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Financial Deepening as a Mediator of Environmental Taxes and Renewable Energy Consumption

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Abstract

This study explores the effect of environmental taxation on renewable energy consumption, while considering financial deepening as a central element that may influence this relationship. Based on a dataset covering 27 European Union member states over the period 2014–2023, renewable energy consumption is included as the dependent variable, while environmental taxes are incorporated into the analysis as the main explanatory variable. In addition, gross domestic product and the human development index are incorporated into the specification as control factors. Financial deepening is specified as the threshold variable, and the empirical analyses are conducted using the panel threshold regression approach. Consequently, the effect of environmental taxes on renewable energy consumption is negative and varies in magnitude depending on whether the level of financial deepening falls

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below or exceeds the threshold value of 0.888. Finally, the results reveal that increases in gross domestic product and Human Development Index levels are associated with higher demand for renewable energy consumption.

Keywords: Renewable energy consumption, environmental taxes, financial deepening, panel threshold regression
JEL Classification: Q20, H230, G100

1. Introduction

This study analyzes the role of financial deepening (FD) in influencing the connection between environmental taxation (ET) and renewable energy consumption (RE) within the European Union (EU). Energy represents a core input across developed and developing economies, supporting activities ranging from production and transport to innovation and industrial expansion. Energy is not merely an input used for economic purposes; rather, it is a multidimensional factor that has become a central focus in various fields of research due to the externalities it generates. This is because the benefits and costs of energy use are not confined to consumers alone but may also lead to far reaching environmental and societal impacts. The heavy reliance of energy supply on fossil fuels increases carbon emissions, thereby contributing to environmental degradation as well as cost-based externalities (Zaman *et al*., 2026; Wang and Azam, 2024; Dong *et al*., 2021). As a way to lessen such adverse consequences, expanding RE has become an increasingly significant priority. In this context, policies designed to encourage the use of renewable energy technologies that reduce environmental harm, along with zero waste measures and broader efforts to mitigate pollution, have begun to be implemented (Aydın, 2024; Jahanger, 2025). Indeed, in line with the Paris Climate Agreement and the European Green Deal, European Union countries have undertaken various policy initiatives to expand renewable energy deployment and to realize the vision of a carbon-neutral economy.

In addition, challenges related to energy supply security in international markets have also contributed to rising demand for renewable energy within EU member states (Ermiş and Güven, 2022). Notably, in 2022, the share of renewable energy sources in overall energy generation within the EU reached 43%, making renewables the leading source of energy production. Moreover, nuclear energy contributed 28% of overall electricity production, ranking behind renewables, whereas solid fuels, natural gas, and crude oil accounted for 19%, 6%, and 3%, respectively (Eurostat, 2024). In this respect, EU member states promote the development of renewable energy as part of broader efforts to limit environmental external costs and lessen reliance on fossil-based energy sources.

Public policymakers may shape market outcomes through regulatory and fiscal measures designed to limit fossil fuel dependence while supporting the transition toward renewable energy (Dogan *et al*., 2023; Omri and Nguyen, 2014). This is because the effects of environmental damage are not confined solely to the polluter; rather, the adverse impacts of such external costs are dispersed across society and the natural environment. Therefore, protecting both the environment and society from the consequences of negative externalities requires the implementation of state-led policy measures and regulatory tools (Yoshino and Taghizadeh-Hesary, 2018).

In this context, environmental taxes can be considered an important instrument for internalizing negative externalities and guiding the behavior of economic actors (Hao *et al*., 2021; Karmaker *et al*., 2021; Turna, 2025). Building on this conceptual approach, Karmaker *et al*. (2021) contend that by increasing the cost of fossil energy consumption through environmental taxation, economic agents can be encouraged to shift toward renewable energy sources. A similar assessment is provided by Wang and Yu (2021), who emphasize that environmental taxes may raise firms' tax burdens and production costs, thereby prompting companies to adopt more environmentally friendly production modes. Tax policies targeting pollution can increase the price burden on conventional energy carriers, reducing the cost advantage of fossil-based fuels. As a result, renewable energy demand in the energy market may gain greater competitiveness, enhancing its attractiveness as a viable alternative for economic actors. In this context, ET serves as a crucial policy tool for correcting market failures, accelerating the energy transition, and supporting the achievement of carbon-neutral objectives.

The strength of the connection between ET and RE appears to depend largely on the degree of FD. Lei *et al*. (2022) reveal that FD plays an enhancing role in increasing RE. Relatedly, Gong *et al*. (2012) highlight that shifts in monetary conditions can shape the scale of investments allocated to cleaner and renewable energy technologies. In this study, this role is interpreted as a structural financial transmission channel through which environmental tax signals influence green investment allocation and, ultimately, renewable energy adoption. Thus, financial deepening may introduce nonlinear regime shifts in how environmental tax policies relate to renewable energy demand. Therefore, it can be stated that at certain levels of financial deepening, environmental taxes may either support or constrain the expansion of renewable energy use.

Research examining how environmental taxes affect renewable energy uptake is still relatively limited. Earlier work has largely relied on linear specifications when exploring how environmental tax measures are associated with renewable energy utilization. Within

such frameworks, the impact of environmental taxation is typically evaluated using a single coefficient, implicitly assuming that this effect remains constant across different economic and financial conditions. However, analyses addressing potential nonlinear mechanisms have largely been neglected in previous empirical work. Building on this limitation, the study examines the possibility that the effectiveness of environmental tax measures in encouraging renewable energy adoption depends on reaching a specific level of financial deepening.

The conditions under which financial deepening alters the effectiveness of environmental tax measures in encouraging renewable energy uptake remain underexplored. Identifying this threshold empirically offers new insight into literature. Unlike prior threshold-based studies that mainly focus on tax energy dynamics, the present study differentiates itself by conceptualizing financial deepening not merely as an empirical threshold splitter, but as a structural financial transmission mechanism through which environmental tax signals are translated into renewable energy outcomes. In this sense, the analysis highlights how financial deepening shapes capital allocation efficiency, liquidity conditions and green investment financing capacity, thereby offering a more mechanism-based contribution to the sustainability finance literature. Motivated by this gap, the present study investigates whether the effect of environmental taxation on renewable energy consumption varies across different levels of financial deepening in EU countries. In particular, the study seeks to determine whether a critical threshold level of financial deepening exists beyond which environmental taxes become more effective in promoting renewable energy use. Against this backdrop, the analysis is structured around three central research questions:

(i) Do environmental taxes significantly influence renewable energy consumption?

(ii) Does this relationship change across different levels of financial deepening?

(iii) Is there an empirically identifiable threshold effect within the EU context?

Furthermore, building on the premise that renewable energy consumption may interact with broader socioeconomic development indicators, such as economic growth and the human development index (HDI), the study provides a more holistic analytical structure and contributes to addressing the omission of key control variables in prior research. Accordingly, panel threshold regression estimates are obtained from observations covering 27 EU economies during the 2014–2023 sample period. Empirical estimates indicate that environmental tax instruments influence renewable energy utilization within a regime dependent manner shaped by financial deepening.

The paper begins by introducing theoretical background, followed by a section summarizing prior research. The next part describes the econometric strategy employed and pres-

ents the main estimated findings. Overall, the concluding section summarizes the main results and presents the overall conclusions derived from the analysis.

2. Theoretical Framework

The analytical logic of the study is anchored in three mutually reinforcing theoretical pillars. Initially, Environmental Kuznets Curve (EKC) maintains that environmental policy instruments become more effective as economies reach higher development stages. In his seminal 1955 study, Kuznets examined how wealth distribution evolved alongside economic progress and identified a nonlinear inverted-U pattern linking growth dynamics with inequality levels. His findings suggest that as societies move to higher levels of economic prosperity, income disparities tend to widen in the initial phases of development, before progressively narrowing as a more advanced stage of growth is reached (Kuznets, 1955). This perspective was later extended to environmental economics through the EKC framework, which posits that ecological degradation tends to intensify during the early phases of economic expansion yet gradually weakens once a critical development level is attained (Grossman and Krueger, 1995). Within this framework, environmental taxes may be viewed as market-based policy instruments that help economies reach this turning point earlier by discouraging carbon-intensive energy consumption and encouraging a shift toward renewable energy sources. Beyond the development driven logic of the EKC, the innovation-based view of environmental regulation offers an additional explanation for how environmental taxes may influence renewable energy transitions.

Second, the Porter Hypothesis complements this perspective by proposing that appropriately structured environmental policies and fiscal instruments may foster technological innovation, enhance the efficient use of resources and accelerate investments in cleaner production technologies. More specifically, Porter (1991) conceptualized this hypothesis by proposing that environmental constraints may enhance efficiency through innovation processes. Within this framework, the proposition that ecological regulations stimulate innovation across industries reflects the innovation-oriented strand of the Porter Hypothesis, whereas the claim that such constraints improve the competitive performance of sectors represents its strong version. In this sense, Porter (1991) suggested that firms innovation efforts to adapt to increasingly stringent environmental requirements may reduce production costs, improve efficiency, and ultimately strengthen their competitive positions. Applied to the energy transition context, this logic implies that environmental taxes may encourage firms to replace fossil-based production and energy use with cleaner technologies and renewable energy alternatives as a cost-efficient strategic response (Porter and van der Linde, 1995; Ambec *et al*., 2013).

Third, financial intermediation theory, rooted in the financial development growth literature (Levine, 1997), provides the core rationale for the threshold structure examined in this study. This perspective suggests that deeper financial systems improve capital mobilization, expand credit availability, and facilitate long term investments in renewable energy infrastructure. From a green investment allocation perspective, deeper financial systems may also accelerate the transmission of environmental tax shocks into lending rates, sectoral credit allocation, and capital reallocation decisions. Recent evidence shows that green finance substantially advances renewable energy production and that innovation serves as an important transmission channel (Alharbi *et al*., 2023). This logic is further substantiated by recent systematic projections showing that green finance contributes to renewable energy expansion only when adequate structural and institutional conditions are in place, underscoring the importance of financial maturity and allocation quality in shaping clean energy outcomes (Datta and Jena, 2026).

In addition, recent global evidence indicates that the influence of green fiscal measures on clean energy technology uptake varies across different development regimes (Nchofoung *et al*., 2023), while threshold-based findings from developed countries also confirm that environmental taxation and clean energy tools interact in a nonlinear manner to strengthen environmental outcomes once critical levels are exceeded (Ghraieb, 2026). If green financing channels remain underdeveloped, this stronger financial transmission may intensify the adverse tax effect by redirecting resources away from renewable energy projects toward lower risk conventional sectors. This mechanism is also consistent with Green Paradox reasoning, which suggests that anticipated future regulatory costs may accelerate resource reallocation toward incumbent sectors (Sinn, 2012). Together, these channels provide the theoretical basis for expecting a nonlinear regime-dependent relationship between environmental taxation and renewable energy consumption. In this context, the effectiveness of environmental taxes in promoting renewable energy utilization can differ across varying degrees of financial deepening, since more developed financial markets can strengthen the transmission of tax incentives into green investment decisions. Accordingly, the environmental taxation renewable energy nexus may exhibit threshold-dependent nonlinearities across different levels of financial deepening.

3. Literature Review

Academic research has increasingly concentrated on the factors shaping renewable energy demand and the shift in environmental governance within the energy domain. Existing evidence has extensively addressed the potential of ET to encourage sustainable energy use

while mitigating carbon emissions (Ekins *et al*., 2012; Köppl and Schratzenstaller, 2021; Bashir *et al*., 2020; Safi *et al*., 2021; Xu *et al*., 2023; Kocoğlu, 2024). Despite this, Wang and Yu (2021) argue that the positive impact of ET on the green transition may not occur in a strictly linear manner and may vary depending on the optimal level of taxation. In addition to environmental regulations, the structure of the financial system has also been highlighted in literature as an important factor influencing renewable energy use (Frutos-Bencze *et al*., 2020; Razmi *et al*., 2021; He *et al*., 2019; Handoko *et al*., 2023).

In addition, contributions by Kacem (2023), Khan *et al*. (2024), and Mehmood and Kaewsaeng on (2025) provide growing evidence that financial deepening and monetary policy-related factors play an important role in shaping renewable energy consumption. Recent evidence also suggests that the impact of environmental taxes on renewable energy consumption is not uniform and becomes substantially stronger when supported by complementary mechanisms. In a similar vein, recent OECD based evidence indicates that environmental policy and green financial policy jointly improve environmental sustainability outcomes, highlighting the importance of financial channels in strengthening the effectiveness of policy driven green transitions (Dao, 2024). For example, Sen *et al*. (2025) demonstrate that the effectiveness of environmental taxes in OECD countries increases significantly when reinforced by strong environmental governance and environmental related technological innovation. This line of evidence is further reinforced by recent global panel findings from 88 countries, which reveal that green fiscal instruments exert a significant positive influence on clean energy utilization and that the magnitude of this effect varies across income groups, pointing to heterogeneous and nonlinear policy responses. (Owusu Atuahene *et al*., 2026).

While prior and more recent studies have increasingly examined environmental taxation, financial system development, and renewable energy use, research explicitly investigating the interaction among these variables through threshold based nonlinear mechanisms remains limited, particularly in the context of EU countries. Table 1 summarizes selected empirical studies examining how environmental tax measures are associated with renewable energy utilization.

Table 1: Literature Review

Authors	Time Period	Method	Findings
Mir-Mohammad Tabar *et al.* (2018)	2004–2016	GMM	Drawing on a panel of 13 countries at different development stages, the study finds that environmental taxes on fossil fuels reduce renewable energy investments, whereas taxes imposed on the transport sector encourage a shift toward renewable energy. The effect is shown to vary depending on the sectoral composition of taxation.
Hajek *et al.* (2019)	2005–2015	Panel Data Regression	Evidence from European countries suggests that ET does not stimulate renewable energy use in the short term, whereas its influence becomes significant over the long term.
Fang, Yang, Tian and Ma (2022)	1998–2019	Dumitrescu–Hurlin Panel Granger Causality Test	Panel causality results for 15 Belt and Road countries show a bidirectional link between ET and RE, with a negative short-run but positive long-run effect.
Bashir *et al.* (2022)	1996–2018	Westerlund cointegration, FMOLS, and quantile regression techniques	OECD-based results indicate a negative link between ET and RE.
Dogan *et al.* (2023)	1995–2019	Panel Data Analysis	EU evidence indicates a negative association between environmental/energy taxes and RE.
Nchofoung, Fotio and Miamo (2023)	1996–2017	FE (Driscoll–Kraay; Newey–West), GMM, and regression methods	ET support renewables in developed countries but hinders adoption in developing economies.
Abbas *et al.* (2023)	2012–2021	Regression Analysis	China-based results suggest that green finance and environmental taxation stimulate renewable energy investment. It further indicates that increases in ET strongly encourage renewable energy investments.
Onwe *et al.* (2023)	1994–2020	MMQreg Test	G7 evidence shows that non-renewable energy enlarges the ecological footprint, while renewable energy, innovation, and environmental taxation help mitigate ecological damage. Bidirectional causality is also observed among environmental taxes, renewables, and the ecological footprint.
Zhou *et al.* (2023)	1995Q1–2018Q4	Wavelet Local Multiple Correlation (WLMC) test	ET, renewable energy use, and economic growth are found to reduce the ecological footprint, with significant positive short- and long-run linkages among these variables.
Kacem (2023)	2011–2021	GMM Model	Evidence from 18 developing countries shows that financial deepening positively influences renewable energy consumption.

Kukharets *et al.* (2024)	2011–2021	Regression Analysis	EU-based findings indicate that higher net savings and environmental tax revenues are associated with greater renewable energy use.
Kurt (2024)	2002–2020	Panel Data Analysis	EU evidence suggests that environmental tax thresholds shape the renewable energy growth link, with a stronger negative growth effect when taxes exceed the threshold.
Değirmenci and Yavuz (2024)	1995–2019	AMG and DCCE estimators	Environmental tax increases boost renewable energy use in Germany and France but reduce it in Spain and Slovenia.
Alofaysan *et al.* (2024)	2006–2021	FD-GMM estimator	In 38 developing economies, GDP hinders the green energy transition below the threshold but supports it once the threshold is exceeded.
Mehmood and Kaewsaeng-on (2024)	1991–2021	Panel Regression Analysis	The study reports that financial development increases the demand for sustainable energy sources.
Wang and Pang (2025)	2000–2020	Dynamic Panel Data Analysis	OECD results show that ET act as a threshold factor, strengthening the positive renewable energy growth effect in high tax countries while weakening it in low tax ones.

Source: Authors' own elaboration based on the relevant literature

4. Methodology

4.1 Dataset and Model

The study evaluates the role of *ET* measures in shaping *RE* under a *FD*-based threshold framework. For this purpose, a sample of 27[1] European Union countries was selected for the period 2014–2023, and a panel threshold regression analysis was conducted. *RE* is used as the outcome variable in the model, consistent with the study's objective. *RE* is measured as the proportion of renewables within each country's overall energy use. In the current research, *ET* indicates the ratio of environmental taxes within gross domestic product and are included in the model as the main explanatory variable. Moreover, *ET* refers to the total taxes related to energy, transportation, pollution, and resources. To account for broader economic conditions influencing renewable energy use, gross domestic product (*GDP*) is included as a control variable. The *HDI* is also included to capture the effect of socioeconomic de-

1 Belgium, Bulgaria, Czechia, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Crotia, Italy, Latvia, Lithuania, Luxembourg, Hungary, Malta, the Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, Norway.

velopment. In the study, *FD*, which reflects the size, diversity, and efficiency of the financial system within an economy, is specified as the threshold variable. The analytical framework of the model is formally represented as follows:

$$RE = f(ET, GDP, HDI, FD) \quad (1)$$

Table 2 summarizes the dataset employed in this analysis along with the relevant data sources.

Table 2: Data Sources and Variable Definitions

Variable	Symbol	Description	Data Source
Renewable Energy Consumption	*RE*	The share of renewables across sectors in total final energy consumption	Eurostat (2025a)
Environmental Taxes	*ET*	environmental tax revenues (% of GDP)	Eurostat (2025b)
Gross Domestic Product	ln *GDP*	expressed in constant 2015 US dollars and log-transformed for estimation	WB (2025a)
Human Development Index	*HDI*	Human Development Index	UN Development Programme (2025)
Financial Deepening	*FD*	Monetary Sector credit to private sector (% of GDP)	WB (2025b)

Source: Authors' own elaboration

4.2 Econometric Methods

Since the study includes cross-sectional data for 27 countries over a ten-year period, panel data analysis is employed. From this perspective, analysis allows for the simultaneous consideration of both cross-sectional and time dimensions, thereby providing a higher degree of freedom, greater variability in observations, and stronger linear relationships among variables (Baltagi, 2005). Although classical panel data analysis can estimate nonlinear effects among variables, it may be insufficient to represent the deeper structural interactions between them (İlarslan, 2025). Therefore, the panel threshold regression model developed by Hansen (1999) makes it possible to analyze structural breaks and abrupt changes arising from the correlation structure among variables. Additionally, threshold regression enables the sample to be divided into regimes based on different levels of the threshold variable, thereby enabling the examination of nonlinear relationships between variables (Ye *et al.*,

2025; Dinh, 2025; Hansen, 1999). Hansen (1999) formulated the panel regression analysis with a single threshold value as follows:

$$y_{it} = \mu_i + \beta_1' + \boldsymbol{x}_{it} \times I(q_{it} \leq y) + \beta_2' \boldsymbol{x}_{it} \times I(q_{it} > y) + \varepsilon_{it} \quad (2)$$

In the formula, the index *i* denotes the cross-sectional unit, *t* represents time, *y* refers to the dependent variable, and ε_{it} is the error term. The term *q* indicates the threshold variable, while *x* represents the *k*-dimensional vector of regressors. Moreover, $I(q_{it} \leq y)$ is considered an indicator function. If the threshold variable q_{it}, is less than or equal to the threshold value γ, the indicator equals 1, and 0 otherwise. Similarly, $I(q_{it} > y)$ denotes the indicator function for the other regime. When q_{it} exceeds the threshold parameter γ, the indicator is assigned a value of 1; otherwise, it equals 0.

In addition, it is also possible to formulate the panel threshold regression equation as follows:

$$y_{it} = \begin{cases} u_i + \beta_1' x_{it} + e_{it} q_{it} \leq y \\ u_i + \beta_2' x_{it} + e_{it} q_{it} < y \end{cases} \quad (3)$$

In this equation y_{it} denotes the dependent variable that varies across both time and cross-sectional units, while x_{it} denotes the set of explanatory variables incorporated into the specification. The term u_i captures unit-specific and time invariant fixed effects. The coefficients β_1' and β_2' capture how the influence of the regressors varies between the two regime classifications. The regimes are defined by whether q_{it} lies below or above the estimated threshold level γ.

Panel threshold regression offers several important methodological advantages. Unlike linear models, the panel threshold regression (PTR) framework allows estimated effects to vary across regimes, such as low and high threshold states. Threshold models rely on the premise that sample observations are partitioned into distinct regimes according to the value of an observed threshold variable. In this respect, the threshold approach constitutes a valuable tool for investigating a wide range of economic phenomena and has been widely applied in finance and macroeconomics (Wang, 2015; Hansen, 1999). In addition, the panel threshold model accommodates heterogeneity across cross sectional units through the inclusion of fixed effects (Akarsu and Gümüşoğlu, 2019). Another important advantage is that, because the sample can be endogenously divided into different regimes, there is no need to introduce dummy variables based on unknown structural breaks (Song, 2021). Furthermore, the method has been progressively extended to incorporate time fixed effects, instrumental variables, covariate dependent thresholds, and dynamic panel structures, which has considerably broadened its field of application (Barassi *et al*., 2026).

Although the method offers notable econometric strengths, certain limitations should also be acknowledged. One important issue is that the large sample behavior of the LS estimator for the threshold parameter depends on a compound Poisson type process involving several nuisance components, including the distributional properties of the regressors and the associated slope coefficients (Miao *et al*., 2020). In addition, the LR criterion applied for threshold detection may show weak performance under limited sample sizes (Wang, 2015). Finally, endogeneity remains an important concern, as widely recognized within conventional OLS based estimation frameworks (Zaefarian *et al*., 2017).

5. Results

5.1 Preliminary Statistical Tests

Before presenting the empirical analyses, descriptive statistics are provided to outline the structure of the variables included in this analysis and the basic characteristics of the dataset. Descriptive statistics form an essential basis for offering a preliminary assessment of the key differences and general trends among variables, as well as for interpreting the empirical results. Accordingly, Table 3 reports the Preliminary Analyses.

Table 3 reports information on the basic descriptive statistics. According to the results reported in Panel A, the mean value of *RE* is 0.249. In addition, the gap between the lowest and highest observations points to considerable heterogeneity across countries. Similarly, the descriptive statistics for the ln *GDP* and *FD* variables also reveal noticeable differences among countries. The high mean value of the *HDI* variable indicates that the countries included in the sample exhibit relatively a high degree of human development. In addition, the average value of the *ET* variable suggests that environmental taxation policies are implemented with varying degrees of intensity across the sample countries. The Jarque Bera statistics also reject normality for the variables at the 1% and 10% significance thresholds.

As reported in the table, Skewness and Kurtosis measures suggest that the variable distributions are noticeably non-symmetric. Drawing on the correlation coefficients provided in Panel B, the dependent variable renewable energy consumption is negatively correlated with financial deepening and human development, while it shows a positive correlation with gross domestic product and environmental taxes. In Panel C, the VIF values for the variables range between 1.08 and 1.81 and all values remain well below the commonly accepted thresholds. This finding suggests that multicollinearity is not a concern in the model and that the independent variables do not exhibit excessively high correlations that could distort the estimation results.

Table 3. Preliminary Analyses

Panel A. Descriptive Statistical Tests					
	RE	***ln GDP***	***HDI***	***FD***	***ET***
Mean	0.249	26.109	0.906	0.757	2.605
Median	0.204	26.125	0.906	0.697	2.470
Maximum	0.773	28.939	0.970	1.734	5.600
Minimum	0.044	23.059	0.817	0.230	0.850
Std. Dev.	0.015	1.417	0.038	0.336	0.800
Skewness	1.446	0.044	−0.341	0.602	0.696
Kurtosis	5.080	2.327	2.199	2.781	3.215
Jarque–Bera	142.794***	5.177*	12.457***	16.878***	22.322***
Panel B. Correlation Analysis					
RE	1				
ln *GDP*	−0.010	1			
HDI	0.272	0.498	1		
FD	0.363	0.397	0.582	1	
ET	−0.023	−0.163	−0.194	0.014	1
Panel C. Multicollinearity Test					
VIF	–	1.38	1.81	1.60	1.08

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' own computations

5.2 Panel Diagnostics: Cross-Sectional Dependence (CSD), Homogeneity, and Stationarity

In analyses, cross-sectional dependence problems may result from developments occurring across units and interdependence among countries. Therefore, in the presence of CSD, the reliability of unit root test results may be weakened (Pesaran, 2004; Pesaran, 2007). For this reason, testing for CSD is of great importance. Accordingly, CSD tests are first applied

in this study, and appropriate stationarity tests are selected based on the obtained results. In this way, the time–series properties of the variables are intended to be accurately identified. Table 4 reports the outcomes of the CSD assessment and the panel unit root diagnostics.

Table 4: Tests of CSD and Stationarity

Panel A. CSD Test Results					
Tests	***RE***	**ln *GDP***	***HDI***	***FD***	***ET***
Breusch–Pagan LM	2,107.280*** (0.000)	2,929.936*** (0.000)	2,377.508*** (0.000)	1,552.585*** (0.000)	1,917.751*** (0.000)
Pesaran scaled LM	66.286*** (0.000)	97.335*** (0.000)	76.485*** (0.000)	45.350*** (0.000)	59.133*** (0.000)
Bias–corrected scaled LM	64.786*** (0.000)	95.835*** (0.000)	74.985*** (0.000)	43.850*** (0.000)	57.633*** (0.000)
Pesaran CD	42.936*** (0.000)	53.852*** (0.000)	47.210*** (0.000)	14.429*** (0.000)	27.823*** (0.000)
Panel B. Panel Unit Root Test Results					
CIPS	–3.520***	–6.478***	–5.290***	–2.202***	–2.695***

Notes: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Parentheses report the corresponding *p*-values.

Source: Authors' own computations

The dependence diagnostics show that the Breusch Pagan LM, Pesaran scaled LM, bias adjusted scaled LM, and Pesaran CD statistics are significant for all variables. These findings suggest the existence of CSD among the countries included in the empirical investigation. Therefore, it can be stated that the assumption of cross-sectional independence does not hold. Since the detection of CSD may reduce the reliability of results obtained from first generation unit root tests, CIPS test, which accounts for CSD, is employed for the stationarity analysis. The CIPS outcomes confirm that all series are level stationary. These findings also indicate that the variables time-series characteristics are appropriate for estimating a panel threshold regression model.

Determining whether slope coefficients are homogeneous represents another important issue in panel data analysis (Wu *et al*., 2026). In a panel dataset consisting of countries with diverse economic backgrounds, the assumption that slope coefficients are identical across units is not realistic (Fan and Lenton, 2026). Therefore, slope homogeneity tests are

applied to examine whether the effects of predictors such as environmental taxes, financial deepening, gross domestic product or human development differ significantly across countries. Table 5 summarizes the slope homogeneity test outcomes.

Table 5: Slope Homogeneity Test

Tests	Δ Delta St.	*p*-value	Δ Adjusted Delta St.	*p*-value
Pesaran and Yamagata (2008)	5.354	(0.000)***	8.466	(0.000)***
Blomquist and Westerlund (2013)	5.674	(0.000)***	8.971	(0.000)***

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' own computations

As shown in Table 5, both the Δ and bias-adjusted Δ statistics are significant at the 1% level across the two homogeneity testing procedures. Accordingly, the hypothesis of common slope coefficients across panel units is rejected. This evidence points to cross-country heterogeneity, implying that the estimated relationships vary across national contexts.

5.3 Linearity Test

In panel data analysis, determining whether the relationship among variables follows a linear structure is crucial for selecting the appropriate econometric model. The validity of the linear model assumption is tested through Wald and LR statistics, and based on the obtained results, the suitability of nonlinear modeling approaches is assessed (Hansen, 1999; Tong, 2012; Gharbi and Othmani, 2022). The outcomes of the linearity assessment are summarized in Table 6.

Table 6: Linearity Tests

	Test Statistics	*p*-value
Wald Test	24.71	(0.000)***
LR Test	29.13	(0.000)***

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' own computations

The Wald and LR test results conducted to examine the linearity assumption are significant at conventional levels at the 1% level. Accordingly, it can be stated that the null hypothesis of a linear model is rejected. Moreover, these findings indicate that the relationship among the variables is nonlinear and that a threshold effect exists. Therefore, it can be concluded that the panel threshold regression model is econometrically appropriate for this study.

5.4 Evaluation of Threshold Effects and Regime Determination

In panel threshold regression analyses, it is important to determine under how many distinct regimes the relationship among variables should be examined. According to Hansen (1999) are applied to assess whether a single-threshold or multiple-threshold structure is valid in the model. Accordingly, the results for different threshold specifications are shown in Table 7.

Table 7: Threshold Effect Tests

Tests	Threshold Estimates Value	F-statistics	*p*-value	Critical Values		
				10%	5%	1%
Single Threshold	0.888	28.33	(0.086)*	26.758	32.103	42.938
Double Threshold	0.888 1.328	10.02	(0.626)	22.059	24.457	31.470
Triple Threshold	0.888 1.328 1.543	24.15	(0.143)	29.568	39.666	54.247

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' own computations

According to the threshold effect test results reported in Table 7, the single-threshold specification is found to be statistically significant. The *F*-statistic calculated for the single threshold model is 28.33, which exceeds the 10% critical value of 26.758, and the corresponding probability value is considered considerable at the 10% level ($p = 0.086$). In contrast, the *F*-statistics for the double-threshold and triple threshold models remain below their respective critical values, and the associated *p*-values are not statistically significant. Therefore, it can be stated that the single threshold structure is valid in the model, while models with a higher number of thresholds are not statistically supported.

5.5 Panel Threshold Regression Estimation Results

Based on the preliminary tests and threshold analysis results, it is determined that a single threshold structure is valid in the model. Accordingly, the panel threshold regression model is estimated under the assumption that the link between the variables may differ across alternative levels of financial deepening. The panel threshold regression approach allows the coefficients to differ for observations falling below or above a certain threshold value of the threshold variable, thereby enabling a more detailed examination of the nonlinear relationship structure. In this context, Table 8 summarizes the estimation results from the panel threshold regression model.

Table 8: Single Threshold Model Estimation Results

Dep. variable: *RE*		Coefficient	Std. err	*t*	*p*-value	[95% conf. interval]
	ln *GDP*	0.073	0.026	2.79	(0.006)***	0.021 0.125
	HDI	0.854	0.300	2.84	(0.005)***	0.261 1.447
ET	$\beta_1^{FD \le 0.888}$	−0.024	0.004	−5.48	(0.000)***	−0.033 −0.015
	$\beta_2^{FD > 0.888}$	−0.036	0.004	−7.39	(0.000)***	−0.045 −0.026
	constant	−2.373	0.529	−4.48	(0.000)***	−3.417 −1.329
Model: $-2.373 + 0.073(\ln GDP) + 0.854HDI - 0.024ET \times I(FD \le 0.888) - 0.036ET \times I(FD > 0.888)$						

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' own computations

Table 8 indicates that the influence of *ET* on *RE* is nonlinear and differs across *FD* regimes. The estimated threshold value for financial deepening is found to be 0.888. Accordingly, the results regarding environmental taxes differ across regimes defined by this threshold level of financial deepening. When financial deepening remains at or below the estimated threshold, environmental taxes are associated with a negative and statistically considerable change in renewable energy use. Once financial deepening moves above the threshold, this adverse relationship persists, but its intensity becomes larger. Overall, the negative influence of environmental taxation on renewable energy consumption strengthens as the level of financial deepening rises. As financial deepening increases, firms may operate within stronger market mechanisms and can more easily pass environmental taxes on to final prices. In such cases, energy costs rise, and renewable energy use may decline in the short term.

Also, the intensification of the adverse influence of environmental taxation on renewable energy demand under greater financial deepening can be explained not only by higher costs but also by several additional mechanisms. These include the transfer of the tax burden to energy prices, the redirection of financial resources toward conventional sectors rather than green investments, and the insufficient channeling of environmental tax revenues into renewable energy incentives. This situation suggests that the performance of environmental tax policies is shaped by financial system characteristics and the extent of policy alignment.

Regarding the control variables, the coefficient of gross domestic product is found to be positive and significant. Consequently, economic growth in EU countries, and consequently rising individual incomes, increases renewable energy consumption. In the sampled countries, higher income levels encourage individuals to shift toward renewable sources in their energy use. For instance, demand for electric vehicles, heating systems, and energy-efficient appliances have increased alongside rising income. Moreover, improvements in human development levels also contribute to greater demand for energy derived from renewable sources in EU countries. As human development-characterized by better education, healthcare services, and higher welfare standards-increases, public awareness of environmental issues and environmental literacy tend to improve. Accordingly, demand for renewable energy consumption rises as individuals become more sensitive to environmental concerns and seek healthier living conditions.

5.6 Robustness Tests

In econometric modeling, an endogeneity problem emerges when one or more regressors are associated with the disturbance term, potentially producing biased and inconsistent coefficient estimates. Accordingly, endogeneity can distort coefficient estimates and undermine the consistency of empirical results (Dyreng *et al*., 2025). In the presence of endogenous regressors, ordinary least squares (OLS) estimates become unreliable and inconsistent, often accompanied by inflated standard errors (Santoso and Wijaya, 2026; Ur Rahman *et al*., 2025). Furthermore, if endogeneity is not properly handled through suitable econometric procedures, the estimated associations may merely reflect spurious comovements between regressors and the outcome variable rather than genuine causal linkages (Santoso and Wijaya, 2026). One widely accepted and effective solution to this issue is the application of *Instrumental Variable* (IV) regression, which has been extensively employed in international empirical research. IV regression is specifically designed to address potential endogeneity concerns and to generate robust and consistent estimates (Zhang *et al*., 2026; Solangi *et al*., 2025). In empirical practice, IV estimation is commonly implemented through estimators

such as the Generalized Method of Moments (GMM) and Two Stage Least Squares (2SLS).

The IV-2SLS framework mitigates endogeneity by relying on an external instrument that extracts the component of variation in the endogenous regressor that is orthogonal to the disturbance term, thereby enabling more reliable and less biased causal inference. For an instrument to be regarded as valid, two core requirements must be met: relevance and exogeneity. The relevance condition implies that the selected instrument must display a sufficiently strong association with the endogenous regressor, ensuring adequate predictive power over its fluctuations (Justiniano Medina and Valentová, 2025). For nonlinear outcomes, consistency often requires the use of two stage residual inclusion or a control function specification rather than relying solely on conventional first-stage fitted values. Nevertheless, one of the main concerns associated with 2SLS is instrument weakness, particularly in small and heterogeneous samples (Al Asady and Groening, 2025).

In addition, to further verify the robustness of the empirical findings, the study also employs the IV GMM estimator as an additional regression framework. The integration of the GMM estimator within the IV framework improves reliability, efficiency, and robustness under nonnormal error distributions. Moreover, this approach helps mitigate endogeneity arising from the relationship between the error component and lagged dependent variables. The GMM estimator has also demonstrated strong performance in handling small sample sizes and exhibits desirable properties in reducing small sample bias (Zia *et al*., 2026; Kendo and Brou, 2025; Wang *et al*., 2025). Furthermore, GMM is particularly effective in alleviating common sources of endogeneity in empirical analyses, including omitted variable bias, simultaneity, and measurement errors. The use of lagged values as instruments helps ensure that the estimated relationships remain unbiased and consistent (Al-Kubaisi and Khalaf, 2025). For these reasons, in order to assess the endogeneity issue in the present study, industrial combustion carbon emissions and energy imports, net (% of energy use) with their lagged values were incorporated as instrumental variables. The corresponding regression results are reported in Table 9 below.

The overidentification test is a standard diagnostic procedure used in GMM and 2SLS models to assess the validity of the instrumental variables (IVs). According to the results reported in Table 9, the statistics and corresponding probability values of both the Hansen's J test and the Sargan Basmann test indicate that the null hypothesis, stating that the instrumental variables are valid and exogenous, cannot be rejected at the 5% significance level. Therefore, the instrumental variables employed in both regression specifications can be considered valid. The endogeneity assessment was further conducted using the GMM C test and the Durbin Wu Hausman test. Based on the reported test statistics and probability

values, the null hypothesis that the variables are exogenous cannot be rejected at the 5% significance level. Accordingly, the findings suggest that the model does not suffer from an endogeneity problem.

Table 9: Robustness Test Results

	IV-GMM Regression				IV-2SLS Regression			
Dep. var: *REN*	**Coeff.**	**Std. err.**	***z*-stat.**	***p*-value**	**Coeff.**	**Std. err.**	***z*-stat**	***p*-value**
ln *GDP*	−0.032	0.007	−4.46	(0.000)***	−0.025	0.010	−2.38	(0.017)**
HDI	0.789	0.345	2.28	(0.022)**	1.358	0.613	2.21	(0.027)**
ET	−0.020	0.038	−0.54	(0.586)	−0.059	0.093	−0.64	(0.523)
Constant	0.427	0.325	1.31	(0.189)	−0.162	0.797	−0.20	(0.838)
Diagnostic tests results								
Overidentifying tests:	**Test stat.**		***p*-value**		**Test stat.**		***p*-value**	
Hansen's *J* test	17.044		(0.106)					
Sargan–Basmann test					17.044		(0.106)	
Endogeneity tests:								
GMM *C* test	0.261		(0.609)					
Durbin–Wu–Hausman test					0.515		(0.472)	

Note: ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively.
Source: Authors' own computations

The panel threshold regression results indicate that the ln *GDP* variable has a positive and statistically significant effect. However, when endogeneity concerns are explicitly addressed using the IV 2SLS and IV GMM estimators, this effect turns negative and remains statistically significant. This discrepancy suggests that the threshold regression estimates may be affected by endogeneity related bias. At the same time, the nonlinear nature of the threshold framework implies that the direction of the relationship may change across different regimes, which may also contribute to this divergence in findings. In contrast, because the instrumental variable approaches are specifically designed to mitigate endogeneity, the IV

2SLS and IV GMM estimates may provide more reliable evidence for causal interpretation. Accordingly, causal inferences regarding ln *GDP* should rely primarily on the IV based results. In this context, structural heterogeneity within the European Union and the continued dependence on fossil fuels in some member states may also contribute to the emergence of this negative relationship. The finding may indicate that economic growth still increases overall energy demand through a scale effect, while the technological effect has not yet become sufficiently dominant. Another possible explanation is that, as income levels rise within the EU, high carbon footprint activities such as luxury consumption, second homes, private jets, and large vehicles may expand. This can increase total energy demand while reducing the relative share of renewable energy consumption. Such a pattern may also point to the redeterioration of environmental indicators at very high-income levels, which is consistent with the N shaped Environmental Kuznets Curve (EKC) hypothesis. In other words, it may be indirectly argued that, during the study period, EU countries are positioned in the third stage of the N shaped EKC. This interpretation is also supported by recent empirical studies providing evidence in favor of the N shaped EKC in EU countries (Boujedra, 2026; Topaloglu *et al*., 2025; Cantero-Galiano, 2025; Liobikiene *et al*., 2025; Saud *et al*., 2024).

The *HDI* variable, on the other hand, exerts a positive and statistically significant effect on renewable energy consumption, which is fully consistent with the panel threshold regression findings. The effect of the *ET* variable on the dependent variable is negative, although it is not statistically significant. Nevertheless, this result is also in line with the panel threshold regression estimates. Overall, the IV GMM and IV 2SLS regression results largely complement the panel threshold findings and provide additional support for the robustness of the relationships among the variables.

6. Conclusion and Policy Implications

Governments can employ a range of policy tools to lessen reliance on fossil-based energy and encourage the expansion of renewable alternatives. Since the effects of environmental damage are not confined solely to polluters, such harms tend to affect a broader segment of society as well as the natural environment. Therefore, protecting both the environment and society from the consequences of negative externalities can be achieved through policy mechanisms developed under state leadership. In this context, environmental taxation is widely viewed as an effective instrument for internalizing negative externalities and guiding the behavior of economic actors. This study examines how environmental tax measures influence renewable energy use by incorporating the financial deepening variable as a threshold value. Accordingly, the analysis is based on panel data from 27 EU member states cover-

ing the years 2014 to 2023. The data was prepared for econometric analysis through basic statistical tests, correlation analysis, cross sectional dependence tests, stationarity analysis, homogeneity tests, and linearity assessments. Using a panel threshold regression framework, the empirical results can be summarized as follows.

First, it is found that the impact of environmental taxes on renewable energy consumption exhibits a nonlinear pattern depending on the level of financial deepening. In this context, the threshold value for the financial deepening variable is estimated to be 0.888.

Second, when financial deepening is at or below the estimated threshold value, environmental taxes are observed to have a negative and statistically considerable effect on renewable energy consumption. However, even when financial deepening exceeds the threshold, the impact of environmental taxes remains negative and significant, with the magnitude of this effect becoming even stronger. This finding suggests that the intensification of the adverse effect of environmental taxes under higher levels of financial deepening may be explained not only by rising costs, but also by the pass through of the tax burden to energy prices, the allocation of financial resources toward conventional sectors rather than green investments, and the insufficient channeling of environmental tax revenues into renewable energy incentives. In practical terms, complementary financial policy tools such as green credit incentives, preferential loan schemes for renewable energy projects, targeted fiscal subsidies, and sustainable finance regulatory adjustments may help redirect credit flows toward green investments and mitigate the stronger negative taxation effect observed under deeper financial regimes.

Third, the coefficient of gross domestic product is found to be positive and statistically considerable. Therefore, economic growth in EU countries, and thus rising individual income levels, positively affects renewable energy consumption. It is understood that individuals in the sampled countries tend to shift toward renewable sources in their energy use as income increases.

Finally, it is found that increases in human development levels raise the demand for renewable energy use in EU countries. Improvements in human development are characterized by factors such as education, healthcare services, and welfare standards enhance environmental awareness and ecological consciousness. This, in turn, encourages individuals to move toward cleaner energy alternatives in order to achieve healthier living conditions. This finding may plausibly reflect a stronger transmission of environmental tax shocks through financial channels under deeper financial regimes, including lending conditions, sectoral credit allocation, and capital reallocation decisions. However, given the absence of direct investment flow indicators, this interpretation should be viewed as a theoretically

informed explanation rather than a definitive causal mechanism. Alternative explanations, such as sector specific fossil fuel dependence, heterogeneous credit market structures, or delayed green investment responses, may also contribute to the stronger negative coefficient observed above the threshold. In addition, earmarking a portion of environmental tax revenues for renewable energy subsidies, grid modernization, and green technology financing may help offset the stronger adverse effect and improve the overall effectiveness of taxation policies in supporting the energy transition.

While the study offers important contributions, certain limitations remain and simultaneously open promising avenues for future research. First, the analysis is limited to 27 EU member states over the 2014–2023 period; future studies may extend the sample to a broader set of developed and emerging economies and longer time horizons to test the robustness of the identified threshold effects. Second, the present study employs financial deepening as the sole threshold variable. Future research may consider alternative financial indicators, such as green credit, sustainable finance instruments, or financial inclusion measures, to examine whether similar nonlinear mechanisms emerge. Finally, disaggregating environmental taxes into energy, transport, pollution, and resource tax components may provide more detailed policy insights into which tax channels most strongly support renewable energy transitions.

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