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POLİCY MİX İN THE TRANSİTİON TO RENEWABLE ENERGY: ENERGY TAXES, FİNANCİAL DEVELOPMENT, AND GREEN INNOVATİON

O PACOTE DE POLÍTICAS NA TRANSIÇÃO PARA AS ENERGIA RENOVÁVEIS: IMPOSTOS SOBRE A ENERGIA, DESENVOLVIMENTO FINANCEIRO E INOVAÇÃO VERDE

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Abstract
This study examines the effects of green innovation, energy taxes, and financial development on renewable energy consumption in selected OECD countries. The analysis is based on a panel dataset covering the period 2002–2021 and consisting of nine countries with high levels of renewable energy consumption. In the study, second-generation panel data methods are employed, taking into account cross-sectional dependence and coefficient heterogeneity. In this context, cross-sectional dependence and homogeneity tests are first conducted, followed by the Fourier KPSS unit root test to examine the stationarity properties of the series. The existence of a long-run relationship is analyzed using the LM Bootstrap and the Westerlund and Edgerton (2008) panel cointegration tests. In the final stage, long-run coefficients are estimated using the Common Correlated Effects (CCE) and Dynamic Common Correlated Effects (DCCE) estimators. The findings reveal the existence of a long-run cointegration relationship among the variables. It is determined that the effect of green innovation on renewable energy consumption varies across countries, while financial development is significant only in certain countries. In contrast, energy taxes are found to have a negative impact on renewable energy consumption both across the panel and in some individual countries. This result indicates that the effectiveness of energy taxes and their policy design should be reconsidered. Overall, the findings suggest that renewable energy policies should be designed within a holistic framework that takes into account country-specific dynamics.

Keywords: Renewable Energy Consumption. Green İnnovation. Energy Taxes. Financial Development. Panel Data Analysis. Cross-

Resumo
Este estudo examina os efeitos da inovação verde, dos impostos sobre a energia e do desenvolvimento financeiro sobre o consumo de energia renovável em países selecionados da OCDE. A análise baseia-se em um conjunto de dados de painel que abrange o período de 2002 a 2021 e inclui nove países com altos níveis de consumo de energia renovável. No estudo, são empregados métodos de dados de painel de segunda geração, levando em consideração a dependência transversal e a heterogeneidade dos coeficientes. Nesse contexto, são realizados primeiro testes de dependência transversal e homogeneidade, seguidos pelo teste de raiz unitária de Fourier KPSS para examinar as propriedades de estacionariedade das séries. A existência de uma relação de longo prazo é analisada utilizando os testes de cointegração de painel LM Bootstrap e Westerlund e Edgerton (2008). Na etapa final, os coeficientes de longo prazo são estimados utilizando os estimadores de Efeitos Comuns Correlacionados (CCE) e Efeitos Comuns Correlacionados Dinâmicos (DCCE) .Os resultados revelam a existência de uma relação de cointegração de longo prazo entre as variáveis. Verifica-se que o efeito da inovação verde sobre o consumo de energia renovável varia entre os países, enquanto o desenvolvimento financeiro é significativo apenas em determinados países. Em contrapartida, constata-se que os impostos sobre a energia têm um impacto negativo sobre o consumo de energia renovável tanto no painel como em alguns países individualmente. Este resultado indica que a eficácia dos impostos sobre a energia e a sua concepção política devem ser reconsideradas. De modo geral, os resultados sugerem que as políticas de energia renovável devem ser concebidas dentro de um

Sectional Dependence. OECD Countries. Second-Generation Econometric Methods.

quadro holístico que leve em conta as dinâmicas específicas de cada país.

Palavras-chave: *Consumo de Energia Renovável. Inovação Verde. Impostos sobre a Energia. Desenvolvimento Financeiro. Análise de Dados de Painel. Dependência Transversal. Países da OCDE. Métodos Econométricos de Segunda Geração.*

1 INTRODUCTİON

Today, global warming and climate change are recognized as among the most critical global challenges threatening environmental, economic, and social balances. In this context, reducing carbon emissions and achieving a sustainable energy transition have become priority issues in both academic research and international policy agendas. Considering the adverse environmental impacts of fossil fuels, the shift toward renewable energy sources not only supports environmental sustainability but also holds strategic importance for economic growth, energy security, and social welfare.

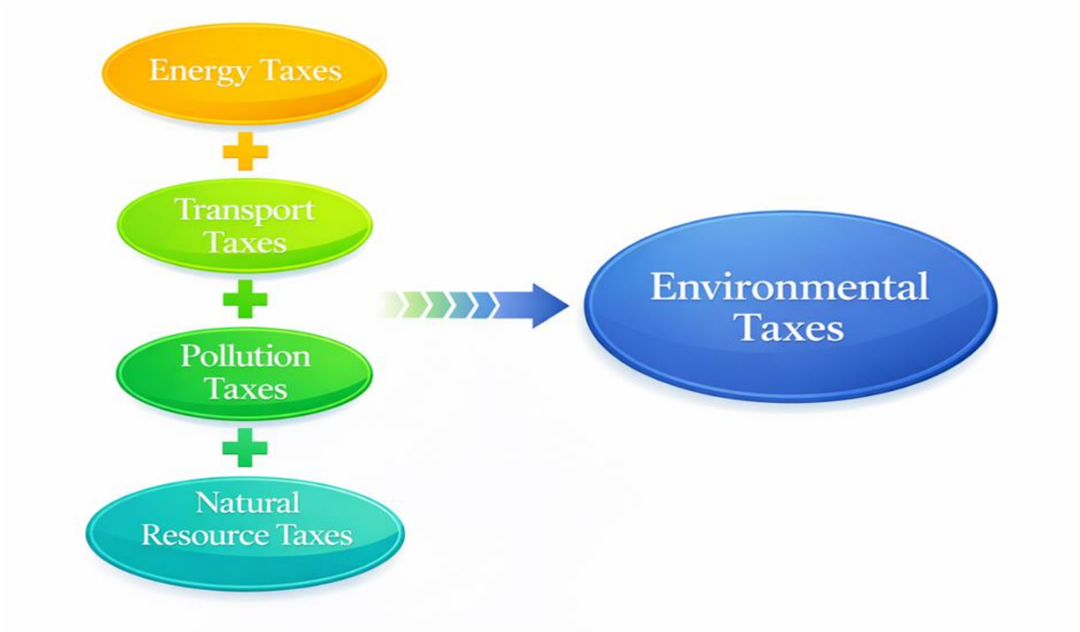
International initiatives such as the Paris Agreement and the United Nations Climate Change Conferences (COP) aim to accelerate the energy transition and establish a common roadmap for combating climate change. The critical role of renewable energy investments in reducing carbon emissions and their key function in achieving Sustainable Development Goal 7 (SDG 7) have made the transition from fossil fuels to renewable energy a strategic approach at the core of contemporary energy policies (Aydın & Erdem, 2024; Kahouli, 2018). However, although total renewable energy consumption increased by approximately one-quarter during the 2010–2019 period, the share of renewable energy sources in total final energy consumption remains at only 17.7%. This indicates that the current pace of progress is insufficient to achieve Sustainable Development Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action) by 2030.

Fossil fuels are among the primary causes of global warming and environmental degradation. Their use leads to increased CO_2 emissions and other greenhouse gases. To facilitate the transition to climate neutrality and sustainable development, countries employ various tax policy instruments. Among these, environmental taxes are one of the most important. As a fiscal policy tool, environmental taxes influence resource consumption and emission levels by increasing the prices of products that have adverse environmental impacts. The main objective of these taxes is to internalize environmental externalities and restructure market prices in a way that promotes environmental efficiency, economic productivity, and lower energy intensity (Özmen & Mutascu, 2023; Doğan *et al*., 2023).

This effect can be observed in changes in consumer behavior due to higher prices of goods and services associated with pollution, as well as in a growing tendency to purchase cleaner energy sources. In addition, environmental taxes can generate government revenue, contributing to the mitigation of environmental problems and supporting taxpayers in increasing production in line with social or economic objectives (Doğan *et al*., 2023). According to the Eurostat methodology, environmental taxes are classified into four categories: energy taxes, transport taxes, pollution taxes, and resource taxes.

Figure 1

Enviromental Taxes Classification



Reference : Bozatlı vd 2026

Within environmental taxes, energy taxes— including carbon dioxide taxes— account for the largest share. Transport taxes stand out as the second most widely used mechanism among environmental policy instruments. Although the transport sector contributes significantly to air pollution through various emissions, energy-based taxes appear to be more predominantly implemented in the fight against climate change. Nevertheless, as energy transition processes accelerate, transport taxes are also expected to assume an increasingly strategic role. In this context, these two types of taxes are more widely and effectively used in practice compared to other environmental policy instruments (Özmen & Mutascu, 2023; Aydın & Bozatlı, 2023).

Energy taxes play a critical role in addressing market failures and steering both producers and consumers toward cleaner and more efficient energy alternatives by increasing the cost of carbon-intensive energy sources. In this regard, energy taxes emerge as a guiding policy instrument in the transition to sustainable energy systems. Empirical studies also support the positive effects of energy taxes on environmental performance. Khastar *et al*. (2020) find that carbon taxes significantly reduce CO_2 emissions, while other studies show that well-designed environmental tax policies promote green innovation and improve energy efficiency (Aydın & Bozatlı, 2023). Furthermore, it is emphasized that when combined with green financing instruments and regulatory policies, energy taxes can further accelerate the energy transition.

Although many countries have developed policies to promote the use of renewable energy, the relatively higher costs of these energy sources compared to conventional fossil fuels, along with the need for intensive technological transformation, continue to pose significant barriers to their widespread adoption (Eren *et al*., 2019).

In this context, the advancement of green innovation plays a critical role in expanding renewable energy capacity and ensuring the long-term, sustainable growth of the global economy. Indeed, the increasing shift toward green technologies contributes to reducing the production and usage costs of renewable energy, thereby accelerating their diffusion, supporting the fight against climate change, and strengthening the achievement of sustainable development goals (Akhtaruzzaman *et al*., 2025).

Another important factor considered to influence renewable energy in this study is financial development. Financial development refers to the diversification of financial instruments and institutions, as well as the more widespread and efficient use of these instruments within the economy. This process affects renewable energy production through several channels. First, developed financial markets facilitate the transformation of savings into investments, thereby contributing to both the expansion of domestic investment and the increase in foreign direct investment inflows. Increased capital mobility, in turn, accelerates the transfer of new technologies and the diffusion of technical knowledge, enhancing countries' productive capacity and competitiveness. This situation supports economic and industrial growth while also leading to an increase in energy demand (Islam *et al*., 2013). In order to meet this rising energy demand in a sustainable manner, renewable energy sources emerge as a critical alternative.

Financial development encourages the use of environmentally friendly energy sources by reducing the financing costs of renewable energy investments and improving the investment environment. Furthermore, the deepening of the financial system not only increases direct investments but also supports green innovation activities. Developed financial markets accelerate the development of clean technologies by facilitating access to R&D investments and ensure their widespread adoption in the energy sector. In this context, green innovation emerges as a crucial transmission channel in the relationship between financial development and renewable energy consumption (Shabaz *et al*., 2021; Yıldız *et al*., 2026). On the other hand, energy imports based on fossil fuels cause significant foreign exchange outflows, especially in developing countries. Increasing the use of renewable energy and strengthening green innovation processes reduces energy import dependence, resulting in foreign exchange savings. These savings are channeled into financial markets, increasing market depth and diversity, thus further reinforcing financial development. This demonstrates a bidirectional and mutually reinforcing relationship between financial development, green innovation, and renewable energy (Shabaz *et al*., 2021).

This study offers three fundamental contributions to the literature. First, it analyzes the determinants of renewable energy consumption from a holistic perspective by considering green innovation, energy taxes, and financial development together within the same model framework. In this respect, it transcends the fragmented approach found in the literature. Second, it produces methodologically stronger and more reliable results by using second-generation panel data methods (Fourier KPSS, LM Bootstrap, Westerlund & Edgerton cointegration tests, CCE and DCCE estimators) that take into account cross-sectional dependence, coefficient heterogeneity, and structural breaks. Third, by examining the long-term relationships between these three key variables in the case of OECD countries, it presents important findings regarding the importance of policy interactions in the energy transition process. Overall, this study makes significant contributions to the literature at both theoretical and empirical levels by demonstrating that the renewable energy transition is shaped not only by individual policy instruments but also through the interactions between green innovation, the financial system, and energy taxes.

2 ENERGY TAX- REN

A large part of the literature confirms the Pigoian expectation that energy taxes (especially carbon taxes) increase renewable energy consumption. Zhang *et al*. (2022) found that strict environmental policies encouraged green innovation in geothermal, hydroelectric, and marine energy, but the same effect was not observed for wind and solar energy. They also found that increased innovation capacity and the level of environmental pressure strengthened the impact of strict environmental policies on green innovation in renewable energy. Shahzad *et al*. (2021), in a study covering the period 1994–2018 and examining 29 OECD countries, analyzed the effects of environmental taxes, environmental technology, and economic growth on renewable energy consumption using a panel cointegration approach. The findings reveal that these variables significantly and positively affect renewable energy use. Peng *et al*. (2022) analyzed the effects of environmental taxes, environmental technology, and economic growth on REC in G-7 countries between 1994 and 2018. Analysis findings show that environmental taxes, environmental technology, and economic growth positively influence REC. Hassan *et al*. (2024), in their study investigating whether environmental policies increase renewable energy consumption in OECD countries, used annual data from 32 OECD countries for the period 1990-2019 and applied both dynamic and static analysis. They found that stricter environmental policies can encourage renewable energy. The study showed that both market-based and non-market environmental policies and technical support policies positively influence green energy use. Aydın and Bozatlı (2023) demonstrate that environmental taxes encourage renewable energy consumption in the long term, and negative shocks in environmental taxes significantly and strongly affect renewable energy consumption in the long term.

3 GREEN İNNOVATİON AND REN

The relationship between green innovation and renewable energy is receiving increasing attention in the sustainable development literature. Green innovation refers to the development of new products, processes, and technologies that reduce environmental impacts and increase resource efficiency, while renewable energy constitutes one of the fundamental components of the transition to a low-carbon economic structure by reducing dependence on fossil fuels. In this context, the effects of green innovation on renewable energy production and consumption have been the focus of both theoretical and empirical studies in recent years. The current literature reveals that green innovation is a significant driving force in increasing renewable energy capacity and ensuring more efficient use of these resources. In particular, technological advancements reduce the cost of renewable energy production, increasing the competitiveness of these energy types and accelerating their adoption. Similarly, Cheng *et al*. (2021) emphasize that green innovation supports the transition to renewable energy by increasing energy efficiency and thus contributes to the reduction of carbon emissions. Akhtaruzzaman *et al*. (2025) stated that technological innovations increase renewable energy production and that government support is important for the development of green energy innovation. Johnstone *et al*. (2010), in their analysis covering 25 OECD countries during the period 1978–2003, examined the effectiveness of five different renewable energy support policies. Their findings revealed that environmental regulations generally encourage innovation activities, but the impact of policy instruments differs depending on the type of technology used. Zhang and Razzaq (2022), based on a panel data analysis of 33 countries covering the period 1990–2015, found that strict environmental policies encourage green innovation in renewable energy technologies, and this effect is stronger in OECD countries and high-income countries. More specifically, non-market and strict environmental policies increase the number of patents related to renewable energy production. The findings also revealed that strict environmental policies support green innovation in geothermal, hydroelectric, and marine energy. Cheng *et al*. (2021) stated that there is a negative relationship between green innovation and carbon emissions, and that green innovation directs the economy towards renewable and cleaner energy sources and increases EQ.

On the other hand, some studies suggest that the effects of green innovation may vary from country to country. In particular, in developed countries, the impact of green innovation on renewable energy becomes more pronounced thanks to strong institutional structures, financial development, and R&D investments, while in developing countries, financing constraints and technological infrastructure deficiencies may cause this effect to remain limited. In addition, the strictness of environmental policies implemented in countries can also negatively affect green innovation towards renewable energy technologies under certain conditions. The fact that renewable energy sources are generally associated with higher costs compared to traditional fossil fuels constitutes a significant obstacle to widespread adoption in this field. One of the main reasons for this cost difference is that the relevant technologies are not yet sufficiently mature. In addition, environmental regulations create additional burdens on firms, causing productive resources such as capital and skilled labor to be directed towards pollution reduction activities. Firms that have to comply with strict environmental policies face high compliance costs; This situation can lead to a diversion of resources away from R&D and innovative activities in renewable energy technologies, weakening green innovation incentives (Yu and Zhang, 2022). This shows that the effectiveness of green innovation depends not only on technological capacity but also on institutional and economic factors.

4 FINANSAL DEVELOPMENT – REN

Financial development is a key factor supporting the financing of renewable energy projects by facilitating access to capital (Zhang and Razzaq, 2022). Improved financial systems can encourage green energy investments through the deepening of credit markets, lower costs of capital, and improved risk distribution mechanisms (Al Mamun *et al*., 2018). Numerous studies in the literature demonstrate that financial development has a positive impact on renewable energy consumption. Brunnschweiler (2010), in a panel of non-OECD countries, confirmed that the development of the financial sector has a significant and positive impact on the amount of renewable energy production. Samour *et al*. (2022) state that financial development increases renewable energy investments. Similarly, Mahalik *et al*. (2017) emphasize that financial development accelerates the energy transition. Zhang and Razzaq (2022) found that financial development, environmental regulations, and the informal economy support renewable energy sources. Eren *et al*. (2019) examined the effects of financial development and economic growth on renewable energy consumption in the case of India. The study's findings reveal the existence of a long-term cointegration relationship between financial development, renewable energy consumption, and economic growth variables. Furthermore, it was determined that both economic growth and financial development have statistically significant and positive effects on renewable energy consumption. However, the causality analysis results show a unidirectional causal relationship from financial development to renewable energy consumption. Athari (2024), in their study considering the role of financial development, technological innovations, and economic growth, aimed to analyze the effects of economic openness and financial stability on renewable energy. The empirical findings reveal that economic openness and financial stability significantly and positively influence renewable energy use, thus indicating that increases in these factors contribute to achieving environmental sustainability. While financial development and technological innovations were found to play a significant and supportive role in increasing renewable energy consumption, economic growth was found to have a statistically significant but negative effect on renewable energy. Liu (2023) examines the dynamic effects of renewable energy investments, financial structure, and environmental regulations on the transition to renewable energy. The findings reveal that green energy investments, financial development, and the rigidity of environmental policies promote sustainable energy transition in the long term. Shahbaz *et al*. (2021) demonstrate a long-term relationship between renewable energy consumption and financial development. They also show that financial development increases demand for renewable energy, thus stimulating consumption in this area, and that green finance instruments (green bonds, sustainable loans, etc.) further strengthen the relationship between financial development and renewable energy. However, some studies also show that financial development does not always lead to positive environmental outcomes. Renewable energy is a very costly investment due to its need for both high-tech infrastructure and a financially developed national economy (Sims *et al*., 2003). Therefore, it can support fossil fuel-based investments in the initial stages, which can increase carbon emissions (Tamasian and Rao, 2010). In this context, the environmental impact of financial development varies depending on the country's institutional structure, regulatory framework, and energy policies (Tamasian and Rao, 2010). Saadaoui (2022), in his study examining the role of institutional factors and financial development in the transition to renewable energy in the MENA region during the 1990-2018 period, found that global financial development did not have a significant long-term impact on the transition process. Le *et al*. (2020), in their study, showed that the positive impact of financial development on renewable energy consumption was statistically significant for high-income countries, while this effect was insignificant in low- and middle-income countries. They also stated that investments in renewable energy require not only financing but also the existence of advanced financial structures that can effectively manage the complex risks specific to emerging technologies. Kim and Park (2016) found that in countries with advanced financial markets, the renewable energy sector grows faster due to easier access to external financing, and consequently, they are relatively more dependent on debt and equity financing. They found that renewable energy sectors exhibited disproportionately higher growth performance in countries with developed financial markets.

5 DATA AND MODEL

This study aims to examine the effects of green innovation, energy taxes, and financial development on renewable energy consumption. For this purpose, a sample of nine OECD countries with the highest levels of renewable energy consumption—subject to data availability—has been selected, covering the period from 2002 to 2021. Accordingly, the following model is specified:

$$lnRENW_{it} = \beta_0 + \beta_1 lnGRIN_{it} + \beta_2 FD_{it} + \beta_3 ETAX_{it} + \varepsilon_{it} \quad (1)$$

In the model, *i* denotes the country, *t* represents time, and ε_{it} is the error term. The coefficients β_0, β_1, β_2, and β_3 correspond to the constant term and the coefficients of *lngrin*, *fd*, and *etax*, respectively. The variables *renw* and *grin* are used in logarithmic form.

Renewable energy consumption (lnRENW) is measured as the percentage of total final energy consumption and is obtained from the World Bank database. Green innovation (lnGRIN) is proxied by patents on environmental technologies (% of all technologies). Data for green innovation and energy tax (ETAX), measured as a % of GDP, are sourced from the OECD database. Finally, financial development (FD) is represented by an index obtained from the IMF database. The descriptive statistics of the variables are provided in Table 1. There are 180 observations (20 years and 9 countries) in total. Since the calculated VIF values are less than 5, there is no multicollinearity problem.

Table 1

Descriptive Statistics

Variables	Mean	Maximum	Minimum	Std. Dev.	VIF
RENW	39.42111	82.90000	11.90000	16.93953	
GRIN	12.93486	27.12053	0.968188	5.094339	1.032
FD	0.633770	0.811824	0.405015	0.091959	1.531
ETAX	1.538851	2.858342	0.629429	0.481395	1.516

6 METHODOLOGY

The empirical analysis of the study consists of four main stages. In panel data analysis, it is essential to first examine CSD and the homogeneity of slope coefficients. To this end, the CSD properties of both the model and the variables are tested using the CDLM1 test of Breusch and Pagan (1980), the CDLM2 test, and Pesaran's CD test (Pesaran, 2021), which are defined as follows:

$$CD = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2} \qquad (2)$$

$$CD_{LM1} = \sqrt{\frac{1}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T\hat{\rho}_{ij}^{2}-1\right) \qquad (3)$$

$$CD_{LM2} = \sqrt{\frac{2T}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^{2} \qquad (4)$$

The hypothesis for all three tests specified as follows:

H_0: there is no CSD and H_1: there is CSD.

Subsequently, slope heterogeneity is examined using the two Delta test statistics proposed by Pesaran and Yamagata (2008):

$$\hat{\Delta} = \sqrt{N}\left(\frac{N^{-1}\tilde{S}-k}{\sqrt{2k}}\right) \quad \text{and} \quad \hat{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\tilde{S}-E(\tilde{z}_{\hat{i}\hat{t}})}{\sqrt{var(\tilde{z}_{\hat{i}\hat{t}})}}\right) \quad (5)$$

Here,

$$E(\tilde{z}_{\hat{i}\hat{t}}) = k,\, var(\tilde{z}_{\hat{i}\hat{t}}) = \frac{2k(T-k-1)}{T+1}. \quad (6)$$

In this context, the null hypothesis assumes slope homogeneity, while the alternative hypothesis indicates slope heterogeneity.

In the second stage of the analysis, the stationarity properties of the variables are examined using the Fourier KPSS test developed by Nazlıoğlu and Karul (2017), which is the panel-data extension of the Fourier KPSS test proposed by Becker *et al*. (2006). This test, referred to as FPKPSS, accounts for both CSD and smooth structural breaks. Unlike conventional unit root tests, its null hypothesis assumes stationarity, and it allows for heterogeneity across cross-sections in the panel.

To capture smooth structural breaks, the following deterministic component is employed:

$$\alpha_i(t) = a_i + \gamma_{1i} sin\left(\frac{2\pi kt}{T}\right) + \gamma_{2i} cos\left(\frac{2\pi kt}{T}\right) \quad (7)$$

The KPSS procedure proposed by Becker *et al*. (2006) is specified as follows, allowing for the estimation of country-specific test statistics based on the optimal frequency parameter k:

$$\eta_i(k) = \frac{1}{T^2}\sum_{t=1}^{T}\frac{\tilde{S}_{it}(k)^2}{\tilde{\sigma}_{\varepsilon i}^2} \quad (8)$$

where,

$\tilde{S}_{it}(k) = \sum_{j=1}^{T} \tilde{\varepsilon}_{ij}$ and $\tilde{\sigma}_{\varepsilon i}^2$ is the estimation of the long-run variance of ε_{it}. The panel statistics $FP(k)$ with the average of the individual statistics developed by Nazlıoğlu and Karul (2017) is as follows:

$$FP(k) = \frac{1}{N}\sum_{i=1}^{N} \eta_i(k) \qquad (9)$$

In the third stage, one of the cointegration tests employed to examine whether the variables move together in the long run is the LM Bootstrap test, which considers CSD. Westerlund and Edgerton used the following test statistics (Westerlund and Edgerton, 2007).

$$LM_N^{+} = \frac{1}{NT^2}\sum_{i=1}^{N}\sum_{t=1}^{T} \widehat{\omega_i}^{-2} s_{it}^2 \qquad (10)$$

In this framework, s_{it}^2 represents the partial sums of error terms, while $\widehat{\omega}_i^{-2}$ denotes the long-run variances of the error terms. The null hypothesis of the bootstrap LM panel cointegration test assumes the presence of cointegration in the model, whereas the alternative hypothesis suggests no cointegration.

Although various cointegration methods are available in empirical research to assess long-run relationships, second-generation tests that account for CSD and structural breaks offer important advantages. Therefore, this study also employs the Westerlund and Edgerton (2008) cointegration test to address key panel data issues, including CSD, autocorrelation, and structural breaks.

The following equation specifies the cointegration model, which is robust to serial correlation:

$$\Delta\hat{S}_{it} = constant + \phi_i \hat{S}_{it-1} + \sum_{J=1}^{p_i} \phi_{ij} \Delta\hat{S}_{it-j} + error \qquad (11)$$

Two panel LM-based test statistics defined by WE (2008) are as follows:

$$LM_{\phi}(i) \coloneqq T\hat{\phi}_i \left(\frac{\widehat{\omega}_i}{\widehat{\sigma}_i}\right) \qquad (12)$$

$$LM_\tau(i) := \left(\frac{\hat{\phi}_i}{SE(\hat{\phi}_i)}\right) \qquad (13)$$

In the final stage of the study, both panel-wide and country-specific coefficients are estimated using the Common Correlated Effects (CCE) estimator developed by Pesaran (2006). Subsequently, the Dynamic Common Correlated Effects (DCCE) estimator proposed by Chudik and Pesaran (2015) is employed as a robustness check to ensure the robustness of the baseline results.

7 EMPIRICAL RESULTS

The results for CSD and slope homogeneity are reported in Table 2. The CSD findings lead to the rejection of the null hypothesis of no CSD, indicating that CSD must be accounted for in the analysis of both the panel model and the variables. Prior to examining the existence of a cointegration relationship, it is essential to assess the homogeneity of the slope coefficients in the cointegration equation. The results based on Pesaran and Yamagata (2008) reveal that the slope coefficients are heterogeneous. This implies that country-specific analyses should be conducted and reported.

Table 2

CSD and Slope Homogeneity test results

Variables	CD	CD_{LM1}	CD_{LM2}
lnRENW	410.0332 *(0.0000)	44.08023 *(0.0000)	10.04104 *(0.0000)
lnGRIN	168.3164 *(0.0000)	15.59364 *(0.0000)	10.00988 *(0.0000)
FD	202.3957 *(0.0000)	19.60992 *(0.0000)	7.309331 *(0.0000)
ETAX	216.6395 *(0.0000)	21.28857 *(0.0000)	6.904121 *(0.0000)
Panel	235.8635 *(0.0000)	23.55414 *(0.0000)	4.256752 *(0.0000)

Slope homogeneity	Statistics	Prob.
$\hat{\Delta}$	9.417*	0.0000
$\hat{\Delta}_{adj}$	10.788*	0.0000

Note: p-values are in the brackets. * p< 0.01.

The FPKPSS stationarity test developed by Nazlıoğlu and Karul (2017) accounts for CSD and, owing to its Fourier-based structure, effectively captures smooth structural breaks. The results reported in Table 3 indicate that the null hypothesis of stationarity is rejected at the level however cannot be rejected at the first-difference level. This suggests that all variables are non-stationary in levels however become stationary after first differencing, i.e. I(1).

Table 3

FPKPSS Stationary Test Results

Variables	Level (I(0))	First differences (I(1))
lnRENW	1.893 (0.02919)**	-0.817 (0.7930)
lnGRIN	3.507 (0.0002266)*	-0.4556 (0.6756)
FD	17.74 (2.22e-016)*	-1.348 (0.9112)
ETAX	6.801 (5.179e-012)*	1.217 (0.1119)

Note: * and ** denote the rejection of the null hypothesis at 1% and % 5% significance levels.

Based on the FPKPSS stationarity test results, the cointegration properties of the panel model are examined using the LM Bootstrap and WE (2008) tests. The LM Bootstrap test, which takes cointegration as the null hypothesis, fails to reject the null, indicating the presence of a cointegrating relationship. In contrast, the WE (2008) test, where the null hypothesis assumes no cointegration, rejects the null. Taken together, the results from both tests consistently support the existence of cointegration in the panel model, pointing to a long-run relationship among the variables. Additionally, the structural break dates for each country are reported in Table 4.

Table 4

Panel Cointegration Test Results

LM Bootstrap				
	Test Stat.		Bootst. p-value	
	3.714		0.933	
Westerlund and Edgerton (2008)				
Model	LM_τ	p-value	LM_φ	p-value
Level-shift	-6.627*	0.000	-6.479*	0.000
Countries	Break Years	Countries	Break Years	
Iceland	2007	Austria	2006	
Norway	2008	New Zealand	2008	
Sweden	2004	Portugal	2016	
Finland	2008	Chile	2009	
Denmark	2005			

Note: * denotes p<0.01. Model with a max number of 5 factors. The null hypotheses of the LM Bootstrap and WE (2008) tests indicate cointegration and no cointegration in the model, respectively. The bootstrap is based on 1000 replications.

Given the evidence of a long-run relationship among the variables, the estimation of long-term coefficients becomes feasible. Tables 5 and 6 present the results obtained from the CCE and DCCE estimators, respectively.

Table 5

CCE Long-run Coefficient Estimation Results

Countries	lnGRIN	FD	ETAX
Iceland	**-.0254108***	-.5153614**	**-.1599576***
Norway	.0246729	.0387948	.0389885
Sweden	-.067854	-.5629108	-.0058108
Finland	-.1280611	-.1999582	.1734934
Denmark	-.0722171	-.095025	-.4677497**
Austria	.0233137	-.5088954	.0488489
New Zealand	-.0333289	.1421078	**-.5527163****
Portugal	-.0959728	-.0004341	-.2078983
Chile	**.1846584***	**1.632757*****	-.1906614
Panel	-.0211333	-.0076584	**-.1470515*****

Note: * p< 0.01, ** p<0.05, and *** p<0.10.

Table 6

DCCE Long-run Coefficient Estimation Results

Countries	lnGRIN	FD	ETAX
Iceland	**-.0209668****	-.3960982	**-.1306151****
Norway	.0307632	.0421799	.0193686
Sweden	-.0235376	-1.069085	.0300216
Finland	-.056878	-.151904	.1654953
Denmark	-.0758042	-.3141882	-.2228964
Austria	.0482542	-.0008836	.0918314
New Zealand	-.0336231	.0717382	**-.5653225****
Portugal	-.0759866	.314697	-.3230437
Chile	**.1853451***	**2.640018***	-.220131
Panel	-.0024927	.1262749	**-.1283658*****

Note: * p< 0.01, ** p<0.05, and *** p<0.10.

According to the long-term coefficient estimates, there is a statistically significant negative relationship between lnGRIN and lnRENW in Iceland, whereas this relationship is positive and significant in Chile. In terms of FD, the robust results indicate a significant relationship with lnRENW only in Chile, suggesting that an increase in FD promotes the use of lnRENW.

Regarding ETAX, the findings reveal a negative relationship with lnRENW in both Iceland and New Zealand. Similarly, the panel-level results also indicate a statistically significant negative relationship between ETAX and lnRENW. In other words, increases in ETAX appear to reduce the use of lnRENW.

8 CONCLUSİON

This study examines the long-term effects of green innovation, energy taxes, and financial development on renewable energy consumption in selected OECD countries. The findings reveal significant results that are both consistent with theoretical expectations and, in some respects, deviate from them.

First, the impact of green innovation on renewable energy consumption appears heterogeneous across countries. A negative and statistically significant relationship was found for Iceland, while a positive and significant effect was observed for Chile. However, no significant relationship was found across the panel. This indicates that the relationship between green innovation and renewable energy consumption is not linear and unidirectional. There may be time lags between innovation processes and the commercialization and widespread application of these innovations in the energy sector. Furthermore, a significant portion of environmental innovations may not directly contribute to renewable energy production but rather to increasing energy efficiency. Therefore, the impact of green innovation varies depending on the institutional structures, energy policies, and sectoral characteristics of the countries.

Secondly, the impact of financial development on renewable energy consumption appears to be limited and country-specific. The findings show that financial development significantly and positively affects renewable energy consumption only in Chile. At the panel level, this relationship was found to be statistically insignificant. This result indicates that financial development alone is not sufficient to incentivize renewable energy investments. The depth of the financial system, efficient allocation of resources, the regulatory framework, and the existence of incentive mechanisms for renewable energy also play a decisive role.

Thirdly, a negative relationship was found between energy taxes and renewable energy consumption, both at the country level and across the panel. This finding contradicts the theoretical expectation that energy taxes should incentivize the use of renewable energy. However, this situation can be explained by several factors. Firstly, the scope and structure of energy taxes may vary between countries and in some cases may indirectly negatively affect renewable energy production and consumption. In addition, the fact that the applied tax rates are not at a level that will create behavioral change, or the adjustment costs that arise in the short and medium term, may also affect this result. Furthermore, structural differences between countries and heterogeneity in policy design may limit the effectiveness of energy taxes.

Overall, the findings indicate that the determinants of renewable energy consumption are shaped by country-specific dynamics and structural characteristics. The presence of cross-sectional dependence and coefficient heterogeneity highlights the importance of using advanced panel data methods in such analyses. From a policy perspective, it is understood that a single policy tool is insufficient to increase renewable energy consumption; instead, the effective implementation of green innovation, the high-quality and targeted functioning of the financial system, and well-designed energy tax policies should be considered together.

While the findings of this study offer important implications, they also contain several areas for improvement for future research. Firstly, measuring the green innovation variable solely through patent data may not fully reflect the application and diffusion dimensions of innovation. Therefore, it is recommended that future studies consider alternative indicators such as R&D expenditures, technology transfer, and renewable energy investments. Secondly, to analyze the unexpected negative impact of energy taxes on renewable energy consumption in more detail, it would be beneficial to decompose the tax structure into its components. In particular, evaluating energy taxes together with incentive and support mechanisms for renewable energy can lead to more reliable results. Thirdly, the limited impact of financial development necessitates a deeper analysis of the nature of the financial system. In this context, studies incorporating green financing tools, sustainable investment funds, and environmental, social, and governance (ESG) criteria will contribute to the literature. Finally, future studies should expand country groups to include developing economies and utilize alternative approaches such as nonlinear models, causality analyses, or machine learning methods to increase the generalizability of the findings.

REFERENCES

Akhtaruzzaman, M., Banerjee, A. K., & Boubaker, S. (2025). Government intervention and green innovation in renewable energy. *Energy Economics*, *145*, 108185.

Al Mamun, M., Sohag, K., Shahbaz, M., & Hammoudeh, S. (2018). Financial markets, innovations and cleaner energy production in OECD countries. *Energy Economics*, *72*, 236-254.

Athari, S. A. (2024). The impact of financial development and technological innovations on renewable energy consumption: do the roles of economic openness and financial stability matter in BRICS economies?. *Geological Journal*, *59*(1), 288-300.

Aydin, M., & Bozatli, O. (2023). The effects of green innovation, environmental taxes, and financial development on renewable energy consumption in OECD countries. *Energy*, *280*, 128105.

Becker R, Enders W, Lee J (2006) A stationarity test in the presence of an unknown number of smooth breaks. J Time Ser Anal 27(3):381–409

Bozatli, O., Erdem, A., Aydin, M., & Bektur, C. (2026). Towards SDG-Aligned Carbon Neutrality in EU Countries: How Energy Policy, Energy R&D Budget, and Sustainable Growth Shape the Transition?. *Sustainable Development*.

Breusch TS, Pagan AR. (1980). The Lagrange multiplier test and its applications to model specification in econometrics. The Rev Econ Stud. 47(1):239–253. doi: 10.2307/2297111 .

Brunnschweiler, C. N. (2010). Finance for renewable energy: an empirical analysis of developing and transition economies. *Environment and development economics*, *15*(3), 241-274.

Cheng, Y., Awan, U., Ahmad, S., & Tan, Z. (2021). How do technological innovation and fiscal decentralization affect the environment? A story of the fourth industrial revolution and sustainable growth. *Technological Forecasting and Social Change*, *162*, 120398.

Chudik, A., & Pesaran, M. H. (2015). Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. *Journal of Econometrics*, 188(2), 393–420.

Dogan, E., Hodžić, S., & Šikić, T. F. (2023). Do energy and environmental taxes stimulate or inhibit renewable energy deployment in the European Union?. *Renewable Energy*, *202*, 1138-1145.

Eren, B. M., Taspinar, N., & Gokmenoglu, K. K. (2019). The impact of financial development and economic growth on renewable energy consumption: Empirical analysis of India. *Science of the Total Environment*, *663*, 189-197.

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*, 107198.

Islam, F., Shahbaz, M., Ahmed, A. U., & Alam, M. M. (2013). Financial development and energy consumption nexus in Malaysia: a multivariate time series analysis. *Economic modelling*, *30*, 435-441.

J. Westerlund, D.L. Edgerton. (2007). A panel bootstrap cointegration test Econ. Lett., 97 (3), pp. 185-190

Johnstone, N., Haščič, I., & Popp, D. (2010). Renewable energy policies and technological innovation: evidence based on patent counts. *Environmental and resource economics*, *45*(1), 133-155.

Kahouli, B. (2018). The causality link between energy electricity consumption, CO2 emissions, R&D stocks and economic growth in Mediterranean countries (MCs). *Energy*, *145*, 388-399.

Khastar, M., Aslani, A., & Nejati, M. (2020). How does carbon tax affect social welfare and emission reduction in Finland?. *Energy Reports*, *6*, 736-744.

Kim, J., & Park, K. (2016). Financial development and deployment of renewable energy technologies. *Energy Economics*, *59*, 238-250.

Le, T. H., Nguyen, C. P., & Park, D. (2020). Financing renewable energy development: Insights from 55 countries. *Energy Research & Social Science*, *68*, 101537.

Liu, W., Shen, Y., & Razzaq, A. (2023). How renewable energy investment, environmental regulations, and financial development derive renewable energy transition: Evidence from G7 countries. *Renewable energy*, *206*, 1188-1197.

Mahalik, M. K., Babu, M. S., Loganathan, N., & Shahbaz, M. (2017). Does financial development intensify energy consumption in Saudi Arabia?. *Renewable and Sustainable Energy Reviews*, *75*, 1022-1034.

Nazlioglu S, Karul C (2017) A panel stationarity test with gradual structural shifts: re-investigate the international commodity price shocks. Econ Model 61:181–192

Özmen, İ., & Mutascu, M. (2025). Don’t look earth: Environmental taxes effect on CO2 emissions, evidence from moments quantile regression for EU countries. *Environment, Development and Sustainability*, *27*(2), 4619-4658.

Peng, G., Meng, F., Ahmed, Z., Oláh, J., & Harsányi, E. (2022). A Path Towards Green Revolution: How do Environmental Technologies, Political Risk, and Environmental Taxes Influence Green Energy Consumption?. *Frontiers in Environmental Science*, *10*, 927333.

Pesaran MH, Yamagata T. (2008). Testing slope homogeneity in large panels. J Econ. 142(1):50–93. doi: 10.1016/j.jeconom.2007.05

Pesaran MH. (2006). Estimation and inference in large heterogeneous panels with a multifactor error structure. Econometrica. 74(4):967–1012. doi: 10.1111/j.1468-0262.2006.00692.x

Pesaran MH. (2021). General diagnostic tests for cross-sectional dependence in panels. Emp Econ. 60 (1):13–50. doi: 10.1007/s00181-020-01875-7

Saadaoui, H. (2022). The impact of financial development on renewable energy development in the MENA region: the role of institutional and political factors. *Environmental Science and Pollution Research*, *29*(26), 39461-39472.

Samour, A., Baskaya, M. M., & Tursoy, T. (2022). The impact of financial development and FDI on renewable energy in the UAE: a path towards sustainable development. *Sustainability*, *14*(3), 1208.

Shahbaz, M., Topcu, B. A., Sarıgül, S. S., & Vo, X. V. (2021). The effect of financial development on renewable energy demand: The case of developing countries. *Renewable Energy*, *178*, 1370-1380.

Shahzad, U., Radulescu, M., Rahim, S., Isik, C., Yousaf, Z., & Ionescu, S. A. (2021). Do environment-related policy instruments and technologies facilitate renewable energy generation? Exploring the contextual evidence from developed economies. *Energies*, *14*(3), 690.

Sims, R. E., Rogner, H. H. ve Gregory, K. (2003). “Carbon Emission and Mitigation Cost Comparisons Between Fossil Fuel, Nuclear and Renewable Energy Resources for Electricity Generation”. Energy Policy, 31/13, 1315-1326

Tamazian, A., & Rao, B. B. (2010). Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. *Energy economics*, *32*(1), 137-145.

Westerlund J, Edgerton DL. (2008). A simple test for cointegration in dependent panels with structural breaks. Ox Bull Econ and Stat. 70(5):665–704. doi: 10.1111/j.1468-0084.2008.00513

Yildiz, Ş., Ediz, Ç., Akpinar, S., & Konuk, F. (2026). Insights into the financial development and renewable energy nexus: A bibliometric analysis. *Energy Reports*, *15*, 109237.

Yu, Y., & Zhang, N. (2022). Environmental regulation and innovation: Evidence from China. *Global Environmental Change*, *76*, 102587.

Zhang, D., Zheng, M., Feng, G. F., & Chang, C. P. (2022). Does an environmental policy bring to green innovation in renewable energy?. *Renewable Energy*, *195*, 1113-1124.

Zhang, R. J., & Razzaq, A. (2022). Influence of economic policy uncertainty and financial development on renewable energy consumption in the BRICST region. *Renewable Energy*, *201*, 526-533.

Zhang, R. J., & Razzaq, A. (2022). Influence of economic policy uncertainty and financial development on renewable energy consumption in the BRICST region. *Renewable Energy*, *201*, 526-533.