





“The impact of policy stringency on green innovation and environmental performance: A system GMM analysis of 25 OECD countries”

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THE IMPACT OF POLICY STRINGENCY ON GREEN INNOVATION AND ENVIRONMENTAL PERFORMANCE: A SYSTEM GMM ANALYSIS OF 25 OECD COUNTRIES

Abstract

Considering the increasing environmental pressures associated with economic growth and industrial expansion, improving environmental quality has become a central challenge for advanced economies. Green innovation is crucial for sustainable development, but its success largely depends on the regulatory context. This paper examines the relationship between green innovation and environmental degradation and assesses how market-based and non-market environmental policy instruments shape this relationship in 25 OECD countries over the period 2000–2020. Building on existing theoretical and empirical frameworks linking environmental regulation, technological innovation, and environmental performance, the study employs a dynamic panel modeling approach using a two-step System-GMM estimator to address endogeneity, heterogeneity, and the persistence of environmental indicators. Empirical results indicate that a 1% increase in green patent activity reduces CO₂ emissions by 0.34% and the ecological footprint by 0.33%. Market-based instruments significantly decrease CO₂ emissions and the ecological footprint with coefficients of -0.679 and -0.068 , respectively, whereas non-market instruments are associated with increases in CO₂ emissions and the ecological footprint with coefficients of $+0.045$ and $+0.038$, respectively. The interaction between market-based instruments and green innovation further reduces CO₂ emissions and the ecological footprint, with coefficients of -0.00004 and -0.0006 , respectively, while the interaction with non-market instruments also yields negative effects (-0.00001 and -0.00002). The aggregate environmental policy stringency index lowers CO₂ emissions by 0.159 and the ecological footprint by 0.041, strengthening the innovation effect. Overall, the findings suggest that well-designed and coherent policy mixes are essential for maximizing green innovation's environmental benefits in advanced economies.

Keywords

green innovation, environmental regulation, policy stringency, CO₂ emissions, ecological footprint, two step system-GMM, OECD countries

JEL Classification

Q54, Q58, O31, C33

INTRODUCTION

Accelerating environmental degradation, driven by sustained economic growth and rising greenhouse gas emissions, has intensified the search for effective pathways to sustainable growth (Lin & Ma, 2022). While this challenge is global, it is especially salient in OECD countries, which account for a significant historical share of CO₂ emissions (Mahmood et al., 2022) and lead in developing green technologies (Peñalosa & Kleine-Rueschkamp, 2024) as well as implementing relatively stringent environmental policies (Tao et al., 2025). This dual position makes them a critical setting for assessing the effectiveness of policy and innovation strategies to mitigate environmental degradation (Hassan et al., 2024).



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Green innovation is widely seen as key to decoupling economic growth from environmental degradation (Carrión-Flores & Innes, 2010), yet empirical evidence remains inconclusive. While some studies document significant emission reductions and environmental improvements associated with green innovation (Xu et al., 2021), others report weak or insignificant effects (Weina et al., 2016). These mixed findings suggest that the environmental benefits of innovation are not automatic but depend on the broader institutional and regulatory context. At the same time, environmental regulation remains a key policy tool for improving environmental quality. The Porter hypothesis posits that well-designed regulations can simultaneously stimulate innovation and improve environmental performance (Porter & van der Linde, 1995). Yet empirical support remains mixed. Non-market-based instruments are often associated with short-term compliance behavior and may constrain productivity, whereas market-based instruments tend to foster longer-term technological adaptation (Zhang et al., 2020). Moreover, recent evidence points to non-linear and heterogeneous effects of regulatory stringency, indicating that the regulation-environment nexus is more complex than traditionally assumed (Zhong et al., 2021). These findings reveal a fragmented literature and highlight the need for further research on how different regulatory approaches affect environmental quality.

Existing studies often examine green innovation and environmental regulation separately, overlooking their interaction. As a result, the role of policy instruments in shaping the environmental impact of innovation remains unclear, which is critical for effective policy design. This study addresses this limitation by developing an integrated framework linking green innovation, environmental policy instruments (both market-based and non-market), and environmental quality. Focusing on OECD countries, it examines how regulatory frameworks influence the environmental returns to innovation, providing insights for more coherent policy design.

1. LITERATURE REVIEW AND HYPOTHESES

Research on the nexus between environmental innovation and improvements in environmental quality has intensified, reflecting heightened attention from both policymakers and the scientific community on mitigating pollutant emissions to advance environmental sustainability while fostering economic performance. Despite this growing interest, empirical evidence remains heterogeneous. Some studies report positive effects of environmental innovation on environmental quality, whereas others find weak or statistically insignificant relationships (Du et al., 2019).

Empirical literature can thus be broadly categorized into two distinct strands. The first strand of the literature provides robust evidence that green innovation enhances environmental quality across diverse institutional and geographical contexts. In the United States, it has been shown to reduce toxic industrial emissions (Carrión-Flores & Innes, 2010), while in China, it has significantly curtailed CO₂ emissions at both provincial and municipal levels (Xu et al., 2021). Similar improvements have been documented in

Italian regions (Ghisetti & Quatraro, 2017) and in France, where energy-related innovations have contributed to lowering carbon emissions (Shahbaz et al., 2018). At a broader scale, green innovation has been associated with reductions in carbon pollution across a sample of 71 countries (Du et al., 2019) and with measurable improvements in environmental quality in 20 OECD economies, particularly those characterized by high ecological footprints (He et al., 2024). The second strand of the literature suggests that environmental innovation does not always lead to significant improvements in environmental quality. For instance, Lin and Ma (2022) find no effect on CO₂ emissions across Chinese provinces and cities. Similarly, Cheng et al. (2021) observe a neutral impact in 35 OECD countries between 1996 and 2015, while Weina et al. (2016) show that green innovations enhanced environmental productivity without significantly reducing emissions across 95 Italian provinces. More recently, Binsaeed et al. (2025) identify a U-shaped, non-linear relationship: green innovation may initially hinder sustainable development due to high R&D costs and technological inefficiencies, before becoming beneficial in the long term as technologies mature and economies of scale emerge.

Concurrently, the impact of environmental regulations on environmental performance has recently garnered increasing attention from both policymakers and the scientific community. The existing literature distinguishes between two categories of instruments: market-based instruments and non-market, command-and-control instruments. Market-based instruments internalize the social costs of pollution through mechanisms such as environmental taxes, tradable emission permits, and subsidies for clean technologies. Their primary advantage lies in their flexibility, allowing firms to adopt cost-effective emission-reduction strategies, thereby improving resource allocation and minimizing economic distortions (Porter & van der Linde, 1995; Hou et al., 2023). Empirical evidence indicates that these instruments can reduce CO₂ emissions and enhance environmental quality when implemented in a credible and sustained manner (Zhang et al., 2020; Murad et al., 2025).

Specifically, using ARDL models across 38 OECD countries, Murad et al. (2025) find that environmental taxes significantly reduce CO₂ emissions and facilitate the transition to cleaner energy sources. In contrast, non-market instruments rely on the imposition of technological standards, environmental regulations, or quantitative emission caps. While such measures can deliver rapid improvements in environmental quality, they may entail high compliance costs, particularly when firm heterogeneity is not accounted for (Wu et al., 2020). For instance, Guo et al. (2021), analyzing panel data for 27 OECD countries from 2005 to 2012, demonstrate that command-and-control regulations reduce greenhouse gas emissions and stimulate technological progress, although their effects differ from those of market-based instruments. Compliance costs typically rise with regulatory stringency, yet these instruments remain essential for establishing stringent environmental constraints.

Recent studies emphasize the complementarity between these instruments: command-and-control regulations provide a foundational regulatory framework, while market-based instruments enhance policy efficiency by incentivizing cost-effective emission reductions (Ji, 2020; Borowiec et al., 2024). The integration of both approaches appears particularly effective in improving environmental quality and supporting industrial transformation,

especially in economies undergoing energy transitions (Wang et al., 2025). However, non-linear effects have been observed: weak regulations fail to meaningfully alter firm behavior, whereas moderate to stringent regulations yield substantial environmental gains without undermining economic performance (Zhong et al., 2021).

Improving environmental quality is the primary objective of environmental regulation policies. Beyond this goal, such policies reshape firms' economic incentives by influencing their technological investment decisions. By promoting the development and adoption of cleaner technologies, regulations stimulate green innovation, thereby contributing to the mitigation of environmental degradation and the enhancement of environmental quality (Wei & Joo, 2025). Two contrasting theoretical frameworks structure this literature. The first, grounded in neoclassical economics, emphasizes the compliance cost effect (Ramanathan et al., 2017). From this perspective, environmental regulations increase production costs, reduce profitability, and constrain R&D investment, thereby weakening firms' incentives to innovate (Albrizio et al., 2017). These pressures can also undermine international competitiveness and encourage the relocation of polluting activities to regions with less stringent standards, in line with the "pollution haven" hypothesis (Rubashkina et al., 2015). From this perspective, environmental policies may hinder green innovation and limit improvements in environmental quality (Du et al., 2021). The second strand, rooted in a dynamic innovation perspective, highlights the incentive role of environmental regulations (Hassan et al., 2024). According to Porter's hypothesis, well-designed but stringent regulations can stimulate technological innovation, enhance productive efficiency, and strengthen firm competitiveness (Porter & van der Linde, 1995). Regulation-induced innovations, such as improvements in production processes, reductions in input costs, or access to new markets, can offset initial compliance costs (Liu et al., 2025). In this way, environmental regulation functions as a catalyst for green innovation and environmental performance rather than as a constraint (Sohag et al., 2024).

Empirical evidence generally supports a positive relationship between environmental regulations and green innovation. Early studies indicate that

the tightening of environmental policies is associated with an increase in environmental patents in advanced economies (Chang et al., 2023). Subsequent international analyses confirm that environmental policies stimulate technological innovation in the energy and industrial sectors (Rubashkina et al., 2015). The magnitude of this effect, however, depends on policy design. Market-based instruments, such as environmental taxes or emission trading systems, typically generate stronger incentives due to their flexibility and the long-term cost-reduction signals they provide (Fabrizi et al., 2018). Command-and-control regulations can also spur innovation by imposing mandatory constraints (Zhu et al., 2021). Recent studies highlight non-linear relationships between regulation and green innovation. U-shaped or inverted U-shaped effects suggest that a moderate level of regulatory stringency can stimulate innovation, whereas excessive compliance costs may discourage innovative efforts beyond a certain threshold (Langinier et al., 2025). These effects vary depending on the level of economic development, organizational capabilities, and firms' ability to transform regulatory constraints into competitive advantages (Lutfi et al., 2023).

Finally, the literature underscores the effectiveness of hybrid regulatory frameworks that combine market-based and command-and-control instruments. Such arrangements strengthen incentives for innovation while ensuring a minimum level of environmental protection, thereby promoting green innovation and facilitating the transition to low-carbon production systems (Wang et al., 2023).

This study is built on previous research examining the relationships among environmental regulations, green innovation, and environmental quality. It aims to investigate the role of environmental regulations in the link between green innovation and environmental pressure. Based on this, we formulate the following hypotheses:

H1: Green innovation significantly reduces environmental degradation in OECD countries.

H2: Strengthening environmental regulations significantly improves environmental quality and reduces pollutant emissions in OECD countries.

H3: Environmental regulations enhance environmental quality by promoting green innovation in OECD countries.

2. METHODS

This study employs a dynamic panel data methodology based on the System GMM estimator to examine how environmental regulations moderate the relationship between green innovation and environmental degradation, specifically CO₂ emissions and the ecological footprint, across 25 OECD countries¹. The analysis covers the period from 2000 to 2020, focusing on a timeframe during which environmental regulation and green innovation became central components of OECD economic and environmental strategies. This period aligns with the implementation of major international climate agreements and the expansion of policy instruments such as carbon pricing and innovation subsidies. The selection of these countries is guided by data availability and methodological requirements. The sample corresponds to the set of OECD countries for which complete and harmonized information is available for all variables over the entire period, enabling the construction of a balanced panel and ensuring reliable estimation. In addition, these countries are economically significant, geographically diverse, and broadly representative of OECD patterns, which supports the external validity of the analysis. The sample ends in 2020, reflecting the latest harmonized data available for the OECD Environmental Policy Stringency Index. The dataset is sourced from the OECD database, the World Bank's Worldwide Governance Indicators (WGI), and the Global Footprint Network (GFN). Selected variables are log-transformed to improve distributional properties and mitigate heteroskedasticity.

The selection of variables is grounded in established theoretical frameworks and prior empirical studies in environmental economics. The baseline model

¹ The annual data for the variables were obtained for the 25 OECD countries, which are Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, the Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Türkiye, the United Kingdom, and the United States, for which the dataset required for the estimation is available.

is extended to incorporate the key variables (Table 1) of interest: green innovation and environmental policy stringency. The dependent variables are CO₂ emissions per capita and the ecological footprint per capita. CO₂ emissions are quantified in metric tons to accommodate population fluctuations and are sourced from the World Bank's World Development Indicators (WDI) database. The ecological footprint is measured in global hectares (gha) per capita and is obtained from the Global Footprint Network (GFN), capturing the environmental pressure associated with consumption patterns and resource use. The independent variables are delineated as follows. Gross domestic product per capita (GDPpc) is measured in constant 2010 US dollars and sourced from the World Bank's World Development Indicators (WDI) database. Green innovation (GPAT) is proxied by green patent applications obtained from the OECD database, following the methodology of Du et al. (2019). The measure focuses on patents filed with the European Patent Office (EPO), classified according to the inventor's country of residence and filing year (Fabrizi et al., 2018). The moderation variable (environmental policy stringency) is measured using the OECD's composite Environmental Policy Stringency (EPS) index (Botta & Kozluk, 2014). This index evaluates the extent to which environmental policies impose explicit or implicit costs on environmentally harmful activities (Langinier et al., 2025). Constructed at the country level, the EPS index integrates both market-based and non-market-based policy instruments, ensuring international com-

parability. It is normalized on a scale from 0 (least stringent) to 6 (most stringent) and is based on 15 indicators primarily targeting climate change and air pollution. The index comprises two equally weighted components: a market-based sub-index, including instruments such as emission taxes (on CO₂, SO_x, NO_x, and diesel fuel), emissions trading systems, feed-in tariffs, and deposit–refund schemes; and a non-market-based sub-index, capturing regulatory standards and research and development subsidies (Martínez-Zarzoso et al., 2019). The control variable is population (POP), measured as the total population of each country and sourced from the World Bank's World Development Indicators (WDI) database.

The model is based on the Environmental Kuznets Curve (EKC), linking environmental degradation to economic development. The baseline model is specified as follows:

$$ENV_{it} = \alpha_0 + \alpha_1 GDPpc_{it} + \alpha_2 GDPpc_{it}^2 + \alpha_3 GPAT_{it} + \alpha_4 EPS_{it} + \alpha_5 GPAT_{it} \cdot EPS_{it} + \sum_{j=1}^K \lambda_j X'_{jit} + v_t + \varepsilon_{it} \quad (1)$$

where $i = 1, \dots, 25$ signifies the country and $t = 2000, \dots, 2020$ shows the year. The terms ENV_{it} denotes CO₂ emissions per capita and ecological footprint, $GDPpc_{it}$ denotes per capita Gross domestic product, $GPAT_{it}$ denotes the green innovation indicator, EPS denotes the environmental regulation indices. $GPAT \cdot EPS$ denotes the interaction between environ-

Table 1. Definition and source of variables

Variable name	Code	Description	Data sources
Dependent variables			
Carbon dioxide emissions	CO ₂	Carbon dioxide emissions in metric tons per capita	WDI
Ecological footprints	EF	Ecological footprints in gha per person	GFN
Independent variables			
Gross domestic product	GDPpc	Measured by per capita USD (2010)	WDI
Green patents	GPAT	Green patent applications at the European Patent Office (EPO), based on country of residence of the inventor(s) and application date	OECD database
Moderation variables			
Market-based instruments	MEPS	Measured by four aspects: taxes on emissions (CO ₂ , SO _x , NO _x , and diesel fuel), emissions trading systems, guaranteed purchase prices, and deposit and refund schemes	OECD database
Non-market-based instruments	NMEPS	Measured by standards and research and development subsidies	OECD Database
Environmental policy stringency index	EPS	The index is based on 15 indicators of environmental policy instruments, focusing primarily on climate and air pollution	OECD database
Control variable			
Population	POP	Total population	WDI

mental innovation and environmental policy instruments. X' is the vector of control variables, which includes population (POP). V_t represents the specific effects of each country. Finally, ε_{it} denotes the error term.

Given the economic, trade, financial, technological, environmental, and institutional interdependence among OECD countries, cross-sectional dependence (CD) and slope heterogeneity are expected. A multi-stage panel data methodology is applied to ensure robust and reliable estimates. The process begins with cross-sectional dependence (CD) using the Lagrange Multiplier (LM) test proposed by Breusch and Pagan (1980), the bias-adjusted LM (Pesaran et al., 2008), the modified LM (CDLM), and Pesaran's (2007) CD test. Slope heterogeneity was assessed using the Pesaran and Yamagata (2008) test, which evaluates the null hypothesis of slope homogeneity. Second-generation unit root tests – the Cross-Sectionally Augmented Dickey-Fuller (CADF) and Cross-Sectionally Augmented IPS (CIPS) tests (Pesaran, 2007) were applied.

The study uses System GMM as the principal estimator to correct for endogeneity and account for unobserved heterogeneity. System GMM produces consistent and efficient estimates for dynamic panel data, particularly when the number of cross-sectional units ($N = 25$) exceeds the number of time periods ($T = 20$). The method also addresses issues such as bidirectional causality, heteroskedasticity, autocorrelation, cross-sectional dependence, and instrument proliferation through first differencing and the use of an optimal weighting matrix (Arellano & Bover, 1995). Endogeneity is tackled in the model by creating an equation with the first difference where lagged values are used as instruments for the estimation (Arellano & Bond, 1991). By applying first differences to the data, Equation (1) becomes:

$$\begin{aligned}
 ENV_{it} - ENV_{it-1} &= \alpha_1 (ENV_{it-1} - ENV_{it-2}) \\
 &+ \alpha_2 (GDP_{it} - GDP_{it-1}) \\
 &+ \alpha_3 (GPAT_{it} - GPAT_{it-1}) \\
 &+ \alpha_4 (EPS_{it} - EPS_{it-1}) \\
 &+ \alpha_5 (GPAT_{it} \cdot EPS_{it} - GPAT_{it-1} \cdot EPS_{it-1}) \\
 &+ \sum_{j=1}^K \lambda_j (X'_{jit} - X'_{jit-1}) + (v_t - v_{t-1}) \\
 &+ (\varepsilon_{it} - \varepsilon_{it-1}),
 \end{aligned}
 \tag{2}$$

If the panel data show a sufficiently long-time dimension, lagged differences ($\Delta ENV_{it} = ENV_{it-1} - ENV_{it-2}$) or lagged values of the variables ENV_{it-1} and ENV_{it-2} can be used as valid instruments for the differenced equation. The other variables in the model can serve as additional instruments for the estimation. This study ensures instrument validity in the System GMM framework using AR(1) and AR(2) tests for autocorrelation and the Hansen J-test.

3. RESULTS

Before conducting the primary estimation, it is essential to examine the characteristics of the panel data. Table 2 displays the results of the cross-sectional dependence (CD). The outcomes of the CD test reject the null hypothesis of cross-sectional independence at the 1% and 5% levels, indicating that shocks in one country are likely to affect others.

Table 3 depicts the results of the slope heterogeneity test. Both the standard delta and the adjusted delta statistics are substantial and statistically significant at the 1% level. This leads to a strong rejection of the null hypothesis, indicating that the slope coefficients are not uniform across OECD countries. Given the presence of CD, second-generation unit root tests, the Cross-Sectionally Augmented Dickey-Fuller (CADF) and Cross-Sectionally Augmented IPS (CIPS) tests (Pesaran, 2007), were applied, showing that all variables are stationary either at level or after first differencing (I(0) or I(1) as shown in Table 4.

The diagnostic tests support the appropriateness of the System GMM estimator for this study. The findings are displayed in Tables 5 and 6. To verify the stability of the two-step System GMM estimates, the Arellano–Bond test shows significant first-order serial correlation (AR(1)) but no evidence of second-order serial correlation (AR(2)), meeting the required model assumptions. Furthermore, the Hansen (1982) test is not statistically significant, confirming the validity and appropriateness of the instruments used.

According to Table 5, the lagged values of CO₂ emissions and the ecological footprint are posi-

Table 2. Cross-sectional dependency tests

Variable	LM	LMadj	CDLM	CD
CO ₂ (ln)	1474*** (0.000)	142.1*** (0.000)	36.12*** (0.000)	44.46*** (0.000)
EFP(ln)	1135*** (0.000)	80.97*** (0.000)	27.06*** (0.000)	65.99*** (0.000)
GDPpc (ln)	2474*** (0.000)	205.9*** (0.000)	43.66*** (0.000)	57.88*** (0.000)
PAT(ln)	1470*** (0.000)	114.7*** (0.000)	30.84*** (0.000)	62.93*** (0.000)
MEPS	1074*** (0.000)	74.81*** (0.000)	13.62*** (0.000)	39.17*** (0.000)
NMEPS	1822*** (0.000)	150.3*** (0.000)	21.94*** (0.000)	62.13*** (0.000)
EPS	2028*** (0.000)	171.1*** (0.000)	37.76*** (0.000)	65.99*** (0.000)
Pop(ln)	2152*** (0.000)	183.5*** (0.000)	2399** (0.016)	29.39*** (0.000)

Note: *** Significance at the 1% level, ** Significance at the 5% level. Values given in parentheses denote prob values.

Table 3. Slope heterogeneity tests

Test	Delta
Slope Homogeneity	5.764***
Slope Homogeneity (Adjusted)	7.625***

Note: *** indicates a 1% significance level.

Table 4. Unit root test results

Variable	CIPS		CADF		Decision
	I(0)	I(1)	I(0)	I(1)	
CO ₂ (ln)	-1.928	-4.089***	-2.168**	-3.516***	I(0)/I(1)
EFP(ln)	-2.594***	-4.695***	-2.204**	-3.302***	I(0)/I(1)
GDPpc (ln)	-1.570	-2.873***	-1.505	-2.031*	I(1)
PAT(ln)	-3.233***	-5.061***	-2.808***	-3.805***	I(0)/I(1)
MEPS	-2.187	-4.485***	-2.074**	-3.230***	I(0)/I(1)
NMEPS	-3.568***	-5.052***	-3.490***	-4.926***	I(0)/I(1)
EPS	-2.630***	-4.718***	-2.615***	-3.771***	I(0)/I(1)
Pop(ln)	-2.352***	-1.579	-2.397***	-1.763	I(0)

Note: CIPS, CADF, I(0), and I(1) denote cross-sectionally augmented IPS, covariate-augmented Dickey-Fuller (CADF), levels, and first difference, respectively. *** for 1% significance level, ** for 5% significance level, and * for 10% significance level, respectively.

tive and statistically significant across all specifications, indicating strong persistence in environmental degradation and potential endogeneity related to past conditions and unobserved factors. These results confirm the relevance of a dynamic approach based on the System GMM estimator. Moreover, the results confirm an inverted U-shaped Environmental Kuznets Curve, where environmental degradation rises with economic growth before declining once a certain income threshold is reached. Models 1 and 4 show that green innovation significantly reduces CO₂ emis-

sions and the ecological footprint, with decreases of 0.34% and 0.33%, respectively, following a 1% increase in innovation. The results support *H1*, demonstrating that green innovation significantly reduces environmental degradation in OECD countries. Market-based environmental policy instruments exert a significant and negative effect on CO₂ emissions and the ecological footprint in OECD countries. Specifically, a one-unit increase in market-based instruments leads to a reduction of 0.6791% in CO₂ emissions and 0.0677% in the ecological footprint. Non-market environmental

policy instruments, such as technology standards and R&D subsidies, are found to have a positive and significant effect on CO₂ emissions and the ecological footprint, with coefficients of +0.045 and +0.038, respectively. The results partially support *H2*, which posits that stronger environmental regulations improve environmental quality and reduce polluting emissions in OECD countries.

Beyond their direct effects, regulatory instruments play a crucial moderating role in the relationship between green innovation and environmental degradation. Models 2 and 5 show that the interaction between market-based instruments and green innovation significantly reduces both CO₂ emissions and the ecological footprint. Moreover, these models indicate that the interaction between market-based instruments and green innovation significantly reduces both CO₂ emissions and the ecological footprint.

Specifically, a one-unit increase in the combined market instrument index and green innovation is associated with a 0.0006-unit decrease in the ecological footprint and a 0.00004-unit decrease in CO₂ emissions, demonstrating that market-based policies are particularly effective when complemented by innovation efforts. Similarly, Models 3 and 6 show that non-market instruments also have a negative moderating effect, albeit smaller: each one-unit increase in the combined non-market instrument index and green innovation corresponds to a 0.00002-unit reduction in the ecological footprint and a 0.00001-unit reduction in CO₂ emissions. Thus, regulatory or non-market measures also contribute to environmental improvements when interacting with innovation. The results confirm *H3*, which emphasizes the moderating role of regulations in the relationship between green innovation and environmental quality.

Table 5. Effects of market and non-market-based instruments on CO₂ emissions and ecological footprint

Variable	Carbon emissions (CO ₂)			Ecological Footprint (EFP)		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
CO ₂ t-1(ln)	0.3463* (0.000)	0.8855* (0.000)	0.6053* (0.000)			
EFPt-1(ln)				0.3393* (0.004)	0.5216* (0.000)	0.2314* (0.004)
GDP (ln)	2.7737* (0.002)	1.5976 (0.166)	4.6764* (0.000)	3.2620*** (0.064)	-0.8618 (0.348)	13.539* (0.000)
GDP ² (ln)	-0.1248* (0.005)	-0.0758 (0.191)	-0.2282* (0.000)	-0.1486*** (0.081)	0.0634 (0.171)	-0.6391* (0.000)
GPAT(ln)	-0.0580* (0.007)	-0.0234** (0.013)	-0.0637** (0.020)	-0.0745*** (0.094)	-0.0819** (0.012)	0.2182* (0.000)
MEPS	-0.6791* (0.021)	-0.0643* (0.000)		-0.0677*** (0.088)	-0.0517** (0.032)	
NMEPS	0.0445* (0.000)		0.02821* (0.000)	0.0380* (0.000)		0.0558* (0.000)
MEPS* GPAT		-0.00004* (0.074)			-0.0006** (0.011)	
NMEPS *GPAT			-0.00001** (0.023)			-0.00002* (0.000)
Pop(ln)	0.13822* (0.002)	-0.0089 (0.748)	0.2121* (0.001)	0.2402* (0.002)	0.2522* (0.003)	0.4457* (0.000)
Constant	13.2326** (0.016)	-13.594** (0.032)	-8.1803 (0.402)	-0.7217 (0.964)	-0.0335 (0.996)	-58.392* (0.001)
Country fixed effect included	Yes	Yes	Yes	Yes	Yes	Yes
AR (1) p-value	0.002	0.001	0.001	0.014	0.013	0.007
AR (2) p-value	0.844	0.907	0.575	0.492	0.330	0.885
Harsen test p-values	0.186	0.128	0.590	0.204	0.125	0.691

Note: ***, **, and * show statistical significance levels of 1%, 5%, and 10%, respectively.

Table 6. The aggregate policy effect on CO₂ emissions and ecological footprint

Variable	Carbon emissions (CO ₂)		Ecological Footprint (EFP)	
	Model 1	Model 2	Model 3	Model 4
CO ₂ t-1(ln)	0.8490*	0.6927*		
	(0.000)	(0.000)		
EFPt-1(ln)			0.3052*	0.3349*
			(0.000)	(0.000)
GDP (ln)	2.2987*	4.9216*	-0.0530	2.2694***
	(0.004)	(0.000)	(0.961)	(0.091)
GDP ² (ln)	-0.1103*	-0.2354*	0.0083	-0.0972
	(0.005)	(0.000)	(0.873)	(0.151)
GPAT(ln)	-0.0210***	-0.0255**	0.0347	-0.0988*
	(0.062)	(0.016)	(0.172)	(0.000)
EPSindex	-0.159**		-0.0407*	0.1224*
	(0.042)		(0.002)	(0.000)
EPSindex* GPAT		-0.00003*		-0.00002**
		(0.001)		(0.024)
Pop(ln)	0.0277	0.1620*	-0.0335	0.1269*
	(0.266)	(0.000)	(0.325)	(0.005)
Constant	-6.5920***	-16.621*	18.469*	15.018**
	(0.056)	(0.002)	(0.010)	(0.045)
Country fixed effect included	Yes	Yes	Yes	Yes
AR (1) p-value	0.001	0.004	0.014	0.016
AR (2) p-value	0.609	0.592	0.591	0.598
Harsen test p-values	0.110	0.149	0.102	0.104

Note: ***, **, and * show statistical significance levels of 1%, 5%, and 10%, respectively.

Given the contradictory direct effects of market-based (MPES) and non-market-based environmental policy stringency (NMPES), we employ the composite environmental policy stringency (EPS) index to capture their net effect on environmental quality. As reported in Table 6, the statistically significant negative effect of the environmental policy stringency (EPS) index on CO₂ emissions and the ecological footprint indicates that stronger overall environmental policies effectively mitigate environmental degradation in OECD countries, consistent with the findings of Sohag et al. (2024). Specifically, a one-unit increase in EPS leads to a reduction of 0.159% in CO₂ emissions and 0.040% in the ecological footprint. Moreover, beyond its direct effect, the environmental policy stringency (EPS) index also moderates the relationship between green innovation and environmental quality, playing a critical role in amplifying the effectiveness of green technologies in improving environmental outcomes in OECD countries. Therefore, the interaction results indicate that a one-unit increase

in EPS, in combination with green innovation, is associated with a 0.00003-unit reduction in CO₂ emissions and a 0.00002-unit reduction in the ecological footprint.

The marginal-effects analysis presented in Figures 1.1-1.6 complements and confirms the regression results by illustrating how the effectiveness of green innovation depends on the environmental regulation. It shows that the environmental benefits of green innovation increase substantially as the intensity of both market-based and non-market policy instruments rises. Under higher MEPS levels, CO₂ emissions decrease from 0.179 to -0.252 units, and the ecological footprint from 0.084 to -0.062 units. Similarly, stronger NMEPS policies lead to reductions from 0.197 to 0.0001 units for CO₂ and from 0.150 to 0.002 units for the ecological footprint. Moreover, under higher levels of overall environmental policy stringency (EPS), CO₂ emissions decrease from 0.212 to -0.071 units, while the ecological footprint decreases from 0.144 to -0.051 units.

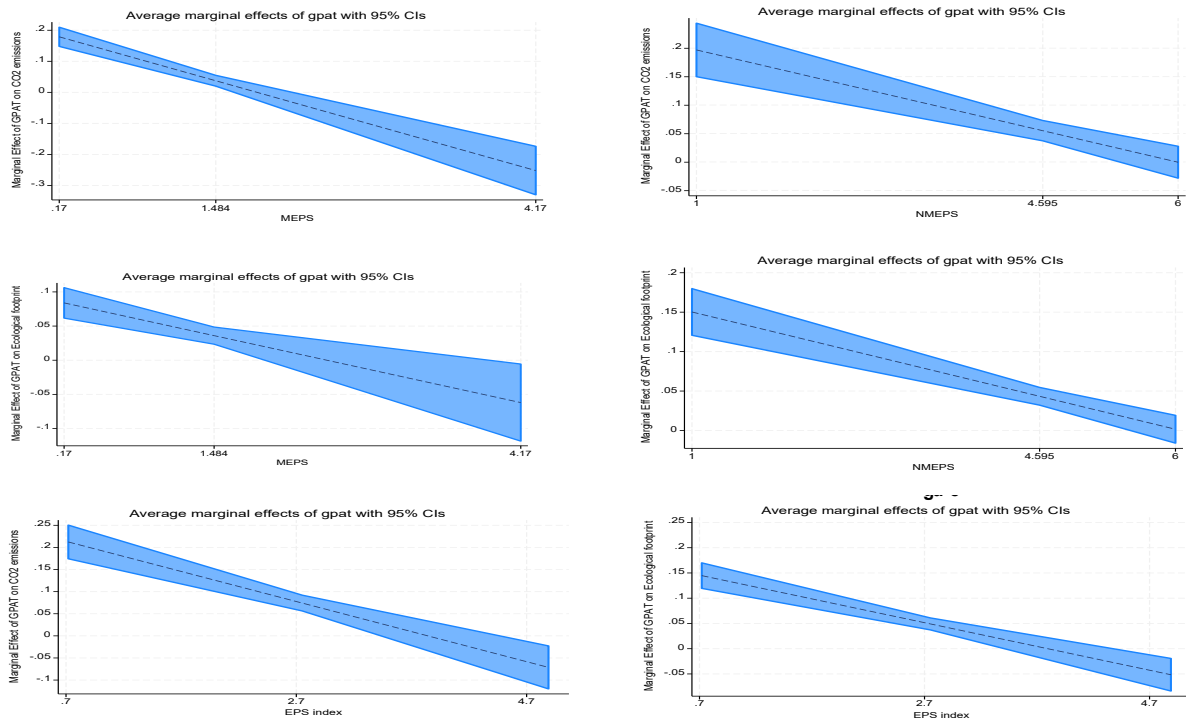


Figure 1. The marginal effects of green innovation depending on the level of market-based (MEPS) and non-market (NMEPS) environmental policy instruments as well as the aggregate environmental policy level, with 95% confidence bound

4. DISCUSSION

Drawing on the System GMM model, our results provide robust evidence that green innovation significantly mitigates environmental degradation, thereby corroborating the findings of Du et al. (2019) and Xu et al. (2021). Specifically, we find that a 1% increase in green innovation reduces CO₂ emissions by 0.34% and the ecological footprint by 0.33%, indicating a substantial elasticity of environmental improvement with respect to innovation activity. These findings highlight the pivotal role of innovation as a lever for enhancing environmental quality, particularly through the reduction of resource intensity and waste generation, which is especially relevant for OECD countries.

In this context, the analysis of environmental policy instruments highlights the pivotal role of market-based tools in reducing both CO₂ emissions and the ecological footprint, with estimated effects of -0.6791% and -0.0677%, respectively. This finding aligns with the evidence of Borowiec et al. (2024) and Liu et al. (2025), who demonstrate the effectiveness of market-based instruments in curbing CO₂ emissions from production and con-

sumption while enhancing environmental productivity. Our study also extends the conclusions of Hassan et al. (2024), who report similar outcomes in the context of OECD countries. Moreover, it is noteworthy that the disparity in intensity between the observed effects on CO₂ emissions and the ecological footprint is particularly instructive. This gap suggests that market-based instruments act more directly on emission sources tied to energy use but are less effective in addressing broader dimensions of environmental pressure. Indeed, the ecological footprint encompasses not only carbon emissions but also deforestation, land use, and the overexploitation of biological and energy resources – factors largely beyond the reach of carbon-pricing mechanisms. Beyond this convergence, our analysis further sheds light on the differentiated effectiveness of these instruments across various dimensions of environmental degradation.

In contrast, non-market environmental policy instruments are positively and statistically significantly associated with environmental degradation, with coefficients of 0.0445 for CO₂ emissions and 0.0380 for the ecological footprint. This counter-intuitive effect diverges from the general find-

ings in the existing literature, including Liu et al. (2025), but aligns with the results of Ramanathan et al. (2017), who show that overly stringent regulations can produce counterproductive outcomes by constraining firms' capacity for technological adaptation. The positive impact of non-market instruments on environmental pressure may be explained by the fact that excessively rigid regulatory measures generate undesirable effects, imposing high compliance costs that limit firms' ability to innovate and effectively adjust production processes. As a result, firms may adopt symbolic or formal compliance rather than achieve substantive emission reductions. From this perspective, our findings support Porter's narrow hypothesis that stricter market-based instruments are more conducive to improving environmental quality than command-and-control policies.

Beyond the direct effects observed, our interaction analysis allows us to explore the moderating role of environmental regulations on the relationship between green innovation and environmental quality. Extending the article of Chang et al. (2023), our results show that combining environmental policy instruments – whether market-based or non-market – with green innovation significantly enhances environmental performance, generating additional reductions in CO₂ emissions and the ecological footprint. Specifically, a one-unit increase in the interaction between market-based instruments and green innovation reduces the ecological footprint by 0.0006 units and CO₂ emissions by 0.00004 units, highlighting the amplified environmental gains when market policies are aligned with innovation efforts. Market-based instruments create price signals that penalize polluting technologies, increasing firms' operational costs while simultaneously encouraging a substantial expansion of renewable electricity production. This mechanism provides direct incentives for innovation, which in turn helps mitigate environmental externalities from productive activities and achieve sustained reductions in CO₂ emissions and ecological footprint across OECD economies. Moreover, our findings indicate that the synergy between non-market instruments and green innovation also contributes to environmental quality. A one-unit increase in this interaction reduces the ecological footprint by 0.00002 units and CO₂ emissions by 0.00001

units. These results suggest that non-market instruments, particularly environmental standards, support Porter's hypothesis only when they promote green innovation rather than imposing strict compliance. Their effectiveness, therefore, depends primarily on their capacity to stimulate learning dynamics and their flexibility in fostering knowledge creation and diffusion. In this way, these mechanisms incentivize firms to strengthen green innovation efforts, which in turn leads to more efficient energy resource management and contributes to the reduction of CO₂ emissions and ecological footprint.

Building on these findings, the environmental policy stringency (EPS) index, which aggregates both market-based and non-market instruments, allows for an assessment of their overall effect on environmental degradation. Our empirical results demonstrate that the EPS significantly reduces environmental degradation in OECD countries, showing that a one-unit increase in the index leads to a 0.159% decrease in CO₂ emissions and a 0.040% reduction in the ecological footprint. These findings are consistent with previous studies by Hassan et al. (2024) and Zhou et al. (2025), which support the argument that higher environmental policy stringency enhances environmental sustainability. Beyond this aggregate effect, a decomposition of the EPS highlights the differentiated role of instruments: market-based instruments (MEPS) appear more effective than non-market instruments (NMEPS). This suggests that the effectiveness of environmental policies depends not only on their stringency but also on their composition. These results corroborate the findings of Wei and Joo (2025), emphasizing the efficiency of market mechanisms while refining the literature on non-market instruments, showing that their effectiveness remains limited unless combined with market-based tools. In this sense, our study demonstrates that the performance of environmental policies relies primarily on the coherence of the policy mix rather than on regulatory stringency alone.

The analysis further reveals a significant moderating role of the environmental policy stringency (EPS) index in the relationship between green innovation and environmental quality. The interaction term is negative and significant:

a one-unit increase in EPS combined with green innovation results in an additional reduction of 0.00003 units in CO₂ emissions and 0.00002 units in the ecological footprint. This finding indicates that environmental regulation extends beyond a direct effect, also enhancing the environmental effectiveness of innovation. In other words, the environmental benefits of innovation are amplified when implemented within a strict and coherent regulatory framework. This result aligns with Chang et al. (2023), Sohag et al. (2024), and Zhou et al. (2025), who highlight the role of environmental policies through innovation channels, while going further by explicitly identifying a moderating effect.

Finally, the analysis of marginal effects confirms that the environmental benefits of green innovation increase with a strengthening regulatory framework. Under high levels of market-

based instruments (MEPS), CO₂ emissions shift from 0.179 to -0.252 units, and the ecological footprint from 0.084 to -0.062 units. Similarly, non-market instruments (NMEPS) reduce emissions from 0.197 to 0.0001 and the ecological footprint from 0.150 to 0.002 units, while the overall EPS leads to a decrease in emissions from 0.212 to -0.071 and the ecological footprint from 0.144 to -0.051 units. These results demonstrate that the impact of green innovation is not uniform but depends strongly on the regulatory context. They help explain the mixed findings reported in the literature, suggesting that such divergences are driven more by differences in institutional frameworks than by the intrinsic effectiveness of innovation. By explicitly accounting for these interactions, this study offers a more comprehensive understanding of the conditions under which innovation effectively enhances environmental performance.

CONCLUSION

This study set out to examine how different forms of environmental policy stringency influence the capacity of green innovation to mitigate environmental degradation in OECD countries over the period 2000–2020. It assessed whether market-based and non-market instruments condition the impact of innovation on CO₂ emissions and the ecological footprint within an integrated analytical framework.

The empirical findings show that green innovation directly improves environmental performance. Market-based instruments further reduce CO₂ emissions and the ecological footprint, while non-market instruments tend to increase them. The moderating effects of policy – captured by market-based instruments, non-market instruments, and the aggregate environmental policy stringency (EPS) index – further mitigate environmental impacts by enhancing the effectiveness of green innovation. Overall, environmental policy stringency strengthens the positive contribution of innovation when regulatory frameworks provide clear incentives and adaptive flexibility.

Several important conclusions emerge from these findings. Firstly, well-calibrated market-based mechanisms can better align economic incentives with environmental objectives, encouraging firms to internalize environmental costs and accelerate technological progress. Secondly, complementary regulatory approaches should support innovation without imposing rigid constraints that limit firms' adaptive capacity. Overall, a balanced and innovation-oriented policy mix is essential to achieve sustained reductions in emissions and ecological pressure.

Several avenues for further research remain open. Future studies could extend the analysis beyond OECD economies to assess how institutional quality and development levels shape policy-innovation dynamics. Greater sectoral disaggregation would also help identify heterogeneous effects across high-emitting industries. In addition, exploring the interaction between environmental regulation, green finance, and technological diffusion could provide deeper insight into the mechanisms that underpin the transition toward a low-carbon and resource-efficient economy.

AUTHOR CONTRIBUTIONS

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REFERENCES

- Albrizio, S., Kozluk, T., & Zipperer, V. (2017). Environmental policies and productivity growth: Evidence across industries and firms. *Journal of Environmental Economics and Management*, 81, 209–226. <https://doi.org/10.1016/j.jeem.2016.06.002>
- Arellano, M., & Bond, S. (1991). Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *The Review of Economic Studies*, 58(2), 277–297. <https://doi.org/10.2307/2297968>
- Arellano, M., & Bover, O. (1995). Another look at the instrumental variable estimation of error-components models. *Journal of Econometrics*, 68(1), 29–51. [https://doi.org/10.1016/0304-4076\(94\)01642-D](https://doi.org/10.1016/0304-4076(94)01642-D)
- Binsaeed, R. H., Khan, Z., Dogan, E., & Rahim, S. (2025). The role of energy efficiency, renewable resources, green innovation, and fiscal decentralization in sustainable development: Evidence from OECD countries. *Utilities Policy*, 95, Article 101915. <https://doi.org/10.1016/j.jup.2025.101915>
- Borowiec, J., Papież, M., & Śmiech, S. (2024). The impact of environmental regulations on carbon emissions in countries with different levels of emissions. *Environmental Science and Pollution Research*, 31(59), 66759–66779. <https://doi.org/10.1007/s11356-024-35702-8>
- Botta, E., & Kozluk, T. (2014). *Measuring environmental policy stringency in OECD countries – A composite index approach* (OECD Economics Department Working Paper, No. 1177). Paris: OECD Publishing. <https://doi.org/10.1787/5jxrjnc45gvg-en>
- Breusch, T. S., & Pagan, A. R. (1980). The Lagrange multiplier test and its applications to model specification in econometrics. *The Review of Economic Studies*, 47(1), 239–253. <https://doi.org/10.2307/2297111>
- Carrión-Flores, C. E., & Innes, R. (2010). Environmental innovation and environmental performance. *Journal of Environmental Economics and Management*, 59(1), 27–42. <https://doi.org/10.1016/j.jeem.2009.05.003>
- Chang, K., Liu, L., Luo, D., & Xing, K. (2023). The impact of green technology innovation on carbon dioxide emissions: The role of local environmental regulations. *Journal of Environmental Management*, 340, Article 117990. <https://doi.org/10.1016/j.jenvman.2023.117990>
- Cheng, C., Ren, X., Dong, K., Dong, X., & Wang, Z. (2021). How does technological innovation mitigate CO2 emissions in OECD countries? Heterogeneous analysis using panel quantile regression. *Journal of Environmental Management*, 280, Article 111818. <https://doi.org/10.1016/j.jenvman.2020.111818>
- Du, K., Cheng, Y., & Yao, X. (2021). Environmental regulation, green technology innovation, and industrial structure upgrading: The road to the green transformation of Chinese cities. *Energy Economics*, 98, Article 105247. <https://doi.org/10.1016/j.eneco.2021.105247>
- Du, K., Li, P., & Yan, Z. (2019). Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data. *Technological Forecasting and Social Change*, 146, 297–303. <https://doi.org/10.1016/j.techfore.2019.06.010>
- Fabrizi, A., Guarini, G., & Melicani, V. (2018). Green patents, regulatory policies and research network policies. *Research Policy*, 47(6), 1018–1031. <https://doi.org/10.1016/j.respol.2018.03.005>
- Ghisetti, C., & Quattraro, F. (2017). Green technologies and environmental productivity: A cross-sectoral analysis of direct and indirect effects in Italian regions. *Ecological Economics*, 132, 1–13. <https://doi.org/10.1016/j.ecolecon.2016.10.003>

15. Guo, X., Fu, L., & Sun, X. (2021). Can environmental regulations promote greenhouse gas abatement in OECD countries? Command-and-control vs. market-based policies. *Sustainability*, 13(12), Article 6913. <https://doi.org/10.3390/su13126913>
16. Hansen, L. P. (1982). Large sample properties of generalized method of moments estimators. *Econometrica: Journal of the Econometric Society*, 50(4), 1029-1054. <https://doi.org/10.2307/1912775>
17. Hassan, M., Kouzez, M., Lee, J. Y., Msolli, B., & Rjiba, H. (2024). Does increasing environmental policy stringency enhance renewable energy consumption in OECD countries? *Energy Economics*, 129, Article 107198. <https://doi.org/10.1016/j.eneco.2023.107198>
18. He, D., Ma, H., Hu, D., Wang, X., Dong, Z., & Zhu, B. (2024). Bio-char for sustainable agriculture: Improved soil carbon storage and reduced emissions on cropland. *Journal of Environmental Management*, 371, Article 123147. <https://doi.org/10.1016/j.jenvman.2024.123147>
19. Hou, S., Yu, K., & Fei, R. (2023). How does environmental regulation affect carbon productivity? The role of green technology progress and pollution transfer. *Journal of Environmental Management*, 345, Article 118587. <https://doi.org/10.1016/j.jenvman.2023.118587>
20. Ji, Z. (2020). Does factor market distortion affect industrial pollution intensity? Evidence from China. *Journal of Cleaner Production*, 267, Article 122136. <https://doi.org/10.1016/j.jclepro.2020.122136>
21. Langinier, C., Martínez-Zarzoso, I., & RayChaudhuri, A. (2025). Environmental regulations and green innovation: The role of trade and technology transfer. *Energy Economics*, 150, Article 108755. <https://doi.org/10.1016/j.eneco.2025.108755>
22. Lin, B., & Ma, R. (2022). Green technology innovations, urban innovation environment and CO2 emission reduction in China: Fresh evidence from a partially linear functional-coefficient panel model. *Technological Forecasting and Social Change*, 176, Article 121434. <https://doi.org/10.1016/j.techfore.2021.121434>
23. Liu, S., Li, S., & Liu, Y. (2025). The impacts of heterogeneous environmental regulations on atmospheric environmental total factor productivity: From an internal structural perspective. *SSRN Electronic Journal*. <http://dx.doi.org/10.2139/ssrn.5257656>
24. Lutfi, A., Alqudah, H., Alrawad, M., Alshira'h, A. F., Alshirah, M. H., Almaiah, M. A., Alsyouf, A., & Hassan, M. F. (2023). Green environmental management system to support environmental performance: What factors influence SMEs to adopt green innovations? *Sustainability*, 15(13), Article 10645. <https://doi.org/10.3390/su151310645>
25. Mahmood, N., Zhao, Y., Lou, Q., & Geng, J. (2022). Role of environmental regulations and eco-innovation in energy structure transition for green growth: Evidence from OECD. *Technological Forecasting and Social Change*, 183, Article 121890. <https://doi.org/10.1016/j.techfore.2022.121890>
26. Martínez-Zarzoso, I., Bengochea-Morancho, A., & Morales-Loge, R. (2019). Does environmental policy stringency foster innovation and productivity in OECD countries? *Energy Policy*, 134, Article 110982. <https://doi.org/10.1016/j.enpol.2019.110982>
27. Murad, S. M. W., Rahman, A., & Mohsin, A. K. M. (2025). From policy to progress: Environmental taxation to mitigate air pollution in OECD countries. *Journal of Environmental Management*, 374, Article 124143. <https://doi.org/10.1016/j.jenvman.2025.124143>
28. Peñalosa, P., & Kleine-Rueschkamp, L. (2024). *The geography of green innovation hubs in OECD regions* (OECD Local Economic and Employment Development (LEED) Papers No. 2024(09)). Paris: OECD Publishing. <https://doi.org/10.1787/c48ad2b1-en>
29. Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of Applied Econometrics*, 22(2), 265-312. <https://doi.org/10.1002/jae.951>
30. Pesaran, M. H., & Yamagata, T. (2008). Testing slope homogeneity in large panels. *Journal of Econometrics*, 142(1), 50-93. <https://doi.org/10.1016/j.jeconom.2007.05.010>
31. Pesaran, M. H., Ullah, A., & Yamagata, T. (2008). A bias-adjusted LM test of error cross-section independence. *The Econometrics Journal*, 11(1), 105-127. <https://doi.org/10.1111/j.1368-423X.2007.00227.x>
32. Porter, M. E., & van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *The Journal of Economic Perspectives*, 9(4), 97-118. <https://doi.org/10.1257/jep.9.4.97>
33. Ramanathan, R., He, Q., Black, A., Ghobadian, A., & Gallea, D. (2017). Environmental regulations, innovation and firm performance: A revisit of the Porter hypothesis? *Journal of Cleaner Production*, 155(2), 79-92. <https://doi.org/10.1016/j.jclepro.2016.08.116>
34. Rubashkina, Y., Galeotti, M., & Verdolini, E. (2015). Environmental regulation and competitiveness: Empirical evidence on the Porter Hypothesis from European manufacturing sectors. *Energy Policy*, 83, 288-300. <https://doi.org/10.1016/j.enpol.2015.02.014>
35. Shahbaz, M., Ali Nasir, M., & Roubaud, D. (2018). Environmental degradation in France: The effects of FDI, financial development, and energy innovations. *Energy Economics*, 74, 843-857. <https://doi.org/10.1016/j.eneco.2018.07.020>
36. Sohag, K., Husain, S., & Soyatas, U. (2024). Environmental policy stringency and ecological footprint linkage: Mitigation measures of renewable energy and innovation. *Energy Economics*, 136, Article 107721. <https://doi.org/10.1016/j.eneco.2024.107721>

37. Tao, M., Tiwari, A. K., Poletti, S., Roubaud, D., & Silva, E. (2025). The credibility of environmental policy stringency: Implications for sustainability in OECD countries. *Energy Economics*, 146, Article 108492. <https://doi.org/10.1016/j.eneco.2025.108492>
38. Wang, X., Chai, Y., Wu, W., & Khurshid, A. (2023). The empirical analysis of environmental regulation's spatial spillover effects on green technology innovation in China. *International Journal of Environmental Research and Public Health*, 20(2), Article 1069. <https://doi.org/10.3390/ijerph20021069>
39. Wang, Y., Shi, M., Zhao, Z., Liu, J., & Zhang, S. (2025). How does green finance improve the total factor energy efficiency? Capturing the mediating role of green management innovation and embodied technological progress. *Energy Economics*, 142, Article 108157. <https://doi.org/10.1016/j.eneco.2024.108157>
40. Wei, H., & Joo, Y. C. (2025). Comparing the dynamic impact of environmental policies on greenhouse gas emission: Evidence from OECD countries. *Journal of Environmental Management*, 394, Article 127226. <https://doi.org/10.1016/j.jenv-man.2025.127226>
41. Weina, D., Gilli, M., Mazzanti, M., & Nicolli, F. (2016). Green inventions and greenhouse gas emission dynamics: A close examination of provincial Italian data. *Environmental Economics and Policy Studies*, 18(2), 247-263. <https://doi.org/10.1007/s10018-015-0126-1>
42. Wu, T., Yang, S., & Tan, J. (2020). Impacts of government R&D subsidies on venture capital and renewable energy investment – An empirical study in China. *Resources Policy*, 68, Article 101715. <https://doi.org/10.1016/j.resour-pol.2020.101715>
43. Xu, L., Fan, M., Yang, L., & Shao, S. (2021). Heterogeneous green innovations and carbon emission performance: Evidence at China's city level. *Energy Economics*, 99, Article 105269. <https://doi.org/10.1016/j.eneco.2021.105269>
44. Zhang, J., Kang, L., Li, H., Ballesteros-Pérez, P., Skitmore, M., & Zuo, J. (2020). The impact of environmental regulations on urban green innovation efficiency: The case of Xi'an. *Sustainable Cities and Society*, 57, Article 102123. <https://doi.org/10.1016/j.scs.2020.102123>
45. Zhong, S., Xiong, Y., & Xiang, G. (2021). Environmental regulation benefits for whom? Heterogeneous effects of the intensity of environmental regulation on employment in China. *Journal of Environmental Management*, 281, Article 111877. <https://doi.org/10.1016/j.jenv-man.2020.111877>
46. Zhou, H., Pervaiz, A., Ather Bukhari, W. A., Ather Bukhari, A. A., & Sadiq, S. Z. (2025). Green technology and stringent environmental policy interactions in a spatial context: Assessing domestic and cross-border CO₂ emission reductions in border sharing OECD economies. *Journal of Environmental Management*, 391, Article 126435. <https://doi.org/10.1016/j.jenv-man.2025.126435>
47. Zhu, X., Zuo, X., & Li, H. (2021). The dual effects of heterogeneous environmental regulation on the technological innovation of Chinese steel enterprises – Based on a high dimensional fixed effects model. *Ecological Economics*, 188, Article 107113. <https://doi.org/10.1016/j.ecolecon.2021.107113>