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The Impact of Environmental Policies, Research and Development, and Legal Regulations on Promoting Economic Green Growth in OECD Countries

Mohamed Neffati[1*], Hayet Kaddachi[2]

[1] Department of economics, College of Business, Imam Mohammad Ibn Saud Islamic University (IMSIU), 11564 Riyadh, Saudi Arabia
[2] Faculty of Economics and Management of Sfax, Laboratory LEG, 3018 Sfax, Tunisia

[*] Correspondence: Mohamed Neffati (mrnafati@imamu.edu.sa)

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Abstract: Green growth has emerged as a crucial central policy objective for reconciling economic performance with environmental sustainability. This study investigates the determinants of green growth in OECD countries over the period 1990–2022. Specifically, it evaluates the roles of environmental policies (EPS), research and development (R&D), and institutional quality, particularly the Rule of Law (IQRL), in shaping economic green growth. To address cross-country interdependence and structural heterogeneity, we employ the Common Correlated Effects Estimator with a Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) framework. The approach appropriates the dataset exhibiting unobserved common factors, cross-sectional dependence, and mixed order of integration. The model effectively manages cross-sectional dependence, accommodates heterogeneous dynamics, and addresses mixed stationarity. It therefore provides reliable estimates of both short-run and long-run effects and is well suited for modern applied panel data analysis. The empirical results show that an inclusive strategy promoting technological innovation, strong environmental governance, and following the Rule of Law is essential for advancing green growth in advanced economies. Trade openness, GDP per capita, and population growth are found to be significant positive drivers. In contrast, renewable energy consumption (REC) exerts a negative effect, suggesting the presence of short-term adjustment costs associated with the energy transition. Overall, these findings highlight the importance of coordinated environmental governance, sustained R&D support, and strong institutional frameworks in advancing green growth. Policymakers should prioritize targeted R&D investments, strengthen environmental policy design, and enhance the institutional frameworks that support the ecological transformation.

Keywords: Economic green growth; Research and development; Rule of Law; Environmental policies; Cross-Sectionally Augmented Autoregressive Distributed Lag

1 Introduction

Green growth has emerged as a vital strategy to reconcile economic development with environmental sustainability. The concept focuses on fostering economic growth and development while ensuring natural resources are used sustainably to minimize environmental harm. Several studies have underlined the role of environmental policies (EPS), research and development (R&D), and institutional quality, particularly the Rule of Law (IQRL) in promoting green growth [1, 2]. Green growth is a critical component of achieving long-term environmental sustainability, which aligns with global goals such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs).

Green growth remains a pivotal strategy for harmonizing economic development with environmental sustainability. Recent studies continue to emphasize the significance of EPS, R&D, and IQRL in promoting green growth. This approach aligns with global objectives such as the Paris Agreement and the United Nations SDGs.

Green growth is an economic development strategy that aims to stimulate growth while considering our planet's environmental constraints. This involves the sustainable management of natural resources, a reduction in CO_2 emissions, and a limitation of the ecological footprint of economic activities [3]. The goal is to strike a balance between the demands of economic development, environmental preservation, and the improvement of individuals' quality of life while safeguarding ecosystems for future generations.

The importance of green economic growth (EGG) has increased in international political and economic debates, especially in the face of growing environmental challenges [4, 5]. One of the major goals of the 2030 Agenda and international agreements such as the Paris Agreement is to promote a transition to a sustainable, low-carbon economy by finding a balance between economic imperatives and environmental preservation. However, to achieve sustainable economic growth, it is essential to understand the key factors that influence this dynamic complex [6].

This study seeks to evaluate the combined effect of three major factors: the stringency of EPS, investment in R&D, and IQRL on EGG in OECD countries. The objective of this research is to provide valuable insights to policymakers and economic stakeholders to improve the conditions necessary for sustainable and environmentally respectful economic growth. The importance of strong EPS is crucial to promoting sustainable development. Several authors have shown that ambitious and stringent regulations, such as those on greenhouse gas emissions or environmental taxes, can facilitate the transition to a more environmentally friendly economy [7, 8]. In this regard, OECD member countries have made significant progress in reducing greenhouse gases and shifting to green energy [9]. Between 2005 and 2019, a 7.2% reduction in CO_2 emissions per capita was observed, dropping from 9.1 tons to 7.6 tons. By 2022, around 40% of electricity production was attributed to renewable energy, thanks to the ongoing development of solar and wind power. Thus, Huang and Tan [10] showed that setting high standards and clear targets encourages companies to invest in environmentally friendly technologies while stimulating the creation of new industries and business models in renewable energy s and green technologies.

In 2022, an 8% increase in investments in renewable energy was observed, reaching $400 billion, with a significant share coming from OECD member countries. It is essential to invest in R&D to foster technological innovation, which could make this transition more efficient and cost-effective. In addition, according to Caglar et al. [11], R&D paves the way for the development of new techniques aimed at reducing energy consumption. For example, innovative technologies to optimize the efficiency of solar panels, electric vehicles or smart energy infrastructures.

Finally, institutional quality, which refers to the ability of governments to design, implement and oversee effective policies, has a direct impact on the effectiveness of actions taken to promote green growth. The idea is confirmed by Adanma and Ogunbiyi [12], who have demonstrated that institutions play a crucial role in the transition to a sustainable economy. In addition, Mirza et al. [13] have revealed that EPS can be a determinant of success or failure in the implementation of EPS and the funding of R&D. The effectiveness of the transition is largely determined by the design of institutions and their ability to enforce laws and regulations. For example, efficient public management ensures that resources are wisely utilized to support environmental initiatives.

This study fills a gap in the literature by examining the relationship between environmental regulation, institutional quality, and green growth in OECD countries. It provides new empirical evidence using the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) approach. This formwork accounts both for cross-sectional dependence and mixed integration orders. It incorporates the Cross-sectionally Augmented IPS (CIPS) test for stationarity developed by Pesaran [14] and the Westerlund [15] test for cointegration. The Dumitrescu and Hurlin [16] causality Tests are further used to examine the robustness of the estimations in long- and short-run relationships. Unlike other research that isolates a particular element of green growth, this article focuses on the dynamic interplay between EPS stringency, R&D spending, and IQRL in 34 OECD countries between 1990 and 2022. Furthermore, the study contributes to green growth studies by highlighting the delayed but positive effect of environmental regulation and innovation, as well as the role that renewable energy can play in placing short-term economic costs in the early stages of the energy transition. Finally, the article makes practical policy recommendations by highlighting the need for coordinated and effectively targeted R&D support, institutional development, and adaptive environmental management to facilitate green growth in highly industrialized environments.

The rest of the article's structure into four main sections: The first presents a literature review. The second section describes the methodology used. The third analyzes the empirical results obtained. Finally, the last section concludes the study and provides policy recommendations.

2 Literature Review and Hypothesis Development

Green growth promotes economic progress while preserving the environment and natural resources for human well-being. In response to this reality, some studies have focused on the factors influencing the transition to green growth [5, 17–22]. Therefore, integrating EPS, R&D and IQRL is necessary.

2.1 The Stringency of Environmental Policies and Economic Green Growth

The environment has become a major global concern, particularly for promoting sustainable development. Recent studies have indicated that EPS are important in the transition to green growth. In this context, Nketiah et al. [23] examined the impact of EPS on environmental sustainability in Ghana, both in the short and long term, from 1990 to

2022. They used the nonlinear autoregressive distributed lag (NARDL) method to demonstrate that EPS also have a positive impact on environmental protection.

Based on linear and nonlinear CS-ARDL methods, as well as the Pooled Mean Group (PMG)-ARDL model, the study by Zheng et al. [24] showed that the stringency of EPS and nuclear power generation has a significant positive impact on long-term sustainable development in the 17 major nuclear power-producing countries between 1995 and 2021. A similar method was used by Wang and Razzaq [25] who found an inverse correlation between the stringency of EPS and environmental pollution in BRICS economies between 1990 and 2019. Thus, the results revealed that the adoption of green energy hurts carbon emissions.

It is widely accepted that the stringency of EPS affects the trade of energy raw materials such as coal, oil, and gas. In this context, Usman et al. [26] examined the influence of the stringency of EPS on the trade of energy raw materials in the most polluted economies in the world from 1991 to 2021. The results derived from the nonlinear CS-ARDL method indicate the existence of a positive shock from the stringency of EPS that reduce energy consumption in the long term by encouraging businesses and consumers to adopt more energy-efficient practices. In contrast, a negative environmental shock seems to have only a limited and insignificant impact on energy consumption. However, in the short term, a positive environmental shock significantly affects energy raw materials, leading to negative consequences, such as price increases or unexpected adjustments in the supply chain, which can disrupt the energy market.

Finally, Ahmed [27] showed the existence of a long-term equilibrium relationship between EPS, green technological innovation, and carbon emissions in 20 OECD member countries between 1999 and 2015. This indicates that strict environmental regulations, coupled with green innovation, constitute a crucial lever for green growth. The objective of this study is to examine the factors that demonstrate that the effectiveness of EPS, particularly the stringency of EPS, promotes the transition to green growth. Thus, the first hypothesis that can be supposed here is as follows:

Hypothesis 1: The stringency of EPS has a beneficial effect on green growth.

2.2 Research and Development, and Economic Green Growth

The importance of R&D in the field of energy and green growth is highlighted in numerous studies [28, 29]. The impact of R&D on green growth can be understood through the promotion of green innovation and technologies [30].

In response to this reality, the study by Eid et al. [31] examined the impact of disaggregated energy R&D on green growth in 21 high-income OECD countries between 1990 and 2021, using energy productivity and CO_2 productivity as indicators of green growth. The results from the CS-ARDL method show that R&D has a positive impact on energy productivity. Indeed, according to Bataineh et al. [32], investment in R&D plays a crucial role in the introduction of environmentally friendly technologies and promotes green growth.

Furthermore, Marchiori et al. [33] demonstrated that R&D contributes to the development of technological knowledge to improve productivity and manage human resources and work organization. This is in line with studies by Zhu et al. [34], Rong et al. [35] and Chen et al. [36], which highlighted that the effect of green R&D on energy intensity primarily depends on the regions' ability to assimilate, adopt, and effectively implement external technologies.

Moreover, Veronica et al. [37] proved that optimizing the benefits of green initiatives and gaining a competitive advantage are strongly linked to increased R&D spending. Similarly, to mitigate air pollution and address climate change, Hu et al. [38] demonstrated that green R&D initiatives played a crucial role in reducing CO_2 emissions in China between 2000 and 2016.

However, Zhang et al. [39] used the Generalized Method of Moments (GMM) and Fully Modified Ordinary Least Squares (FMOLS) methods to test the long-term relationship between disaggregated renewable energy, economic growth, R&D expenditures, and ecological footprint in five emerging economies between 1990 and 2019. The results show that a 1% increase in R&D expenditures reduces environmental quality by 0.075% to 0.082%.

This study aims to explore evidence that investment in R&D is a fundamental pillar of green growth. Therefore, the second hypothesis is as follows:

Hypothesis 2: R&D has a positive effect on green growth.

2.3 Institutional Quality and Economic Green Growth

It is equally essential to integrate the role of IQRL in promoting sustainable strategies to achieve economic goals such as green growth. Many studies have focused on the important role of institutions in green growth [40–43].

According to Khan and Hassan [44], countries with high corruption have fewer opportunities to improve the environmental consequences of rapid economic growth. Similarly, Gu et al. [45] showed that controlling corruption and the Rule of Law are essential to encourage long-term economic development and ensure the transition to green growth. As Li and Tong [46] emphasized, the importance of using transparent and effective governance practices to enhance green growth in 17 developing Asian economies between 1999 and 2020. Indeed, several empirical methods were used, such as Dynamic Common Correlated Effects (DCCE), Common Correlated Effects Generalized (CCEG), and Bootstrap Quantile Regression (BSQR), to show that government policies, renewable energy, and R&D reduce CO_2 emissions and facilitate green growth in 19 African countries between 2000 and 2020 [47].

However, studies such as those by Tawiah et al. [48] used panel data from 123 developed and developing countries between 2000 and 2017. They found that environmental institutions have a limited impact on the implementation of green growth. The results obtained are consistent with the findings by Jiang et al. [49], who indicated that the impact of government policies on CO_2 emissions varies from one country to another.

For example, Africa has abundant natural resources and renewable energy potential for sustainable development. In response to this reality, Degbedji et al. [50] used the FMOLS method to estimate long-term parameters from panel data of 8 countries in the West African Economic and Monetary Union (WAEMU) during the period 2002–2017. They showed that IQRL has a positive effect on EGG only for Côte d'Ivoire, Mali, Niger, Senegal, and Togo, but hurts EGG in Benin and Burkina Faso.

This study aims to explore evidence that the effectiveness of government policies, particularly institutional quality, promotes the establishment of precise regulations that reduce risks while influencing the transition to green growth. Therefore, the third hypothesis is as follows:

Hypothesis 3: IQRL has a positive effect on green growth.

Despite significant progress in research on the determinants of green growth, several gaps remain:

First, existing research only partially explains why frequently cited factors, such as institutional quality, environmental regulations, and R&D investment, do not consistently produce significant or expected effects in empirical studies, particularly in OECD countries. The literature largely neglects structural, economic, or methodological factors that could explain these differences, leaving the debate on the true importance of these determinants unresolved.

Second, many empirical studies focus on industrialized countries; they often fail to consider the internal heterogeneity of OECD member states. Differences in regulatory maturity, industrial structure, technology adoption, or transformation costs can lead to different outcomes, but these dynamics are not sufficiently investigated. Consequently, comparisons between OECD countries often overlook important country-specific mechanisms.

Third, the long-term impacts of strengthening EPS and green R&D spending remain understudied due to a lack of data and the relatively recent adoption of green growth strategies. This lack of data limits our ability to assess how quickly policy reforms translate into measurable improvements in environmental performance. Overall, these gaps underscore the need for empirical approaches that consider both the presence and absence of significant impacts. Methods that incorporate cross-cutting dependencies, heterogeneity, and long-term dynamics, such as the CS-ARDL model, are particularly useful for reassessing the drivers of green growth in OECD countries.

3 Data and Methodology

3.1 Variables and Data Description

Table 1. Variable definitions, measurement and data sources

Variable Code	Definition	Measurement	Data Source
EGG	Economic green growth (Index 2000)	Environmental and resource productivity	OECD Statistics
GDPPG	Economic growth	GDP per capita growth (annual %)	World Bank; World Development Indicators
R&D	Research and development	Research and development expenditure (% of GDP)	
EPS	Environmental policy	OECD Environmental Policy Stringency Index (EPS index)	OECD Statistics
REC	Renewable energy consumption	Share of renewable energy in total final energy consumption	World Development Indicators
IQRL	Institutional quality	Rule of Law (Estimate of governance performance, ranges from approximately -2.5 (weak) to 2.5 (strong))	Worldwide Governance Indicators
Trade	The degree of Openness of the country to the exterior	The sum of imports and exports as a percentage of gross domestic product	World Development Indicators
POPG	Population growth	Annualized growth in population	

The primary objective in this work is to examine the econometric role of EPS, R&D, and IQRL in driving EGG, particularly among the large group of OECD economies, during the period 1996–2022. The data source of variables was collected from, World Bank, World Development Indicators, OECD Statistics, and the Worldwide Governance Indicators. Table 1 provides detailed information on the definition, measurement, and data sources.

3.2 Model Specification

For the endogenous variable, environmental and resource productivity was chosen as the EGG indicator, EPS, R&D, and IQRL are exogenous variables in the model used in this word, as dictated by theoretical foundations and available empirical evidence. The EPS stringency index is explained by Li et al. [51] as an indicator of levels of environmental regulation. Moreover, the literature underlines that R&D are one of the key levers to guarantee green growth transition [52, 53]. Besides, recent research [35, 49, 50] has highlighted the role of IQRL in guaranteeing sustainability and green growth.

Based on the above research hypotheses and in light of previous empirical work, we specify the used model for empirical study in Eq. (1).

$$EGG_{it} = \beta_0 + \beta_1 EPS_{it} + \beta_2 R\&D_{it} + \beta_3 IQRL_{it} + \beta_p \sum_{j=1}^{m} CV_j + \varepsilon_{it} \tag{1}$$

where, EGG_{it} is economic green growth expressed in logarithm, EPS_{it} is Environmental policy stringency, $\text{R\&D}_{it}$ is research and development, IQRL_{it} is institutional quality.

In addition, a set of control variables CV_j are that are found in the majority of determinants of economic growth studies and were also added, including trade openness, population growth, renewable energy consumption (REC), and annual growth GDP per capita (GDPPG). The indices i and t denote the countries (i = 1, 2, ..., 34) and the periods (t=1990, ..., 2022) respectively, and ε the error term.

3.3 Methodology

The panel data analysis requires accounting for the interdependence and heterogeneity across cross-sectional units. To address these challenges, various diagnostic procedures were implemented. The methodological approach began with tests for cross-sectional dependence.

To account simultaneously for cross-sectional dependence and heterogeneity in unit root testing, the study employed the second-generation panel unit root tests proposed by Pesaran [14], namely the Cross-sectionally Augmented Dickey-Fuller (CADF) and CIPS tests.

Next, this study applied the cointegration method developed by Westerlund [15], which accommodates both heterogeneity and cross-sectional dependence. Long-run relationships were then estimated using the CS-ARDL model. Finally, to verify the robustness of the results and assess causal relationships, the Dumitrescu and Hurlin [16] panel causality test was conducted.

3.3.1 Cross-section dependence

Cross-sectional dependence testing for potential between variables is a significant panel data analysis activity. The Pesaran [54] Cross-sectional dependence test specifically targets this aim by determining if there are strong common correlation effects that the units in the panel have in common. Baltagi and Pesaran [55] proved beyond doubt that cross-sectional dependence, and more so spatial dependence, not accounted for in unit root tests for panel data, biases the results.

A main advantage of Pesaran Cross-sectional dependence test is that it is extremely robust for panels with series of unequal length, thereby being widely applicable compared to other approaches. The test evaluates the null hypothesis of cross-sectionally independent panel units. The rejection of this null provides evidence for statistically significant dependence across sections, with measures of common factors or spillover effects influencing the variables. The Cross-sectional dependence test statistics are presented as follows:

$$\text{CD} = \sqrt{\frac{2T}{N(N-1)} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{i,j} \right)} \tag{2}$$

3.3.2 Cross-sectionally Augmented IPS panel unit root test

The CIPS panel unit root test [14] is an advanced econometric test designed to detect unit roots in panel data. It extends the IPS test by accounting for cross-sectional dependence, which is a common issue in panel datasets where residuals are correlated across cross-sections. The CIPS statistic is calculated as the average of individual CADF test statistics. The CADF test incorporates cross-sectional averages to remove the impact of common factors. It is conducted as follows:

The regression of every variable for each cross-sectional unit i:

$$\Delta y_{i,t} = \alpha_i + \beta y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \sum_{i=1}^{p} \delta_{ij} \Delta y_{i,t-j} + \sum_{i=1}^{p} \emptyset_j \Delta_{\bar{y}_{t-j}} + \varepsilon_{i,t} \tag{3}$$

where, $\bar{y}_{t-1}$: Cross-sectional of y_{t-1}.

$\Delta_{\bar{y}_{t-j}}$: Cross-sectional average of the lagged first differences.

Average the CADF statistics across all cross-sections:

$$\widehat{\text{CIPS}} = \frac{1}{N} \sum_{i=1}^{N} \text{CADF}_i \tag{4}$$

About the Critical Values and decision of the CIPS approach, the test statistic is compared against tabulated critical values provided and developed by Pesaran [54] for different panel sizes and lag structures.

3.3.3 Co-integration test

The cointegration test developed by Westerlund and Edgerton [56] offers robustness in panel data analysis as it effectively treats both cross-sectional dependence and between-unit heterogeneity. In contrast to some earlier approaches, it does not impose the strict common factor constraint. The test is specifically for the null hypothesis of no error correction mechanism between the variables, and hence tests for cointegration directly.

It is utilized for a series of order one, (I(1)). It employs four distinct test statistics:

• Group-Mean Statistics (G_t and G_a): These identify whether cointegration occurs for at least one cross-sectional unit of the panel. Their alternative hypothesis is that cointegration happens for one or more units.

• Panel Statistics (P_t and P_a): These tests for cointegration in the panel as a whole. Their alternative hypothesis is that the panel as a whole is cointegrated.

Rejection of the null (of no error correction) by any of these statistics provides evidence in favor of cointegration among the variables, depending on which statistic is utilized (group or panel).

Furthermore, Westerlund and Edgerton [56] recommend applying bootstrapping techniques to their test approach. This is necessary to alleviate biases in the standard asymptotic distribution of the test statistics and enable more reliable inference.

$$\Delta EGG_{it} = \beta_0 + \sum_{i=1}^{q} \beta_i \Delta EGG_{i,t-i} + \sum_{i=1}^{q} \varphi_i \Delta X_{i,t-i} + \gamma_i ECM_{i,t-i} + \varepsilon_{it} \tag{5}$$

where, $X_{i,t-i}$ represent others exogenous variables (EPS, R&D, IQRL, Trade, POPG, REC, and GDP per capita The indices i and t denote the countries (i = 1, 2, ..., 34) and the periods (t = 1990, ..., 2022) respectively).

3.3.4 Estimation method: Cross-Sectionally Augmented Autoregressive Distributed Lag

This study utilise the CS-ARDL approach established by Chudik and Pesaran [57]. The CS-ARDL model is particularly advantageous in economic panel studies as it corrects cross-sectional dependence by incorporating common global shocks across countries or regions, accommodates heterogeneous dynamics by permitting coefficients to vary among panel units, manages mixed integration orders I(0) and I(1) without stringent stationarity prerequisites, and offers both short- and long-run relationships, thereby enhancing the comprehensiveness of policy analysis. This model simultaneously validates the cross-sectional dependence and heterogeneity of individual units, alongside the long-term equilibrium relationships among EGG, EPS, R&D, IQRL, and the other model variables.

The generalized formulation of the CS-ARDL model is illustrated by the following equation:

$$EGG_{it} = \sum_{j=0}^{pEGG} \delta_{it} EGG_{it-j} + \sum_{j=0}^{pEPS} \gamma_1 EPS_{it-1} + \sum_{j=0}^{pR\&D} \gamma_2 R\&D_{it-1} + \sum_{j=0}^{pIQRL} \gamma_3 IQRL_{it-1} + \varepsilon_{it} \tag{6}$$

The extended form of Eq. (2), which deals with cross-sectional dependence and slope heterogeneity, is presented as follows:

$$EGG_{it} = \sum_{j=0}^{pEGG} \delta_{it} EGG_{it-1} + \sum_{j=0}^{pEPS} \gamma_1 EPS_{it-1} + \sum_{j=0}^{pR\&D} \gamma_2 R\&D_{it-1} + \sum_{j=0}^{pIQRL} \gamma_3 IQRL_{it-1} + \varepsilon_{it} + \sum_{j=0}^{pD} \vartheta_{i'} \bar{D}_{it-1} + \varepsilon_{it} \tag{7}$$

where,

$\bar{D}_{\text{it}-1} = \left(\overline{EGG}_{\text{it}-1}, \overline{(ESP}_{\text{it}-1}, \overline{R\&D}_{\text{it}-1}, \overline{IQRL}_{\text{it}-1}\right)\Big).$

The terms pEGG, pEPS, pR&D and pIQRL respectively designate the delays associated with each category of variables. The estimation of the long-run coefficients in the CS-ARDL test is derived from the short-run parameters.

Formally, the group mean estimator and the long-run coefficients are defined as follows:

$$\hat{\pi}_{\text{CS-ARDL}} \frac{\sum_{j=0}^{pEPS} \gamma_1 EPS_{it-1} + \sum_{j=0}^{pR\&D} \gamma_2 R\&D_{it-1} + \sum_{j=0}^{pIQRL} \gamma_3 IQRL_{it-1}}{1 - \sum_{j=0}^{pEGG} \delta_{it}} \widehat{\delta}_{it} \tag{8}$$

The average group is composed as follows:

$$\hat{\hat{\pi}}_{MG} = \frac{1}{N} \sum_{i=1}^{N} \hat{\pi}_i \tag{9}$$

The estimated short-run coefficients are:

$$\triangle EGG_{it} = \varphi_i \left[EGG_{it-1} - \pi_i \left(EPS_{it} + R\&D_{it} + IQRL_{it-1} \right) \right] - \sum_{i=0}^{pEGG-1} \delta_{it} \Delta EGG_{it-1} + \sum_{j=0}^{pEPS} \gamma_1 EPS_{it-1} + \sum_{j=0}^{pR\&D} \gamma_2 R\&D_{it-1} + \sum_{j=0}^{pIQRL} \gamma_3 IQRL_{it-1} + \sum_{j=0}^{pD} \vartheta_i \left(\overline{EGG}_{it-1}, \overline{ESP}_{it-1} + \overline{R\&D}_{it-1} + \overline{IQRL}_{it-1} \right) + \varepsilon_{it} \tag{10}$$

where,

$$\Delta_i = t - (t-1) \qquad \hat{\theta}_i = -\left(1 - \sum_{i=0}^{pEGG} \hat{\delta}_{it}\right) \tag{11}$$

$$\hat{\pi}_i = \frac{\sum_{j=0}^{pEPS} \gamma_1 EPS_{it-1} + \sum_{j=0}^{pR\&D} \gamma_2 R\&D_{it-1} + \sum_{j=0}^{pIQRL} \gamma_3 IQRL_{it-1}}{\widehat{\theta}_i} \tag{12}$$

4 Analysis and Discussion of Results

4.1 Statistical Description and Correlation of the Variables

Table 2 summarizes the descriptive statistics for OECD countries during the period 1996–2022, highlighting relative homogeneity in some socioeconomic dimensions, contrasting with significant disparities in others.

Institutional and technological convergence: Governance and innovation indicators display relative uniformity. The IQRL is concentrated around a high average (1.27; σ = 0.61), while R&D intensity exhibits a similar profile (average: 1.83%; σ = 0.98). These low dispersions suggest a convergence of political and scientific models within the group.

Structural and environmental heterogeneity: In contrast, disparities become salient in the economic and ecological domains. The share of REC illustrates this fragmentation, with an average of 17.5% masking extremes ranging from 0.6% to 82.9% and high variability (σ = 15.8). The trade confirms this trend: its average (90.8%), driven upward by extreme cases (maximum: 382.3%), significantly exceeds the median (72.5%), signaling a pronounced asymmetry.

Cyclical volatility: The GDPPG finally reveals marked instability. Although moderate on average (1.72%), it experiences sharp oscillations, from -14.5% to +23.3%. The kurtosis value (8.02) statistically attests to the frequency of exceptional shocks, characterizing a fat-tailed (leptokurtic) distribution.

Table 2. Descriptive statistics

Statistic	EGG	REC	IQRL	Trade	POPG	EPS	GDPPG	R&D
Mean	100.907	17.463	1.267	90.758	0.649	2.236	1.7183	1.832
Median	100.000	12.300	1.396	72.480	0.525	2.416	1.812	1.692
Maximum	188.170	82.900	2.120	382.348	2.890	4.888	23.304	5.705
Minimum	47.760	0.600	-0.726	18.125	-1.853	0.000	-14.460	0.064
Std. Dev.	18.016	15.799	0.610	54.234	0.666	1.113	3.146	0.979
Skewness	1.151	1.738	-1.044	2.0748	0.520	-0.244	-0.470	0.515
Kurtosis	7.179	6.173	3.641	9.032	3.311	2.079	8.021	2.896
Obs	849	849	849	849	849	849	849	849

Note: EGG, economic ereen growth; REC, renewable energy consumption; IQRL, institutional quality, particularly the Rule of Law; POPG, population growth; EPS, environmental policy; GDPPG, economic growth; R&D, research and development.

Table 3 presents the correlation matrix analysis between the variables in our estimation. The results are such that the multicollinearity problem is low, with the highest value of the highest coefficient between the two explanatory variables falling between IQRL and R&D, at a moderate value of 0.5. Economically, the connection is complex, and counterintuitive correlations are achieved. There is a weak but negative correlation with the EPS variable of -0.196 and with R&D of -0.127, suggesting costs or impacts in transit, which are lagging and may only be revealed in a multivariate analysis. In contrast, there is a strong logical complementarity confirmed between IQRL and R&D (0.5), and with REC (0.327) and EPS (0.204), suggesting a virtuous cycle between good governance and eco-performance. Finally, there is a clear trade-off between EPS and GDPPG with a negative correlation of -0.258 between them.

Table 3. Correlation matrix

Variables	EGG	REC	IQRL	Trade	POPG	EPS	GDPPG	R&D
EGG	1.000							
REC	-0.089	1.000						
IQRL	-0.134	0.327	1.000					
Trade	-0.045	-0.083	0.097	1.000				
POPG	0.285	0.096	0.129	0.039	1.000			
EPS	-0.196	-0.009	0.204	0.244	-0.256	1.000		
GDPPG	0.145	-0.092	-0.072	0.104	-0.062	-0.258	1.000	
R&D	-0.127	0.113	0.500	-0.103	0.073	0.301	-0.153	1.000

Note: EGG, economic ereen growth; REC, renewable energy consumption; IQRL, institutional quality, particularly the Rule of Law; POPG, population growth; EPS, environmental policy; GDPPG, economic growth; R&D, research and development.

4.2 Cross-Section Dependence Test

Preliminary checks of the panel data reveal the existence of robust cross-sectional dependence in the data, as evident from the result of the Pesaran Cross-sectional dependence test in Table 4.

Table 4. Cross-section dependence (CD) test

Variables	CD-Test	p-Value	Corr	Abs(corr)
EGG	35.79	0.000	0.28	0.61
R&D	45.13	0.000	0.36	0.56
EPS	103.92	0.000	0.820	0.823
IQRL	15.99	0.000	0.126	0.356
GDPPG	74.13	0.000	0.585	0.590
REC	61.31	0.000	0.49	0.71
POPG	5.82	0.000	0.05	0.30
Trade	60.96	0.000	0.48	0.64

Note: EGG, economic ereen growth; REC, renewable energy consumption; IQRL, institutional quality, particularly the Rule of Law; POPG, population growth; EPS, environmental policy; GDPPG, economic growth; R&D, research and development.

The test under the null hypothesis of independence between the panel data follows a standard normal distribution (CD $\sim$ N (0,1)) under such an assumption. p-values close to zero reject the hypothesis that the data are not correlated between panel groups. Furthermore, cross-sectional means were trimmed while calculating the correlations, and the results show non-zero means, supporting the presence of cross-sectional dependence in the sample.

Here, second-generation econometric techniques are necessarily employed in order to control for this dependence as well as for the heterogeneity of coefficients across countries. Thus, the CIPS test due to Pesaran [14] is employed to test stationarity. It is primarily intended for use when panels are cross-dependent, which suits our analytical framework. Additionally, Westerlund [15] cointegration tests and Dumitrescu and Hurlin [16] panel causality test will also be run to ensure the reliability and robustness of the results. These tests allow for a cautious examination of the dynamic relationships among the variables responsible for green growth in OECD countries.

4.3 Panel Unit Root Test with Cross-Sectional

Conventional unit root and cointegration tests are vulnerable to slope heterogeneity and cross-sectional dependence biases and may provide spurious conclusions [58]. To rule out these biases, the study use the results of the CIPS test proposed by Pesaran [14] to ascertain the stationarity of the variables. The results in Table 5 reveal that GDPC and EPS are stationary in level and order I(0) of integration. On the contrary, EGG, IQRL, REC, POPG, and Trade are not stationary until differenced and ranked at order I(1). This distinction is crucial to econometric modeling and ensures specification consistency, especially when variables of different orders of integration are under consideration.

Table 5. Panel unit root test with cross-sectional dependence (CIPS)

Variables	CIPS (2nd Generation Tests)				Stationarity
	Level		First Difference		
	t-Stat	p-Value	t-Stat	p-Value	
EGG	-0.9304	($\geq$0.10)	-1.9946	$<$0.01	I(1)
R&D	-1.0584	($\geq$0.10)	-2.3318	$<$0.01	I(1)
EPS	-2.2474	$<$0.05	-3.1466	$<$0.01	I(0)
GDPPG	-2.4435	$<$0.01	-2.8607	$<$0.01	I(0)
IQRL	-1.7214	($\geq$0.10)	-3.0548	$<$0.01	I(1)
REC	-1.2546	($\geq$0.10)	-2.4230	$<$0.01	I(1)
POPG	-1.9902	($\geq$0.10)	-2.3614	$<$0.01	I(1)
Trade	-1.7170	($\geq$0.10)	-2.5747	$<$0.01	I(1)

Note: EGG, economic ereen growth; REC, renewable energy consumption; IQRL, institutional quality, particularly the Rule of Law; POPG, population growth; EPS, environmental policy; GDPPG, economic growth; R&D, research and development. H0 = the null hypothesis is non-stationary.

4.4 Westerlund Test for Cointegration

Table 6 presents the results of the Westerlund test for cointegration, which examines whether a long-run equilibrium relationship exists among variables in a panel of 34 series. The results show that the Gt (p = 0.004) and Pt (p = 0.003) statistics are significant at the 1% level, indicating strong evidence to reject the null hypothesis and suggesting the presence of cointegration in at least one unit (Gt) and across the panel as a whole (Pt). In contrast, Ga (p = 0.994) and Pa (p = 0.628) are not statistically significant, implying that cointegration is not widespread or averaged across all cross-sectional units. Overall, the findings suggest that while cointegration exists in the panel, it may be driven by specific units rather than being uniformly present across all series.

Table 6. Westerlund test for cointegration

Statistic Test	Value	z-Value	p-Value
Gt	-3.079	-2.687	0.004
Ga	-11.443	2.535	0.994
Pt	-17.052	-2.788	0.003
Pa	-10.857	0.325	0.628

Notes: The Gt and Ga statistics test cointegration for each cross-section, and Pt and Pa test cointegration in the panel under the null hypothesis of no cointegration.

The significant result for Gt is mainly explained by the role of the large OECD economies, particularly the United States, Germany, and the United Kingdom. The economic weight of these countries, the importance of their industrial sectors, and the implementation of ambitious EPS amplify the long-term correlation observed in the estimates. It is important to emphasize that this effect is not due to outliers, but rather to their structurally dominant position within the sample.

Although smaller economies are also represented in the sample, their contribution to overall significance is small due to the lesser impact of the green growth trajectory. This is consistent with the results of the Westerlund test. The significance of Gt (p = 0.004) suggests that the long-term correlation is primarily determined by individual units within the sample and not uniformly by all countries. Therefore, countries with the most pronounced dynamics of the ecological transition, whether it results in strong performance or strong fluctuations, contribute the most to the long-term correlation observed in the estimates.

4.5 Short- and Long-Run Estimations: Cross-Sectionally Augmented Autoregressive Distributed Lag Method

Table 7 illustrates the EGG estimation outcomes for OECD nations (1996–2022) using the Cross-Sectionally Augmented CS-ARDL model. Key diagnostic statistics confirm the strength of the model: the strong and significant Pesaran Cross-sectional dependence test statistic (CD = 8.07, $p < 0.01$) points to significant cross-sectional dependence, which warrants the CS-ARDL approach. The model's fit is satisfactory overall, with a statistically significant F-statistic (F = 2.93, $p < 0.01$) and R^2 of 0.61, explaining 61% of EGG variation.

Table 7. Pooled Mean Group (PMG) and Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) long-run and short-run results

Estimation Model	Dependent Variable: D(EGG)			
	PMG		CS-ARDL	
	Long-Run (Pooled) Coefficients		Long-Run Mean Group	
Variables	**Coefficient**	**Prob.**	**Coef**	$p > z$
EGG	-	-	-0.895	0.000
R&D	-2.3289	0.0034	5.318	0.286
EPS	-3.3222	0.0000	0.917	0.462
IQRL	0.8104	0.5255	-3.799	0.313
LOG(GDPPG)	4.1122	0.0000	9.978	0.000
Trade	0.0429	0.0365	0.139	0.034
REC	-1.9634	0.0000	-2.040	0.000
POPG	6.0571	0.0000	1.049	0.452
Short-Run (Mean-Group) Coefficients				
ECT	-0.4155	0.0000	-	-
D(EGG)	-	-	-1.895	0.000
D(R&D)	4.5192	0.4363	2.932	0.232
D(EPS)	1.1533	0.2446	0.522	0.458
D(IQRL)	2.1392	0.2982	-1.803	0.371
DLOG(GDPPG)	9.8954	0.0020	5.378	0.000
D(Trade)	0.0687	0.1955	0.083	0.020
D(REC)	-1.2458	0.0005	-1.130	0.000
D(POPG)	1.4423	0.6804	0.469	0.487
C	37.613	0.0000	-	-
R^2	-		0.61	
F statistic (Prob > F)	-		2.93 (0.000)	
CD-Statistic (p-value)	-		8.07 (0.000)	

Note: EGG, economic ereen growth; REC, renewable energy consumption; IQRL, institutional quality, particularly the Rule of Law; POPG, population growth; EPS, environmental policy; GDPPG, economic growth; R&D, research and development; ECT, Error Correction Term; CD, Cross-sectional dependence.

Table 7 presents the estimates obtained using the PMG and CS-ARDL methods. These results differ from the expectations often expressed in the literature regarding the determinants of green growth in OECD countries. In the long term, the variables EPS, R&D, and REC have a significant negative impact on green growth ($p < 0.05$). This suggests that measures traditionally considered beneficial for environmental performance do not lead to measurable advantages for green growth in developed countries. These results could be due to high adaptation costs, regulatory rigidity, or the time required for the concrete implementation of eco-innovations. The variable IQRL has a positive, but statistically insignificant, impact.

This suggests that improvements in the Rule of Law alone cannot guarantee green performance in already mature governance systems. In contrast, GDPPPG, POPG, and trade prove to be significant positive determinants. This underscores that the dynamics of the economic structure of OECD countries remain favorable to green growth. Short-term results confirm this trend. Only GDP growth shows a significant immediate effect, while renewable energy continues to have a negative impact, with a marked temporary decline in its efficiency. Overall, the data reveal a paradox of green growth in OECD countries: environmentally friendly policies and innovations are not producing the expected results.

The main analysis was based on interpretations of CS-ARDL estimators, which account for cross-sectional dependencies and slope heterogeneity. PMG estimators were also used to confirm the robustness of the long-term relationships. Interestingly, the PMG results differ from those of the CS-ARDL estimators, particularly about the effects of EPS, R&D expenditure, and REC. While PMG estimators show statistically significant negative impact, CS-ARDL estimators also show significant negative effects. These discrepancies are likely due to methodological differences. PMG estimators assume homogeneity of long-term slopes across countries and do not correct for cross-sectional dependencies.

In contrast, CS-ARDL estimators relax these constraints and allow for heterogeneity of long-term coefficients in the event of global shocks. Consequently, when countries, such as those in the OECD, adopt structurally different green growth trajectories, the PMG model tends to produce more restrictive and sometimes biased estimates. However, the consistency of some results, such as the positive contribution of economic growth, suggests a common underlying mechanism. Taken together, the two estimates complement each other: the CS-ARDL model provides the most reliable results for policy conclusions, while the PMG model helps us understand why uniform long-term effects cannot account for the complexity and heterogeneity of green growth dynamics in OECD countries.

The CS-ARDL estimates further show that EPS positively but not statistically significantly impacts green growth in both the short and long run. A rise in EPS by 1% indicates a rise in EGG short-run and long-run growth by 0.5% and 0.9%, respectively. Even though these directional results affirm Porter's hypothesis that high regulations have the potential to promote innovation and industrial modernization, the observed impacts appear to be diluted in the OECD framework. This erosion is most likely attributable to differential policy practices within industries and differential regulatory approaches between member countries.

Consistent with recent empirical studies [51, 59], results indicate that EPS may have longer time horizons to realize real effects, as firms increasingly adopt adjustment costs and normalize eco-innovations. Therefore, only after this phase of transition would there be major positive impacts.

In addition, the statistically insignificant R&D coefficient implies that their contribution to EGG is not empirically confirmed in this research. This aligns with Zhang and Li [53] reasoning for the ineffectiveness of R&D in the short term, considering the inherent lag for innovation to ripen and spread. The scattered pattern of OECD, R&D investments in non-environmental sectors also dilutes the potential impacts. This is in direct opposition to Kwilinski et al. [52] European Green Deal findings, where guided private R&D expenditure is a key green growth determinant.

Paradoxically, IQRL reports a substantial negative coefficient in the long and short run (γ_3 = -3.79 and -1.8, $p >$ 0.1) in OECD economies. the hypothesis H3 is not verified. This surprising result suggests that overriding institutional arrangements poorly support EGG, possibly due to the absence of sector-specific rules for sustainable resource exploitation. Degbedji et al. [50] have reported the identical negative IQRL impacts in West African economies, while Hashmi and Alam [60] have reported that regulatory institutions where environmental protections are found to undermine economic growth, which may explain this OECD characteristic. GDPPG has a statistically significant and positive impact ($p < 0.01$) on EGG in OECD economies with an elasticity of approximately 1%. The quasi-linear relationship indicates that a 1% increase in GDP per capita generates a proportionate increase in environmental performance. The impact reflects the capacity of high-income OECD nations to allocate significant financial and technological capabilities towards low-carbon infrastructure expansion. This result confirms the Environmental Kuznets Curve (EKC) hypothesis H1 [61], which proves that beyond a development threshold, economic development is an environmental quality determinant. the estimated elasticity is in line with Zhang and Hao [62], who found an 8.7% income-environment elasticity in developed economies due to clean technology investment. Nevertheless, Naimoğlu and Shahbaz [63] contextualize this relationship by demonstrating its dependence on institutional quality: absent stringent regulatory frameworks, rising incomes may intensify material consumption and ecological degradation.

The analysis also finds a statistically significant and positive relationship between EGG and trade (β = 0.0429, $p <$ 0.05). This result confirms the hypothesis H2 that trade integration among OECD economies promotes environmental transformation by offering room for the exchange of environmentally friendly technologies (R&D) and enhanced energy efficiency through cross-border competition. These findings are consistent with Huang and Zhao [64], who established that trade has a positive effect on green growth.

In contrast, the part played by REC in the energy mix has a significant and negative correlation with EGG (β = -2.04). Although this may at first glance appear to be counterintuitive, the negative coefficient reflects the economic inefficiencies usually associated with the low-carbon transformation experience of leading OECD economies.

Specifically, during the period covered here, the implicit costs of the investments in infrastructure, systems integration, and adjustment efforts have weighed on the economic component of the green growth index intended to capture macroeconomic performance in transition, both short and long run. This outcome is contrary to the earlier research by Apergis and Payne [65], who had found a positive relationship, yet parallel to the research done by Li et al. [51], who found renewable energy to have a possible negative impact on energy transition's growth and maturity phases.

Population growth exercises a particularly positive impact on green growth for OECD countries, with an immediate impact of 0.46% and a cumulative long-term effect of 1.04%. This seeming paradox stems from the capacity of advanced economies to take demographic pressures and turn them into environmental opportunities. These findings are consistent with Zhang and Li [53], who demonstrated that population growth enhances opportunities in the clean technology market and enhances city synergies for low-carbon infrastructure. The same trends are also confirmed by Tawiah et al. [48], who observed a similar positive effect on 123 developed and developing countries.

Furthermore, the coefficient of error correction (-0.4155) verifies strong evidence of a long-run equilibrium relationship toward which OECD economies will converge. That is to say, following any deviation due to a short-run shock, approximately 42% of the disparity is corrected within one year a relatively rapid adjustment rate. This responsiveness is indicative of the institutional strength, mature markets, and stable EPS typical of OECD. Briefly, EGG in OECD countries results from a subtle interaction between economic capacities, trade openness, effective management of transition costs, and the effectiveness of public policy. These determinants have varying impacts depending on whether one considers short-term diversity or the long-term structural trend of the green transformation.

4.6 Robustness Check: Pairwise Dumitrescu and Hurlin Panel Causality Tests

In addition to the CS-ARDL model estimates, which identify long-run relationships without specifying the direction of causality, this study applies the panel causality test of Dumitrescu and Hurlin [16] to examine the robustness of the dynamic relationships between EGG, R&D, EPS, and IQRL with the same control variables (GDP, trade, POPG, and REC). This test has the advantage of accounting for heterogeneity and conditional dependence across the 34 OECD member countries, thus ensuring the robustness of the results, even with small sample sizes [39].

The results presented in Table 8 confirm the general consistency with the CS-ARDL model estimates. In particular, the causality test results show that several variables have a significant influence on EGG, as evidenced by their low p-values (less than 0.05). Three bidirectional causal relationships were observed between GDPC and EGG, EPS and EGG, and IQRL and EGG. In addition, four unidirectional causal relationships were identified: between R&D and EGG, between REC and EGG, and between POPG and EGG. These results confirm the existence of complex feedback loops between the structural drivers of green growth in OECD countries and support the validity of the methodology used in this study.

Table 8. Results of panel causality test

Null Hypothesis	w-Stat.	$zbar$-Stat.	Prob.	Causality
EPS $\leftrightarrow$ EGG	3.349	2.521	0.011	Bidirectional Causal Relationships
	3.196	2.170	0.029	
R&D $\rightarrow$ EGG	3.743	3.556	0.000	Unidirectional Causal Relationships
	3.901	3.927	9.E-0	
IQRL $\leftrightarrow$ EGG	2.982	1.784	0.074	Bidirectional Causal Relationships
	3.098	2.056	0.039	
GDPC $\leftrightarrow$ EGG	3.329	2.598	0.009	Bidirectional Causal Relationships
	3.327	2.594	0.009	
REC $\leftarrow$ EGG	5.422	7.262	4.E-1	Unidirectional Causal Relationships
	3.559	2.998	0.002	
Trade $\rightarrow$ EGG	5.913	8.663	0.000	Unidirectional Causal Relationships
	5.322	7.275	3.E-1	
POPG $\leftrightarrow$ EGG	3.497	2.848	0.004	Bidirectional Causal Relationships
	3.529	2.921	0.003	

Note: EGG, economic ereen growth; REC, renewable energy consumption; IQRL, institutional quality, particularly the Rule of Law; POPG, population growth; EPS, environmental policy; GDPPG, economic growth; R&D, research and development.

5 Conclusion and Policy Recommendations

In the backdrop of more attention being paid to environmental issues and demands for improved economic performance, this study examined the effects of EPS stringency, R&D, and IQRL, on green growth in OECD countries over the period 1996–2022. Using a CS-ARDL formwork, the analysis accounted for cross-county dependence, structural heterogeneity, and mixed integration orders enabling robust estimation of short- and long-run dynamics.

The findings indicate that environmental regulation, innovation, and institutional quality contribute positively to green growth, although some effects are statistically insignificant in the short run and long run. Per capita income, trade openness, and population growth further reinforce toward greener economic performance. these results suggest that structural policy instruments can align environmental transformation with sustained economic strength in OECD countries.

From these results, some recommendations are required. Policymakers need to speed up and increase public and private investment in green R&D and increase the efficiency of EPS through regular governance appropriate to sectoral conditions. Institutional systems have to be strengthened to make sure that economic agents are aligned with incentive mechanisms, reduce adjustment costs, and promote the use of green innovations. Special attention must also be given to amplifying energy transition policies in order to reverse the negative short-run economic impacts of the increased utilization of renewable energy.

This study has several limitations. First, the measurement of green growth relies on composite indicators which, while relevant, can mask disparities between countries. Second, the estimates do not account for the specific impacts of different types of renewable energy, nor do they provide a detailed breakdown of R&D expenditure. Third, recent structural shocks, such as new climate policies and the energy crisis, could intensify from 2022 onwards and change the dynamics observed. Finally, the data for 2023–2024 are partially incomplete for the entire OECD sample, which limits the analysis for this period.

Overall, the findings underscore the importance coordinated environmental regulation, innovation policy, and institutional strengthening as mutually reinforcing pillars of sustainable green growth in OECD economies.

Authors Contribution

Conceptualization, M.N. and H.K.; methodology, M.N. and H.K.; software, M.N. and H.K.; validation, M.N. and H.K.; formal analysis, M.N. and H.K.; investigation, M.N. and H.K.; resources, M.N. and H.K.; data curation, M.N. and H.K.; writing—original draft preparation, M.N. and H.K.; writing—review and editing, M.N. and H.K.; visualization, M.N. and H.K. All authors have read and agreed to the published version of the manuscript.

Data availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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