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Analyses of Topical Policy Issues

The complementary role of human capital in innovation-driven decarbonization[☆]

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ABSTRACT

Achieving net-zero emissions requires not only technological innovation but also the capacity to absorb and implement it effectively. This study investigates how absorptive capacity, defined as the interaction between tertiary education and R&D investment, amplifies the impact of innovation on carbon emissions. Using fixed effects and Difference-in-Differences models, the analysis shows that while R&D alone reduces emissions, its effect is significantly stronger in countries with higher levels of education. Mechanism analyses reveal that absorptive capacity enhances environmental outcomes by strengthening policy enforcement, accelerating the diffusion of green technologies, and improving energy efficiency. These findings highlight the importance of aligning education and innovation policies to unlock the full decarbonization potential of climate technologies.

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).

Among these factors, education and R&D stand out as long-term investments that can accelerate decarbonization. Education enhances a society's capacity to absorb and implement new knowledge, while R&D fosters the creation of low-carbon technologies (Balaguer and Cantavella, 2018; Shahbaz et al., 2016). Yet, the effectiveness of R&D in mitigating emissions may depend critically on the presence of a highly skilled workforce. Without the capacity to translate innovation into widespread application, through behavior change, policy enforcement, or institutional adoption, technological advances alone may fall short of delivering sustained emissions reductions.

These dynamics are not only theoretical but are central to major policy frameworks. For example, the European Union's 2020 Strategy explicitly linked education, innovation, and sustainability as pillars of its growth agenda, and the European Green Deal reinforces this by emphasizing skills development and research investments to accelerate the clean energy transition. Similarly, in

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the United States, large-scale initiatives such as ARPA-E and, more recently, the Inflation Reduction Act illustrate how governments combine R&D support with workforce and institutional capacity to foster green innovation.

This study is motivated by the urgent need to ensure that the large public and private investments in innovation effectively translate into measurable emissions reductions. Despite unprecedented spending on clean technologies, their environmental impact remains uneven across countries (Agency, 2024; Montague et al., 2024). By explicitly analyzing the role of absorptive capacity, this paper provides insights into why some economies succeed in converting innovation into carbon reductions while others lag behind. The results can inform policymakers designing green industrial and education policies, and guide firms investing in R&D to align their innovation strategies with broader societal capabilities.

This study tests the core hypothesis that absorptive capacity, defined as the interaction between education and R&D, plays a central role in reducing CO₂ emissions. The argument is that while R&D expands the technological frontier, its effectiveness in reducing emissions depends critically on a country's capacity to recognize, adopt, and implement new knowledge and practices. Education amplifies this effect by strengthening human capital, institutional readiness, and the societal demand for cleaner technologies. This interaction reflects more than statistical correlation: it captures a theory-driven mechanism grounded in development economics and innovation theory (Cohen et al., 1990; Romer, 1990). To examine this hypothesis, the analysis is guided by three questions: First, does R&D alone reduce carbon emissions, or is its effectiveness conditional on the presence of a highly educated population? Second, do these dynamics vary across income levels and stages of development? Lastly, through which specific mechanisms does absorptive capacity operate to shape emissions outcomes?

While prior research has examined the independent effects of education (e.g., its role in supporting renewable energy adoption, see Zafar et al. (2020)) and R&D (e.g., green innovation as a strategic resource, see Khanra et al. (2022)) on environmental outcomes, much less is known about how they operate jointly. This represents an important gap, as theory suggests that the effectiveness of R&D in reducing emissions depends critically on the absorptive capacity provided by education. By focusing on this interaction, and by identifying the concrete mechanisms through which it operates, this paper contributes new empirical evidence to a literature that has so far treated education and R&D largely in isolation.

Using cross-country panel data from 91 countries between 1995 and 2019, the analysis first estimates a two-way fixed effects model to isolate the relationship between education, R&D, and carbon emissions while controlling for country-specific and time-specific confounders. Results show that R&D investments alone reduce emissions by approximately 4.9%, but become significantly more effective when combined with higher education levels, amplifying the effect to 6.4%, reflecting the critical role of absorptive capacity in strengthening decarbonization outcomes. To address potential endogeneity concerns, an instrumental variables (IV) strategy is implemented. Lastly, a Difference-in-Differences (DiD) framework leverages the EU 2020 Strategy as a quasi-experimental policy shock. This approach confirms that emissions declined more sharply in countries with stronger education and R&D systems following the reform, supporting the causal interpretation of the interaction effect.

A central contribution of this study lies in uncovering the mechanisms through which education and R&D jointly reduce emissions. Specifically, the analysis highlights three key pathways: technology diffusion, energy efficiency improvements, and environmental policy enforcement. These mechanisms are not merely outcomes. They serve as the channels through which absorptive capacity translates innovation into a measurable environmental impact. The results show that countries with stronger education and R&D systems are significantly more effective at deploying green technologies, achieving energy efficiency gains, and enforcing climate policies, leading to deeper and more sustained emissions reductions.

This paper contributes to the broader decarbonization literature by providing new empirical evidence on how human capital enhances the climate effectiveness of innovation. While prior studies have examined the independent effects of education and R&D on environmental outcomes, this paper is the first to systematically test their interaction and to empirically identify the institutional and technological mechanisms, diffusion, efficiency, and enforcement, through which that interaction reduces emissions. In doing so, the paper emphasizes the role of absorptive capacity as a critical lever for translating innovation into decarbonization at scale.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 outlines the empirical strategy. Section 4 presents the main results, followed by robustness checks in Section 5 and mechanism analysis in Section 6. Section 7 concludes.

2. Literature review and hypotheses development

To clarify the conceptual foundations of this study, Section 2 is structured into two parts. Section 2.1 reviews the main strands of literature that motivate the analysis, including prior work on decarbonization, education, and innovation. Section 2.2 then develops the mechanisms through which absorptive capacity may influence carbon emissions.

2.1. Background literature

The Environmental Kuznets Curve (EKC) hypothesizes an inverted-U relationship between income per capita and environmental degradation: emissions rise during early development but fall as countries grow richer and adopt cleaner technologies. While some evidence supports this pattern (Shahbaz et al., 2013; Balsalobre-Lorente et al., 2018), the EKC has been widely critiqued.

Ward et al. (2016) argue that observed decoupling trends often reflect outsourcing, financialization, or inequality rather than genuine progress. Vollebergh et al. (2009) show that CO₂ emissions in OECD countries continue to rise, with stabilization better explained by regulatory shifts than income growth. Other studies note N-shaped curves at higher income levels due to rebound effects or technological obsolescence (Balsalobre-Lorente et al., 2018).

Cross-country variation further challenges the EKC's universality. [Dinda and Coondoo \(2006\)](#) and [Munir et al. \(2020\)](#) show that income–emissions relationships vary by region and development stage. [Friedrichs and Inderwildi \(2013\)](#) describes a “carbon curse” in fossil-fuel-rich countries, where growth sustains high emissions due to weak institutions and subsidies.

These critiques highlight a key limitation: the EKC overlooks the structural and institutional mechanisms that translate income into emissions reductions. As [Stern \(2008\)](#) argues, climate stabilization requires deliberate structural shifts, not just economic growth. This motivates the focus on complementary drivers such as education and R&D.

Green R&D and environmental patents are critical to decarbonization, but their effects on emissions are not automatic. [Cheng et al. \(2019\)](#) shows that green patenting in BRIICS countries has a limited impact when diffusion and regulatory support are weak. [Secundo et al. \(2020\)](#) emphasizes that intellectual capital must be embedded in education and governance to advance the Sustainable Development Goals (SDGs). Sectoral studies of steel and cement find that without policy instruments like carbon pricing, uptake of low-carbon technologies remains limited ([Van Ruijven et al., 2016](#)). These findings underscore that innovation alone is insufficient and that supportive mechanisms are essential.

Prior research highlights that the effectiveness of R&D in reducing carbon emissions is shaped by several complementary factors. One important condition is the direction of technological change, which responds strongly to policy incentives such as fuel prices and carbon markets. Higher energy prices and the EU Emissions Trading System (ETS), for instance, have been shown to shift innovation away from “dirty” technologies toward cleaner alternatives, thereby increasing low-carbon patenting and reinforcing clean innovation trajectories ([Acemoglu et al., 2012](#); [Aghion et al., 2016](#); [Calel and Dechezleprêtre, 2016](#)). Relatedly, clean technologies generate larger knowledge spillovers than fossil-intensive ones, amplifying the case for policy support and absorptive capacity ([Popp, 2010](#); [Dechezleprêtre et al., 2014](#)).

The type of R&D also matters. Evidence suggests that disaggregated measures of energy R&D, particularly investments in renewables and efficiency, are more tightly associated with gains in energy and carbon productivity than aggregate R&D measures ([Popp, 2019](#); [Mamkhezri and Khezri, 2024](#)). Sector-specific studies reinforce this conclusion: building efficiency standards and power-sector policies have spurred innovation in related technologies, while fuel price increases pushed the auto industry toward cleaner patenting ([Noailly, 2012](#)).

At the aggregate level, cross-country evidence suggests that energy-related R&D is associated with reductions in carbon emissions, though effects are heterogeneous across technologies and time horizons. For instance, [Verdolini and Galeotti \(2011\)](#) find that domestic and international energy R&D jointly contribute to emission reductions, with important lags in diffusion. Similarly, [Johnstone et al. \(2010\)](#) show that targeted R&D policies foster renewable energy innovation that ultimately translates into lower emissions. Reviews of energy R&D programs emphasize that while such investments can be effective, their impact is often limited without complementary policies and sufficient absorptive capacity ([Popp, 2006](#); [Baker and Adu-Bonah, 2008](#)). These studies suggest that R&D can reduce emissions under the right conditions, but technological progress also depends on societies’ capacity to absorb and apply new knowledge, a role played by education.

Education enhances “absorptive capacity”, i.e., the ability to recognize and apply new knowledge, making it a crucial enabler of innovation. It may also influence emissions directly, through changes in individual behavior, environmental awareness, and demand for cleaner technologies. [Zafar et al. \(2020\)](#) find that tertiary education amplifies the emissions-reducing effect of renewable energy in OECD countries. In a long-run study of Australia, [Balaguer and Cantavella \(2018\)](#) document a nonlinear trajectory: education initially raises emissions (via higher consumption) but ultimately lowers them by improving technological uptake and environmental awareness. [Camilleri and Camilleri \(2020\)](#) similarly frame education as essential for equipping individuals and institutions to achieve sustainability goals. [Al-Emran and Griffy-Brown \(2023\)](#) show that technology adoption succeeds only where human capital, institutions, and policies align.

Collectively, this literature positions education not merely as a background variable but as a key driver of decarbonization, both by directly shaping societal behavior and by conditioning the effectiveness of innovation inputs. While education and R&D are widely studied, most empirical work examines them in isolation. A few studies suggest they are complementary. For instance, [Secundo et al. \(2020\)](#) argue that human and structural capital jointly enable green technology diffusion. [Khanna et al. \(2022\)](#) describe them as interdependent resources that support sustainable competitiveness.

Yet, despite these insights, there is little empirical work on their combined effect, especially in the context of emissions. No existing study systematically tests whether education enhances the emissions-reducing impact of R&D across countries. This paper addresses that gap by estimating the interaction between education and R&D, and by identifying the mechanisms, technology diffusion, energy efficiency, and policy enforcement, through which absorptive capacity translates innovation into decarbonization.

2.2. Mechanisms of absorptive capacity

While prior work highlights the separate roles of education and R&D in innovation, little is known about how their interaction, absorptive capacity, shapes environmental outcomes. The mechanisms linking absorptive capacity to emissions remain underexplored. Understanding these mechanisms is crucial, since innovation alone does not guarantee decarbonization unless it is diffused, adopted, and embedded in institutions. Guided by this insight and drawing on the literature, I outline several potential mechanisms and formulate corresponding hypotheses.

A first pathway is through the creation of new knowledge. Education raises the stock of human capital and the ability to engage with advanced ideas, while R&D provides the resources and institutional setting to transform these ideas into tangible outputs. In this sense, absorptive capacity may increase the rate of environment-related inventions, which could serve as a channel to reduce emissions.

H1a. Higher absorptive capacity generates more green inventions, which may mediate reductions in CO₂ emissions.

Even when inventions are created, their impact may remain limited unless they spread across borders and industries. Absorptive capacity may facilitate this process by strengthening networks, fostering collaboration, and enhancing the exchange of ideas across institutions and markets. Through greater diffusion, inventions that have already proven effective can contribute to lower emissions.

H1b. Higher absorptive capacity enhances the diffusion of green inventions, which may serve as a channel for reducing CO₂ emissions.

Beyond the exchange of ideas, absorptive capacity may also support the adoption of concrete technologies within production and energy systems. Unlike inventions, which remain abstract until applied, technologies represent practical tools that replace high-carbon processes with low-carbon alternatives. By enabling large-scale technological adoption, absorptive capacity may directly lower emissions.

H1c. Higher absorptive capacity more effectively diffuses green technologies, which may mediate reductions in CO₂ emissions.

Another pathway may arise through the institutional environment. Education and R&D not only generate knowledge but also enhance the design and enforcement of public policies. An educated citizenry can create social and political pressure for ambitious environmental regulations, while strong research systems supply policymakers with the expertise required to craft effective rules. These regulations can, in turn, steer economies toward cleaner production and lower emissions.

H2. Higher absorptive capacity supports stricter environmental regulations, which may provide a pathway to reduce CO₂ emissions.

Absorptive capacity may further contribute by improving how energy is used in the economy. More educated and innovative societies may more readily develop and adopt efficiency-enhancing practices, from cleaner industrial processes to renewable integration and household-level energy savings. By lowering the emissions produced per unit of output, energy efficiency becomes a direct mediator of decarbonization.

H3. Higher absorptive capacity improves energy efficiency, which may mediate reductions in CO₂ emissions.

Finally, absorptive capacity may shape the labor market by shifting employment toward sustainability-related activities. Investments in education and R&D may expand the pool of workers with relevant skills and stimulate the demand for such jobs, leading to structural change in employment patterns. While job creation alone may not directly cut emissions, it may contribute indirectly by supporting the diffusion and adoption of green technologies and policies.

H4. Higher absorptive capacity creates more green jobs, which may act as an intermediary mechanism in lowering CO₂ emissions.

3. Empirical strategy

This section presents the empirical strategy used to analyze how education and R&D, individually and in combination, affect carbon emissions across countries, and to test whether education amplifies the emissions-reducing effect of innovation. The section is divided into two parts. Section 3.1 outlines the empirical model, and Section 3.2 describes the data and variables used in the analysis.

3.1. Model specification

To begin, a baseline fixed effects model is estimated to assess how education and R&D influence carbon emissions across countries over time. This approach is particularly well-suited for macro-level panel data, as it accounts for unobserved, time-invariant country characteristics such as geographic location, institutional history, or long-run development trajectories that could bias the estimated effects. Additionally, time-fixed effects absorb global shocks that affect all countries, such as international oil price fluctuations or coordinated policy responses to climate change. The following equation represents the main estimation framework:

$$\begin{aligned} \log CO_{2it} = & \beta_1 \log GDPpc_{it} + \beta_2 \log GDPpc_{it}^2 + \beta_3 \log Educ_{it} + \beta_4 \log Educ_{it}^2 \\ & + \beta_5 \log R&D_{it} + \beta_6 \log R&D_{it}^2 + \beta_7 \text{Absorptive Capacity}_{it} \\ & + \beta_8 X_{it} + \alpha_i + \delta_t + \epsilon_{it} \end{aligned} \quad (1)$$

where $\log(CO_2)_{it}$ captures the natural logarithm of carbon emissions per capita measured in metric tons in the country i at time t . The income level is modeled through $\log(GDPpc)_{it}$ and its squared term, capturing the potential nonlinear relationship implied by the EKC. Education effects are introduced via $\log(Education)_{it}$ and its squared term, allowing for diminishing or nonlinear impacts of human capital on emissions. Similarly, $\log(R&D)_{it}$ and its squared term assess the role of research and development in influencing emissions, with potential nonlinearities.

The inclusion of squared terms for education and R&D is motivated by prior evidence of nonlinearities in both human capital and innovation. Absorptive capacity theory suggests that education enhances the impact of R&D only after a threshold level of skills is reached, while very high levels may face diminishing marginal returns (Cohen et al., 1990; Balaguer and Cantavella, 2018). Likewise, empirical studies on R&D show nonlinear effects on productivity and environmental outcomes, consistent with inverted-U or diminishing return patterns (Popp, 2019). Allowing for these nonlinearities ensures the specification captures these theoretically and empirically grounded dynamics.

In this specification, “Absorptive Capacity_{it}” is defined as the interaction between tertiary education and R&D investment: $\text{Absorptive Capacity}_{it} \equiv \log(\text{Educ}_{it}) \times \log(R&D_{it})$. This term captures the hypothesis that the effect of R&D on emissions reduction depends on a country’s level of human capital. In other words, education enhances a country’s ability to absorb, implement, and scale up emissions-reducing innovations. This idea is consistent with the concept of absorptive capacity as developed in the innovation

literature, where it refers to the ability to recognize the value of new information, assimilate it, and apply it to commercial or policy ends (Cohen et al., 1990).

The control variables, X_{it} , capture 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. While fixed effects estimation is robust for controlling unobservable heterogeneity in macro cross-country panels, concerns about endogeneity may still arise. For instance, countries experiencing rapid economic growth (i.e., increases in GDP per capita over time) and rising emissions might simultaneously increase education and R&D investment, making the direction of causality unclear. Moreover, unobserved institutional factors could simultaneously drive both educational expansion and emissions regulation.

While the model includes several potentially correlated variables, such as GDP per capita, R&D expenditures, and their interaction terms, these are included by design to capture nonlinearities and theoretically justified interactions. Multicollinearity is an expected feature of such models, but it does not bias coefficient estimates; rather, it may inflate standard errors. To assess this concern, variance inflation factors (VIFs) were calculated using a pooled OLS version of the baseline fixed effects model. The results, reported in Appendix A.2, indicate that multicollinearity is within acceptable bounds and does not materially affect inference.

To address potential endogeneity concerns, the analysis is complemented by a DiD design, presented in Section 5. This approach exploits the quasi-experimental setting of the EU 2020 Strategy, which introduced coordinated policies promoting education, innovation, and emissions reduction across member states (European Commission, 2010). By comparing treated EU countries with a control group of non-EU advanced economies, and examining pre- and post-policy trends, the DiD framework offers additional evidence to validate the main findings. In this setting, endogeneity is addressed by leveraging plausibly exogenous variation in the timing and implementation of EU-wide climate and innovation policies. If additional concerns about omitted variable bias remain, an IV approach is explored in the Appendix B.

3.2. Data

The dataset covers a balanced panel of 91 countries over a 25-year period from 1995 to 2019.¹ The dependent variable, CO₂ emissions per capita in metric tons, is sourced from the Our World in Data database (Ritchie et al., 2023). Income inequality data, measured by the disposable Gini coefficient, is obtained from the Standardized World Income Inequality Database (SWIID) (Solt, 2020). Additional variables, including GDP per capita (constant 2015 US\$), tertiary education enrollment (gross %), R&D expenditures, energy use (kg of oil equivalent per capita), and trade openness, come from the World Bank's World Development Indicators (WDI). The variable R&D is defined as the gross domestic expenditure on research and development (public and private) as a percentage of GDP, covering business, government, higher education, and private non-profits. Countries are classified as high-, middle-, or low-income economies following the World Bank's income classification. Table A.3 in the Appendix classifies all countries in the analysis by income levels. Additionally, the Appendix presents summary statistics and a correlation matrix in Tables A.1 and A.2.

CO₂ emissions per capita vary across countries, reflecting differences in economic structures and energy consumption patterns. These differences are also appreciated in Table 1 that presents summary statistics by income classification. As expected, CO₂ 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 income 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.

Fig. 1 provides a descriptive overview of the relationship between GDP per capita and CO₂ emissions per capita. The scatterplot, with a lowess fit, shows a non-linear association consistent with EKC dynamics: emissions increase at low and middle income levels, but flatten and eventually decline at higher income levels. For completeness, Appendix Figures A.1a and A.1b present the evolution of Pearson correlation coefficients over time for the full sample and by income groups, respectively.

4. Results

Table 2 presents the regression results examining the relationship between income levels, tertiary education, R&D expenditures, and CO₂ 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 EKC hypothesis, suggesting that CO₂ emissions initially rise with income levels but decline beyond a certain income threshold. This is consistent with the large body of EKC evidence (e.g., Grossman and Krueger, 1995; Stern, 2018), which similarly finds an inverted-U relationship between income and emissions.

¹ The focus is on the period 1995–2019 because macro-level indicators are not consistently available across countries beyond 2019. This ensures comparability and avoids introducing selection bias due to incomplete or irregular post-2019 reporting in cross-country panel data.

Table 1
Summary statistics by income level.

	N	Mean	St. Dev.	Min	Max
Log CO₂ 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 3.

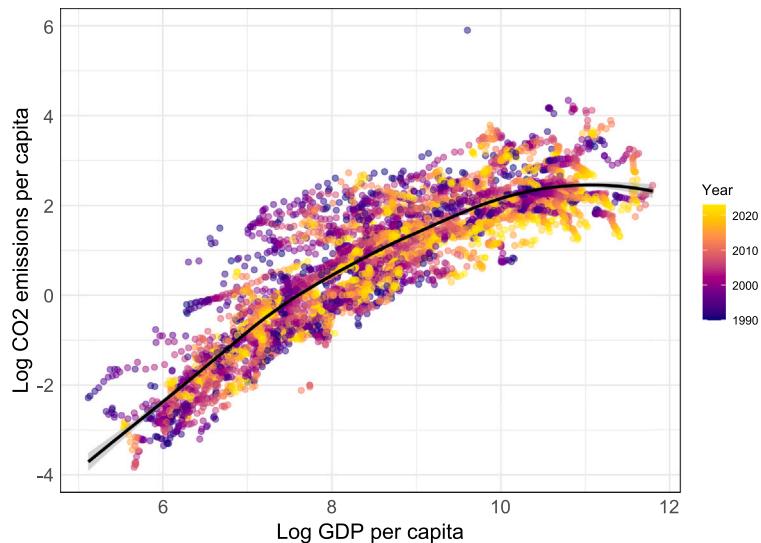


Fig. 1. Relationship between GDP per capita and CO₂ emissions per capita (1995–2019).

Note: Each point represents a country-year observation (colored by year). A lowess smoothing curve highlights the non-linear pattern consistent with EKC dynamics.

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 CO₂ 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. This

Table 2
Impact of education and R&D on CO₂ emissions.

	(1)	(2)	(3)	(4)
Log GDP p.c	2.523*** (0.090)	1.797*** (0.100)	1.324*** (0.143)	1.176*** (0.145)
Log GDP p.c Sq.	-0.142*** (0.005)	-0.098*** (0.006)	-0.071*** (0.009)	-0.062*** (0.009)
Log tertiary enrollment	0.213*** (0.020)	0.172*** (0.049)	0.090* (0.051)	
Log tertiary enrollment Sq.	-0.034*** (0.004)	-0.032*** (0.007)	-0.026*** (0.007)	
Log R&D Exp.		-0.049*** (0.017)	0.204*** (0.053)	
Log R&D Exp. Sq.		-0.010** (0.005)	0.003 (0.005)	
Absorptive capacity			-0.064*** (0.013)	
Log energy use	0.766*** (0.023)	0.861*** (0.023)	0.976*** (0.031)	0.955*** (0.031)
Log trade	0.083*** (0.016)	-0.006 (0.016)	-0.037* (0.021)	-0.022 (0.021)
Income inequality	-0.002 (0.002)	-0.005*** (0.002)	-0.001 (0.002)	-0.001 (0.002)
Observations	2471	1793	984	984
Adjusted R ²	0.56	0.70	0.69	0.70

Note: Driscoll-Kraay robust standard errors in parentheses. Results are robust to clustering by country. All specifications include country and year fixed effects. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is log CO₂ per capita. Column (1) includes only income level variables, column (2) adds education, column (3) introduces R&D, and column (4) examines the interaction between education and R&D.

finding is consistent with evidence that education moderates the EKC, facilitating the shift toward cleaner technologies and reduced emissions (Balaguer and Cantavella, 2018). 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. These results align with findings that the effects of energy R&D on environmental performance are nonlinear (Popp, 2019).

Column (4) introduces the interaction term between tertiary education and R&D, which changes the interpretation of the main effects. The coefficient on R&D alone now reflects its effect when education is zero (a hypothetical baseline), while the interaction term captures how the effect of R&D varies with education levels. In this specification, the standalone R&D coefficient turns positive, but the interaction term is negative and highly significant.

Taken together, the combined effect at observed levels of education is negative, confirming that higher education strengthens the emissions-reducing role of R&D. This finding is consistent with the concept of absorptive capacity (Cohen et al., 1990), which emphasizes the role of human capital in enabling economies to internalize and apply new knowledge. These results extend this idea by providing systematic evidence that education conditions whether R&D translates into emissions-reducing innovation.

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.

Across all models, energy use remains a strong positive predictor of CO₂ emissions. Trade openness has a small and marginally significant negative effect, suggesting that higher trade 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.

To assess whether these findings depend on the specific proxies chosen for human capital and R&D, I re-estimated the models using alternative measures: upper-secondary and post-secondary educational attainment, as well as researchers in R&D per million people as a proxy for R&D inputs. The results, reported in Appendix Table C.1, confirm the robustness of the absorptive capacity effect, which remains negative and statistically significant across all specifications. This suggests that the finding is not an artifact of a particular proxy choice: whether absorptive capacity is measured via tertiary enrollment, upper-secondary or post-secondary attainment, or combined with alternative R&D input proxies, the moderating effect of human capital on the decarbonization impact of R&D holds consistently.

To address concerns about omitted-variable bias, I extend the baseline specification with additional controls in three groups, reported in the Appendix, section D. First, I add variables for the energy mix (renewables share, fossil share, fossil and renewable consumption levels, coal-based electricity; Table D.1). Second, I incorporate industrial structure and energy imports (sectoral employment shares, energy import dependence; Table D.2). Third, I add demographic controls (log population, urban share, population growth, labor force participation; Table D.3). I also present a “full set” specification combining one proxy per theme

Table 3
Impact of education and R&D on CO₂ emissions by income level.

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

Note: Driscoll-Kraay robust standard errors in parentheses. Results are robust to clustering by country. All specifications include country and year fixed effects. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is log CO₂ per capita. Columns (1), (2), and (3) correspond to high-income, middle-income, and low-income countries, respectively. Control variables include the log of energy use, trade, and income inequality.

(Table D.4). Additionally, it includes net foreign direct investment (FDI) as it captures cross-border capital flows that can bring technology transfer, innovation spillovers, and exposure to foreign production practices. Across all specifications, the absorptive capacity effect remains negative and statistically significant, while the additional variables behave as expected. This provides reassurance that the main findings are robust to alternative specifications.

To address concerns about both potential reverse causality and delayed effects, I re-estimated the preferred specification using one- and two-period lagged values of education, R&D, and absorptive capacity. This approach allows for the possibility that decarbonization drivers operate with a delay due to structural, technological, or behavioral factors, while also mitigating simultaneity concerns. The results, presented in Table E.1 in the Appendix, remain highly consistent with the contemporaneous model. In all cases, the absorptive capacity effect continues to be negative and statistically significant. This robustness check provides reassurance that the main findings are not driven by simultaneity and that they persist when allowing for delayed effects.

4.1. Heterogeneous effects by income level

Given the wide variation in institutional quality, innovation capacity, and economic structure across countries, this research explores whether the relationship between absorptive capacity and emissions differs by income group. Table 3 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 CO₂ 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 income growth alone is insufficient to drive emissions reductions.

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 the 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

Table 4
Quantile regression results.

	Q25	Q50	Q75	Q90
Log GDP p.c	1.069** (0.192)	0.631*** (0.160)	0.648*** (0.134)	0.642*** (0.139)
Log GDP p.c Sq.	-0.050*** (0.011)	-0.027*** (0.010)	-0.030*** (0.008)	-0.034*** (0.009)
Log tertiary enrollment	0.187** (0.085)	0.051 (0.031)	0.180*** (0.026)	0.226*** (0.078)
Log tertiary enrollment Sq.	-0.028** (0.012)	-0.018*** (0.005)	-0.033*** (0.005)	-0.031*** (0.011)
Log R&D Exp.	-0.028 (0.021)	-0.071*** (0.020)	-0.041** (0.017)	-0.045** (0.018)
Log R&D Exp. Sq.	-0.010** (0.004)	-0.025*** (0.005)	-0.020*** (0.003)	-0.029*** (0.005)
Absorptive capacity	-0.094** (0.038)	-0.145*** (0.031)	-0.124*** (0.020)	-0.023 (0.042)
Observations	984	984	984	984

Note: Bootstrap standard errors (500 replications) in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is log CO₂ 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. Additional control variables such as trade openness, energy use, income inequality, and the constant term are omitted for brevity. All models include country and year fixed effects.

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.

4.2. Quantile regression

In addition to OLS, I employ Quantile Regression (QR) following Koenker and Bassett Jr (1978). QR is particularly well-suited for this setting because the effect of education and R&D on emissions may not be constant across the distribution of the outcome. For instance, high-emission economies may respond differently to policy or absorptive capacity than low-emission economies. By estimating conditional quantiles of the emissions distribution, QR allows me to assess heterogeneity in the effects of education and innovation, which OLS cannot capture as it only recovers the conditional mean. This distinction is important in the context of environmental policy, where distributional impacts matter for both efficiency and equity considerations (Koenker and Hallock, 2001; Koenker, 2005). For the QR estimates, I use the standard Koenker–Bassett estimator with standard errors obtained via bootstrapping with 500 replications, which is the recommended approach for inference in QR models.

While the estimates presented in this section are not intended to imply causal relationships, the quantile regression results provide useful descriptive insights into how the association between education, R&D, and carbon emissions varies across the emissions distribution. Table 4 explores the heterogeneous effects of education and R&D on carbon emissions across different levels of emissions. It 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 income growth is associated with higher emissions. The squared term is negative and significant, confirming the EKC 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.

5. Robustness check

To assess the robustness of the main findings, this section implements an additional identification strategy. A DiD design addresses potential endogeneity concerns and strengthens the causal interpretation of the results.

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 (European Commission, 2010). One of the key components of this strategy was

Table 5
Difference-in-differences estimation of EU 2020 policy impact.

	(1)	(2)
Post × Treated	−0.15*** (0.06)	−0.06*** (0.02)
Post-treated absorptive capacity	0.00 (0.01)	
L2.Post-treated absorptive capacity		−0.01*** (0.00)
Log GDP p.c	0.84* (0.47)	1.21** (0.60)
Log GDP p.c Sq.	−0.05* (0.03)	−0.06* (0.03)
Country FE	Yes	Yes
Year FE	Yes	Yes
Observations	236	191
Adjusted R^2	0.87	0.92

Note: Country-clustered (Arellano) standard errors in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable is log CO₂ per capita. Both specifications include country and year fixed effects. As a result, the main effects of Treated and Post are absorbed by the fixed effects and not reported. The coefficient on Post × Treated is the DiD estimator of the EU 2020 policy. Control variables include log enrollment in tertiary education, log R&D, log R&D squared, log energy use, trade, and income inequality.

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 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).

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

where $\log(\text{CO}_{2it})$ represents per capita carbon emissions, α_i are country fixed effects and δ_t are year fixed effects. The main effects of Treated (time-invariant) and Post (time-specific) are absorbed by these fixed effects and therefore not separately estimated. The coefficient of interest is β_1 , which captures the DiD effect of the EU 2020 policy. 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 5 presents the results, showing a significant reduction in emissions for treated countries. The negative and significant coefficient for the Post × Treated interaction in column (1) indicates that the EU 2020 policy led to an immediate 15% reduction in CO₂ 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 income before declining at higher income levels.

The delayed role of absorptive capacity is consistent with the view that human capital conditions whether R&D translates into productivity-enhancing or emissions-reducing innovations (Cohen et al., 1990; Popp, 2010), while the persistence of the inverted-U pattern confirms that the EKC relationship is robust to policy-induced structural breaks, in line with cross-country evidence from Dinda and Coondoo (2006) and Vollebergh et al. (2009).

I also estimated the model using only country fixed effects, which allows the Post dummy to be estimated explicitly. The results are nearly identical to those reported in **Table 5**, with the coefficient on the interaction Post × Treated remaining identical in magnitude and significance. This confirms that the causal effect is robust to alternative specifications. I prefer the Difference-in-Differences specification with country and year effects reported here, as it flexibly accounts for time-invariant differences across countries and common shocks over time.

Table 6
Mediation analysis: Development of inventions.

	Dependent variable:		
	Dev. inventions	Log CO ₂ p.c.	
		(2)	(3)
Development inventions		-0.00 (0.00)	-0.00 (0.00)
Absorptive capacity	0.43*** (0.14)		-0.08*** (0.01)
Observations	869	1763	869
Adjusted R ²	0.10	0.70	0.74

Note: Driscoll-Kraay robust standard errors in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of absorptive capacity on the development of green inventions. Model (2) estimates the effect of green inventions on CO₂ emissions. Model (3) includes both the direct and mediated effects. All models control for log GDP per capita, education, R&D (and their squared terms), trade, energy use, and income inequality. All models include country and year fixed effects, but are omitted for brevity. Coefficients for control variables are omitted for clarity.

Table 7
Mediation analysis: Diffusion of inventions.

	Dependent variable:		
	Diff. Inventions	Log CO ₂ p.c.	
		(2)	(3)
Diffusion inventions		-0.002*** (0.00)	-0.002** (0.00)
Absorptive capacity	1.36*** (0.48)		-0.06*** (0.01)
Observations	852	1659	852
Adjusted R ²	0.26	0.73	0.77

Note: Driscoll-Kraay robust standard errors in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of absorptive capacity on Diffusion Innovation. Model (2) estimates the effect of Diffusion Innovation on CO₂ emissions. Model (3) includes both the direct and mediated effects. All models control for log GDP per capita, education, R&D (and their squared terms), trade, energy use, and income inequality. All models include country and year fixed effects, but are omitted for brevity. Coefficients for control variables are omitted for clarity.

6. How does absorptive capacity affect emissions?

To deepen the interpretation of the main results, this section examines the channels through which absorptive capacity contributes to decarbonization. I first test whether absorptive capacity reduces emissions through the development of green inventions. The results are presented in Table 6. Column (1) shows that absorptive capacity has a positive and significant effect on the share of environment-related inventions. However, Column (2) indicates that newly developed green inventions have no significant effect on CO₂ emissions. As a result, Column (3) confirms that this channel does not mediate the relationship between absorptive capacity and emissions.

Several factors may explain this disconnect. First, many green inventions remain in early stages, such as patents, and face commercialization and adoption hurdles. Second, time lags in scaling and regulatory approval delay their environmental impact. Third, weak market incentives or insufficient policy support can limit firm adoption. Lastly, established high-carbon technologies may crowd out new solutions. These results align with prior evidence that the diffusion of climate mitigation technologies lags behind invention (Probst et al., 2021). These findings suggest that while the absorptive capacity expands the frontier of green innovation, their environmental benefits might depend on complementary policies that ensure the adoption and scaling of these technologies.

Next, in Table 7, I examine whether absorptive capacity reduces emissions through the diffusion of green inventions. Column (1) shows that absorptive capacity has a positive and significant effect on the diffusion of environment-related inventions, suggesting that education strengthens a country's ability to absorb, adapt, and disseminate green technologies, reflected in increased patent citations, licensing, and international collaboration. Column (2) indicates that greater diffusion significantly reduces CO₂ emissions, underscoring the environmental gains associated with the broader uptake of green technologies. Finally, Column (3) confirms that absorptive capacity indirectly lowers emissions through diffusion. These results reinforce the idea that green invention development alone is insufficient; diffusion must be prioritized to fully realize the potential of environmental technologies. This is consistent with evidence that the diffusion of clean technologies across borders, through patent citations and licensing, plays a more critical role in decarbonization than invention alone (Verdolini and Galeotti, 2011; Dechezleprêtre et al., 2014).

Table 8
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)
Absorptive capacity	1.99** (0.92)		-0.06*** (0.01)
Observations	852	1659	852
Adjusted R ²	0.07	0.73	0.77

Note: Driscoll-Kraay robust standard errors in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of absorptive capacity on Diffusion Technology. Model (2) estimates the effect of Diffusion Technology on CO₂ emissions. Model (3) includes both the direct and mediated effects. All models control for log GDP per capita, education, R&D (and their squared terms), trade, energy use, and income inequality. All models include country and year fixed effects, but are omitted for brevity. Coefficients for control variables are omitted for clarity.

Table 9
Mediation analysis: Environmental policy stringency index.

	Dependent variable:		
	EPSI	Log CO ₂ p.c.	
	(1)	(2)	(3)
EPSI		-0.04*** (0.00)	-0.04*** (0.01)
Absorptive capacity	0.83*** (0.21)		-0.06** (0.03)
Observations	495	916	495
Adjusted R ²	0.69	0.83	0.82

Note: Driscoll-Kraay robust standard errors in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of absorptive capacity on the EPSI. Model (2) estimates the effect of EPSI on CO₂ emissions. Model (3) includes both the direct and mediated effects. All models control for log GDP per capita, education, R&D (and their squared terms), trade, energy use, and income inequality. All models include country and year fixed effects, but are omitted for brevity. Coefficients for control variables are omitted for clarity.

I then turn to the diffusion of green technologies. Column (1) of Table 8 shows that absorptive capacity has a positive and significant effect on technology diffusion, suggesting that education enhances a country's ability to integrate green technologies into production and energy systems. Column (2) reveals that technology diffusion significantly reduces CO₂ emissions, and Column (3) confirms that absorptive capacity indirectly lowers emissions through this channel.

Unlike invention diffusion, which emphasizes knowledge sharing, technology diffusion directly impacts emissions by enabling the replacement of high-carbon production methods with low-carbon alternatives. These findings underscore that innovation alone is not enough and that education and supportive policy environments are critical to accelerating the large-scale adoption of green technologies and realizing their environmental benefits. This echoes the directed technical change literature, which finds that the environmental benefits of innovation depend on the large-scale adoption of low-carbon technologies in production systems (Acemoglu et al., 2012; Aghion et al., 2016).

The results in Table 9 suggest that absorptive capacity contributes to stronger environmental regulation. Column (1) shows a positive association with the Environmental Policy Stringency Index (EPSI), indicating that countries with higher education and R&D levels are more likely to adopt stringent policies. Column (2) confirms that stricter environmental policies reduce CO₂ emissions. Column (3), which includes both direct and mediated effects, indicates that part of the absorptive capacity's impact on emissions operates through regulatory pathways. While technology and skills are essential, their full impact depends on regulatory frameworks that guide behavior and enforce compliance. These findings complement evidence that stronger innovation systems and human capital support the implementation of stringent environmental policies (Noailly, 2012; Fankhauser and Jotzo, 2018; Botta and Koźluk, 2014).

Table 10 indicates that absorptive capacity is associated with lower carbon intensity of GDP (Column 1), pointing to improvements in energy efficiency. Column (2) shows that higher carbon intensity is strongly linked to greater per capita emissions, and Column (3) suggests that part of the effect of absorptive capacity on emissions operates through this channel. Overall, the results are consistent with the view that more educated and innovative economies are better able to reduce emissions by improving the efficiency of energy use. This is consistent with studies showing that absorptive capacity fosters energy efficiency improvements, thereby reducing carbon intensity (Lanzi et al., 2011).

Table 10
Mediation analysis: Carbon intensity.

Dependent variable:			
	Carbon Int. GDP		Log CO ₂ p.c.
	(1)	(2)	(3)
Carbon Int. GDP		0.28*** (0.01)	0.12*** (0.02)
Absorptive capacity	-0.13*** (0.02)		-0.05*** (0.01)
Observations	978	2451	978
Adjusted R ²	0.61	0.62	0.72

Note: Driscoll-Kraay robust standard errors in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of absorptive capacity on Carbon Intensity (Carbon Int. GDP). Model (2) estimates the effect of Carbon Intensity on CO₂ emissions. Model (3) includes both the direct and mediated effects. All models control for log GDP per capita, education, R&D (and their squared terms), trade, energy use, and income inequality. All models include country and year fixed effects, but are omitted for brevity. Coefficients for control variables are omitted for clarity.

Table 11
Mediation analysis: Green jobs.

Dependent variable:			
	Green jobs		Log CO ₂ p.c.
	(1)	(2)	(3)
Log green jobs		-0.02 (0.03)	-0.02 (0.05)
Absorptive capacity	1.02*** (0.26)		0.09 (0.11)
Observations	92	111	92
Adjusted R ²	0.49	0.82	0.77

Note: Driscoll-Kraay robust standard errors in parentheses. Significance levels are: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Model (1) estimates the effect of absorptive capacity on Green Jobs. Model (2) estimates the effect of Green Jobs on CO₂ emissions. Model (3) includes both the direct and mediated effects. All models control for log GDP per capita, education, R&D (and their squared terms), trade, energy use, and income inequality. All models include country and year fixed effects, but are omitted for brevity. Coefficients for control variables are omitted for clarity.

Table 11 shows that absorptive capacity is positively associated with green job creation, as shown in Column 1. However, Column 2 shows that green employment has no significant effect on emissions, nor does it mediate the overall relationship, as shown in Column 3. These results suggest that while stronger education and innovation systems generate more jobs in sustainability-related sectors, employment shifts alone do not directly reduce emissions without complementary technological or policy changes. One limitation is the smaller and less consistent sample of green employment data, which may affect robustness. This resonates with recent work emphasizing that green employment growth must be coupled with complementary technological and regulatory changes to translate into measurable emissions reductions (Secundo et al., 2020; Khanra et al., 2022).

To enforce temporal ordering and reduce concerns of reverse causality, education and R&D are lagged by one period, while mechanisms (e.g., diffusion of inventions, carbon intensity, EPSI, etc.) and emissions are measured contemporaneously. This ensures that absorptive capacity precedes the mediating channel, which in turn contemporaneously affects emissions. The results, shown in the Appendix H, remain consistent with the contemporaneous specification: diffusion and EPSI continue to play a significant mediating role, carbon intensity remains a strong channel, while technology diffusion and green jobs do not show robust effects. These findings confirm that the mediating role of absorptive capacity is not driven by simultaneity or omitted variable bias, but reflects a robust pathway linking education and R&D to environmental outcomes.

7. Discussion and conclusions

Technological innovation is central to decarbonization, but its impact depends on the conditions under which it operates. This study shows that absorptive capacity, defined as the combination of education and R&D, amplifies the effectiveness of green innovation in reducing CO₂ emissions. In other words, innovation must be embedded within a skilled and adaptive society to yield higher environmental returns. The clear policy implication is that governments cannot rely on technological progress alone; they must invest in human capital, education systems, and technical skills to unlock their full potential. These initial findings speak directly to the study's central objective of assessing whether human capital enhances the decarbonization impact of innovation.

The results confirm a non-linear relationship between income, education, and emissions. While R&D alone reduces emissions by 4.9%, its effect grows to 6.4% when combined with a strong knowledge base, highlighting a 30% larger decarbonization impact. This interaction is particularly strong in middle-income economies, where innovation uptake is more dynamic. The Difference-in-Differences analysis further supports these findings. It shows that the EU 2020 policy led to an immediate 15% reduction in CO₂ emissions among treated countries, which moderated to 6% in the longer term. Importantly, in countries with stronger absorptive capacity, those with higher levels of tertiary education and R&D, emissions fell an additional 1 percentage point, bringing the total long-term reduction to 7%. This pattern suggests that the benefits of climate policy deepen over time in knowledge-intensive economies, where education and innovation foster structural change and support the adoption of cleaner technologies. The findings provide consistent empirical support for the hypothesis that absorptive capacity conditions the effectiveness of both innovation and climate policy. These results emphasize that the same climate policy can deliver very different outcomes depending on a country's absorptive capacity. Countries with weak education and R&D systems may implement ambitious policies yet obtain limited emissions reductions, highlighting the need for climate finance and capacity-building mechanisms that target institutional and human capital constraints.

To unpack the channels driving this relationship, the analysis explores five potential mechanisms. First, green invention development alone does not reduce emissions, highlighting that innovation must move beyond the patent stage to widespread adoption. In contrast, the diffusion of inventions and technologies significantly lowers emissions. Second, absorptive capacity enhances regulatory effectiveness: countries with strong human capital and R&D implement more stringent environmental policies, which in turn reduce emissions. Third, efficiency gains are a key driver; lower carbon intensity reflects improved production methods rather than reduced output. Fourth, green job creation is positively associated with absorptive capacity but does not directly drive emissions reductions, suggesting employment shifts alone are insufficient without technology deployment. These channels reinforce the conceptual expectation that absorptive capacity operates through innovation uptake, regulatory strength, and efficiency improvements, thereby supporting the study's mechanism-based research objectives. These mechanisms point to a simple message: absorptive capacity transforms potential into realized impact. For policymakers, this means that accelerating diffusion, strengthening regulatory capacity, and improving energy efficiency should be treated as complementary pillars of national decarbonization strategies.

These findings reinforce the importance of integrated strategies that align education, innovation, and policy. Building on this, the results yield differentiated policy implications across country groups. For advanced economies, where absorptive capacity is already relatively high, the key challenge lies in aligning existing R&D investments with decarbonization goals. This can be achieved by coupling innovation policies with strong carbon pricing, targeted subsidies for clean technologies, and mission-oriented programs that direct technological change toward low-carbon outcomes. For emerging and developing economies, the results suggest that increasing R&D spending alone may be insufficient without parallel investments in human capital and institutional quality. Policies that expand access to higher education, strengthen technical training, and improve governance structures are essential for translating innovation into measurable environmental benefits. In this context, international cooperation and technology transfer can also play a complementary role in accelerating the diffusion of low-carbon technologies. Together, these group-specific strategies highlight that while innovation is a necessary engine of decarbonization, its effectiveness ultimately depends on the absorptive capacity of the societies where it is deployed. More broadly, the findings imply that unequal levels of absorptive capacity may widen differences in the pace of the low-carbon transition across countries, making capacity-building a global climate priority. Looking ahead, climate strategies should incorporate absorptive capacity as a core design principle rather than a background condition. Integrating human capital development, which enables the uptake of innovation and institutional change, into decarbonization planning can significantly accelerate emissions reductions and prevent countries from falling behind in the global transition.

While this study offers new insights, several limitations remain. Measurement inconsistencies in some indicators, such as green employment, and the potential for omitted variable bias must be acknowledged. In addition, the analysis is based on country-level data and does not capture within-country heterogeneity or firm-level dynamics. Future research could explore how absorptive capacity affects emissions at subnational or sectoral levels, and examine the equity implications of innovation-driven transitions, particularly the challenges faced by lower-skilled workers. Reskilling and workforce adaptation policies will be crucial to ensure that the green transition is both effective and inclusive.

CRediT authorship contribution statement

Fernando Loaiza: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.eap.2026.01.066>.

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