event Study: Policy Impact on CO_2

D.3 Parallel Trend Assumption

E Appendix: Additional Information - Mechanisms

Table 17: Definitions of Green Patent Mechanisms and Related Indicators

Mechanism	Definition
Development Inventions	The creation of new green technologies through domestic research efforts. This indicator measures innovation output in terms of patented inventions in environment-related fields, reflecting technological progress and the effectiveness of R&D policies.
Diffusion Inventions	Measures the extent to which patented green inventions spread beyond their country or organization of origin. It captures international spillover effects, indicating the transfer, citation, or licensing of green patents across jurisdictions.
Diffusion Technology	Evaluates the adoption and implementation of green technologies within industries and sectors. Unlike the diffusion of inventions, this metric focuses on the practical application of environmental technologies in production processes, improving energy efficiency, regulatory compliance, and industrial decarbonization.
EPSI	Measured by the OECD Environmental Policy Stringency Index, which quantifies the strictness of environmental policies across countries. Stringency is defined as the degree to which policies impose an explicit or implicit cost on polluting or environmentally harmful behavior. The index ranges from 0 (least stringent) to 6 (most stringent) and is based on 13 environmental policy instruments related to climate and air pollution. It covers 40 countries from 1990 to 2020. Source: OECD data.
Carbon Int. GDP	Measures the carbon intensity of GDP, expressed as kilograms of CO_2 equivalent (kg CO_2e) per constant 2015 US dollar of GDP. A lower carbon intensity indicates improved environmental efficiency in economic activities, reducing reliance on carbon-intensive energy sources.
Green Jobs	Employment in the production of environmental goods and services, measured in full-time equivalent (FTE) jobs. FTE is defined as the total hours worked divided by the average annual working hours in a full-time job. This reflects the labor market's transition toward sustainability-focused industries such as renewable energy, pollution control, and energy efficiency.

Note: This table provides definitions of key mechanisms related to green patents, environmental policies, and sustainability transitions.

E.1 Development of Inventions

Table 18: Mediation Analysis: Development of Inventions

	Dependent Variable:		
	Dev. Inventions	Log CO_2 p.c.	
	(1)	(2)	(3)
Development Inventions		-0.00	-0.00
		(0.00)	(0.00)
Log Tertiary Enrollment × Log R&D	0.43***		-0.08***
	(0.14)		(0.01)
Log GDP p.c	-0.41	1.91***	1.22***
	(1.46)	(0.08)	(0.15)
Log GDP p.c Sq.	0.05	-0.11***	-0.06***
	(0.09)	(0.01)	(0.01)
Log Tertiary Enrollment	2.93***		0.01
	(0.78)		(0.08)
Log Tertiary Enrollment Sq.	-0.40***		-0.02*
	(0.11)		(0.01)
Log R&D Expenditure	-0.77		0.30***
	(0.59)		(0.06)
Log R&D Expenditure Sq.	0.19***		0.01**
	(0.05)		(0.01)
Observations	869	1,763	869
Adjusted R^2	0.10	0.70	0.74

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of education and R&D on Development Innovation, Model (2) estimates the impact of Development Innovation on CO_2 emissions, and Model (3) includes both direct and mediated effects. Additional control variables include the log of trade, energy use, and income inequality.

E.2 Green Jobs

Table 19: Mediation Analysis: Green Jobs

	Dependent Variable:		
	Green Jobs	Log CO_2 p.c.	
	(1)	(2)	(3)
Log Green Jobs		-0.02	-0.02
		(0.03)	(0.05)
Log Tertiary Enrollment × Log R&D	1.02***		0.09
	(0.26)		(0.11)
Log GDP p.c	-18.83***	0.58	-0.11
	(5.20)	(1.04)	(2.09)
Log GDP p.c Sq.	0.97***	-0.03	0.00
	(0.25)	(0.05)	(0.10)
Log Tertiary Enrollment	-0.22		-0.09
	(0.81)		(0.30)
Log Tertiary Enrollment Sq.	-0.02		0.01
	(0.11)		(0.04)
Log R&D Expenditure	-2.90***		-0.37
	(1.07)		(0.41)
Log R&D Expenditure Sq.	-0.63***		-0.02
	(0.15)		(0.06)
Observations	92	111	92
Adjusted R^2	0.49	0.82	0.77

Note: Standard errors are in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of education and R&D on Green Jobs, Model (2) estimates the impact of Green Jobs on CO_2 emissions, and Model (3) includes both direct and mediated effects. Additional control variables include the log of trade, energy use, and income inequality.