



EXPLORING THE RELATIONSHIP BETWEEN ENVIRONMENTAL TAXATION AND ENERGY PRODUCTIVITY IN VIETNAM: AN ARDL ANALYSIS

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Abstract: This study investigates the impact of environmental taxation on green growth in Vietnam over the period 2010–2022, situated within the broader context of sustainable development and energy transition. Utilizing annual time-series data, the study employs the Autoregressive Distributed Lag (ARDL) model and its associated Error Correction Model (ECM) to examine both short-run dynamics and long-run relationships. Empirical results reveal that economic growth and renewable energy consumption are positively associated with energy productivity, particularly regarding the long-run coefficients. Renewable energy exhibits a relatively stable and positive relationship, highlighting its vital role in improving energy efficiency and supporting the transition toward a low-carbon economy. While environmental taxation is not statistically significant in the short run, it shows a positive long-run association. While the error correction term is negative and statistically significant, the Bounds test provides only limited evidence of cointegration, likely due to the small sample size. The findings suggest that environmental taxes have possible associations in the Vietnam context over the sample period. The study provides policy-relevant insights for improving environmental tax design and promoting sustainable growth strategies in emerging economies.

Keywords: environmental taxation, green growth, energy productivity, renewable energy, ARDL model, Vietnam

1. Introduction

In recent decades, there have been increasingly severe environmental challenges, particularly climate change, natural resource degradation, and environmental pollution at a global level. The global average temperature has risen by approximately 1.1°C above pre-industrial levels, mainly due to greenhouse gas emissions from human production and

consumption [1]. In addition, the International Energy Agency (IEA) reported that global CO₂ emissions reached about 37.5 billion tons in 2022, the highest level in history, reflecting the substantial pressure of the traditional fossil-fuel-based growth model [2].

Several countries and international organizations have shifted toward green growth models to sustain economic growth while minimizing adverse environmental impacts. The World Bank defines green growth as a process of promoting economic growth and development while ensuring that natural resources continue to provide essential environmental services for people [3]. Within this framework, environmental taxes are regarded as an important economic policy instrument, playing a key role in influencing production and consumption behavior and internalizing environmental externalities. According to data from the Organisation for Economic Co-operation and Development (OECD), environmentally related taxes, including energy and emissions taxes, account for a significant share of GDP in many economies, reflecting their extensive use in public policy. Statistical evidence shows that environmentally related tax revenue in many developed countries is equivalent to around 1–2% of GDP or higher, depending on each country's tax structure.

Viet Nam, a rapidly developing economy, faces similar challenges. During 2010–2022, Viet Nam maintained relatively high GDP growth, averaging about 6–7% per year, while CO₂ emissions increased rapidly, mainly from the energy and industrial sectors. According to the Global Carbon Project, Viet Nam's CO₂ emissions rose from about 148 million tons in 2010 to nearly 328 million tons in 2022, making the country one of the fastest-growing emitters in Southeast Asia [4]. Recognizing the negative impacts of the traditional growth model, the Vietnamese Government has gradually developed and implemented policies aimed at green growth and sustainable development. A key milestone was the enactment of the Law on Environmental Protection Tax in 2010, effective from January 1, 2012. This was the first specific tax in Viet Nam targeting products and goods that have adverse environmental effects, such as petroleum, coal, plastic bags, and ozone-depleting substances.

In practice, environmental protection tax revenue in Viet Nam increased sharply during 2012–2019, rising from about VND 11.4 trillion in 2012 to more than VND 64 trillion in 2019, accounting for approximately 0.8% of GDP, before declining in 2020–2022 due to policy measures supporting economic recovery after the COVID-19 pandemic [5]. However, the key question is whether this increase and adjustment in environmental taxes has truly contributed to green growth or has mainly served as a source of budget revenue. Although several studies have addressed environmental taxes or greenhouse gas emissions in Viet Nam, research

directly examining the relationship between environmental taxes and green growth during 2010–2022 remains limited, especially studies using empirical data utilizing the ARDL approach to provide scientific evidence for improving environmental tax policy as Viet Nam pursues sustainable development and long-term carbon neutrality.

2. Literature reviews

In recent decades, the relationship between environmental taxation and green growth has attracted considerable attention from scholars worldwide, particularly in the context of climate change and the transition toward a low-carbon economy. International studies have primarily approached this issue by examining the impacts of environmental taxes or related fiscal instruments on greenhouse gas emissions, economic growth, renewable energy consumption, and various indicators reflecting green growth. A common strand of the literature focuses on the nexus between environmental taxation, economic growth, and CO₂ emissions. The theoretical foundation for using taxes to internalize negative externalities, and subsequent empirical studies have tested the effectiveness of this instrument in modern contexts [6]. [7] finds that environmental tax reforms in European countries can reduce emissions without significantly harming long-term economic growth. Similarly, [8] suggests that well-designed environmental taxes, combined with appropriate revenue recycling, can support sustainable growth.

Recent studies increasingly employ panel or time-series data to examine the long-term effects of environmental taxes on economic and environmental indicators. For instance, [9] using OECD country data over an extended period, shows that environmental taxes are positively associated with green growth once economies reach a certain development threshold, while also reducing carbon emission intensity. These findings highlight the role of environmental taxes in shaping energy consumption behavior and facilitating the transition to a green economy. In addition, some studies explicitly explore the interlinkages among environmental taxation, economic growth, and renewable energy, which constitute the core components of green growth. [10] using global data, find that environmental taxes promote renewable energy use and thereby indirectly reduce CO₂ emissions, particularly in countries with relatively strong institutional frameworks.

Other contributions extend the analysis by incorporating key control variables such as per capita income and renewable energy consumption to better capture the impact of environmental taxes on emissions. For example, [11] demonstrates that environmental taxes,

together with economic growth and the expansion of renewable energy, significantly improve environmental performance and reduce CO₂ emissions in the long run. This approach underscores the importance of jointly considering economic conditions, tax policy, and energy structure in green growth analysis. Moreover, evidence from developing and middle-income countries suggests that the effects of environmental taxation may differ from those observed in advanced economies. [12] focusing on ASEAN countries, finds that environmental taxes and economic growth are associated with improvements in environmental quality; however, the magnitude of the effect depends on the share of renewable energy in the national energy mix.

In addition to conventional indicators such as carbon emissions and environmental quality, energy productivity has gained increasing attention as a comprehensive measure of sustainable economic performance. Energy efficiency (EE) plays a pivotal role in fostering sustainable economic growth while mitigating environmental degradation, particularly in the context of global climate change. A key dimension of EE is energy intensity (EI), which measures the amount of energy required to generate economic output. Improvements in EE contribute to reducing EI through technological innovation, structural transformation, and behavioral change. Closely related to these concepts is energy productivity (EP), defined as the amount of GDP generated per unit of energy consumption. EP serves as a measure of how efficiently an economy, industry, or society uses energy to generate economic value. The higher energy productivity means that less energy is needed to produce a unit of economic value. As the inverse of EI, EP reflects how efficiently an economy utilizes energy to create value and serves as a partial-factor productivity indicator of energy use. Consequently, higher energy productivity signifies improved energy efficiency, enhanced economic performance, and reduced environmental pressure. This makes EP a robust and policy-relevant proxy for assessing green growth and sustainable development [13].

Overall, the international literature indicates that environmental taxation is a policy instrument capable of influencing green growth through multiple channels, including economic growth, energy consumption, and the transition toward renewable energy. However, empirical findings remain mixed and context-dependent, varying with country-specific conditions, levels of economic development, and tax design. This provides a key rationale for further examining the impact of environmental taxes on green growth in Viet Nam using an appropriate quantitative approach and data for the period 2010–2022.

In Vietnam, research on environmental taxation and green growth has gained increasing attention since the Environmental Protection Tax Law came into effect in 2012 and the National

Green Growth Strategy was introduced. Most domestic studies approach the issue from a policy perspective, focusing on tax revenue performance and the impacts of environmental taxes on state budget revenues, environmental protection, and sustainable development. Overall, the findings suggest that environmental taxes contribute to environmental improvement, although their effectiveness depends on economic growth conditions and the structure of energy use. Several studies indicate that increases in environmental tax revenue are associated with reductions in CO₂ emissions in Viet Nam. Specifically, [14] finds a long-run negative relationship between environmental tax revenue and CO₂ emissions, implying that such taxes can help curb polluting activities. This supports the view of environmental taxation as an economic instrument for steering production and consumption toward lower-emission patterns. Similarly, [15] shows that environmental taxes continue to play a positive role in improving environmental quality when considered alongside other economic factors. Their findings confirm that both environmental taxes and renewable energy consumption contribute to reducing CO₂ emissions, whereas economic growth, in the absence of energy structure transformation, tends to increase emissions. This highlights that the effectiveness of environmental taxes is more pronounced when the economy shifts toward cleaner energy sources. Furthermore, several domestic studies examine the relationship between economic growth and CO₂ emissions, reflecting the characteristics of Viet Nam's growth model. [16] finds that economic growth leads to higher CO₂ emissions in the long run, indicating that Viet Nam's growth process remains closely tied to energy consumption and resource exploitation, thereby exerting considerable pressure on the environment.

3. Method

3.1. Data sources

The study employs secondary annual time-series data for the period 2010–2022, collected from official and reliable sources. The variables used in the analysis include:

Energy productivity (EP): serves as a key proxy for green growth, measuring the amount of economic value (GDP) generated per unit of energy consumption. EP is calculated as the ratio of GDP to total energy consumption. GDP is typically expressed at constant 2015 USD using purchasing power parity (PPP), while energy consumption is measured in kilotons of oil equivalent (ktoe). It indicates how efficiently an economy uses energy to produce value, with higher values reflecting greater efficiency and sustainability. Data are sourced from Enerdata (2025) and the World Bank (2025).

Environmental tax (ET): measured by environmentally related tax revenue (% of GDP), capturing the extent to which tax instruments are used to regulate environmentally harmful activities. Data are obtained from OECD (2023).

GDP per capita (GDPpc): representing the level of economic development and the capacity for investment in technology, innovation, and energy efficiency. Data are sourced from the World Bank (2025).

Renewable energy consumption (REC): measured as renewable energy consumption (% of total final energy consumption), reflecting the share of renewable energy in total energy use and the transition toward cleaner and more sustainable energy sources. Data are obtained from the World Bank (2025).

3.2. Data analysis

Based on the dataset and the specified model, this study employs the Autoregressive Distributed Lag (ARDL) approach to examine the relationship between environmental taxation and green growth in Viet Nam. The ARDL model is selected due to its suitability for small-sample time-series data and its ability to accommodate variables with mixed orders of integration, namely $I(0)$ and $I(1)$.

The empirical analysis follows a structured procedure to ensure the robustness and reliability of the results. First, descriptive statistics are conducted to summarize the main characteristics of the dataset and to examine the trends and variability of the variables over time. Next, the stationarity of the time series is tested using the Augmented Dickey–Fuller (ADF) test to determine the order of integration of each variable, providing a basis for appropriate model selection.

Subsequently, the ARDL model is estimated with optimal lag lengths determined by information criteria, allowing for a comprehensive representation of the dynamic relationships among variables. Then, the Bounds test is performed to assess the existence of a long-run cointegration relationship among the variables. Once cointegration is confirmed, the Error Correction Model (ECM) is employed to simultaneously analyze short-run dynamics and the speed of adjustment toward long-run equilibrium.

Finally, a series of diagnostic tests is conducted to evaluate the model's adequacy and reliability. In addition, standard errors are corrected using the Newey–West method in the presence of potential violations of classical econometric assumptions. Given the short time dimension of the dataset, the study acknowledges that unit root and cointegration tests may

have limited power and therefore adopts a cautious interpretation of pretesting and long-run results.

4. Results

4.1. Descriptive statistics

Prior to conducting econometric analyses and estimating the ARDL model, descriptive statistics are performed to provide an overview of the characteristics, trends, and variability of the variables used in the model. This step not only offers a preliminary assessment of data validity but also serves as an important basis for selecting appropriate models and estimation techniques in subsequent analyses.

The dataset consists of 13 annual time-series observations covering the period from 2010 to 2022. The variables include EP, ET, GDPpc, and REC. All variables are subsequently transformed into natural logarithms to mitigate heteroskedasticity and to allow the estimated coefficients to be interpreted as elasticities.

Table 1. Descriptive statistics analysis of variables

Variable	Obs	Mean	S.D	Min	Max
ln_EP	13	-5.722	0.044	-5.798	-5.638
ln_ET	13	-0.717	0.441	-1.427	-0.198
ln_GDPpc	13	-5.909	0.190	-6.200	-5.621
ln_REC	13	3.325	0.258	2.939	3.634

Source: Author' work

After transforming the variables into natural logarithms, the descriptive statistics indicate that ln_EP, ln_ET, ln_GDPpc, and ln_REC exhibit more stable distributions, with substantially reduced standard deviations compared to the original variables. Specifically, ln_EP has a mean of -5.7223 with a standard deviation of 0.0445; ln_ET has a mean of -0.7176 with a standard deviation of 0.4410; ln_GDPpc has a mean of -5.9094 with a standard deviation of 0.1906; and ln_REC has a mean of 3.3252 with a standard deviation of 0.2585. The reduction in data dispersion after logarithmic transformation suggests that this approach is appropriate and improves the statistical properties of the time series.

Overall, the descriptive statistics confirm that the variables are suitable for econometric analysis. The data do not exhibit significant outliers, and the variables adequately capture the economic–energy trends over the study period. Moreover, the logarithmic transformation enhances data stability, providing a solid foundation for subsequent unit root testing and ARDL model estimation in the following sections.

4.2. Testing the stationarity of time series

Before estimating the ARDL model, testing for stationarity is an important step to avoid spurious regression and to guide model selection. In principle, the ARDL approach can be applied when variables are integrated of order $I(0)$ and/or $I(1)$, provided that non are integrated of order two, $I(2)$. Therefore, unit root testing is a prerequisite to confirm the suitability of the ARDL methodology for this study. However, in small samples, unit root tests such as the Augmented Dickey–Fuller (ADF) test often suffer from low statistical power, which may lead to inconclusive or ambiguous results.

In this study, the ADF test is conducted with a lag length of one, which is appropriate given the limited number of observations (13 annual data points). The results at levels suggest that all variables (\ln_EP , \ln_ET , \ln_GDPpc , and \ln_REC) are non-stationary, as the test statistics fail to reject the null hypothesis of a unit root at conventional significance levels. However, these findings should be interpreted cautiously, as the small sample size reduces the reliability of the test in distinguishing between stationary and non-stationary processes.

Table 2. Level testing with a lag of 1

Variable	ADF statistics	1%	5%	10%	P-value
\ln_EP	-2.484	-3.750	-3.000	-2.630	0.1193
\ln_ET	-1.704	-3.750	-3.000	-2.630	0.4291
\ln_GDPpc	-0.209	-3.750	-3.000	-2.630	0.9374
\ln_REC	-0.507	-3.750	-3.000	-2.630	0.8907

This implies that there is insufficient evidence to reject the null hypothesis (H_0) of a unit root, indicating that \ln_EP is non-stationary in levels. Similarly, \ln_ET has a test statistic of -1.704 with a p-value of 0.4291; \ln_GDPpc has a test statistic of -0.209 with a p-value of 0.9374; and \ln_REC has a test statistic of -0.507 with a p-value of 0.8907. These results consistently confirm that all logarithmic variables are non-stationary at levels.

Table 3. Level testing with a lag of 1

Variable	ADF statistics	1%	5%	10%	P-value
$\Delta \ln_{EP}$	-2.406	-3.750	-3.000	-2.630	0.1401
$\Delta \ln_{ET}$	-1.980	-3.750	-3.000	-2.630	0.2955
$\Delta \ln_{GDPpc}$	-5.586	-3.750	-3.000	-2.630	0.0000
$\Delta \ln_{REC}$	-3.568	-3.750	-3.000	-2.630	0.0064

When the test is applied to the first-differenced series, \ln_{GDPpc} and \ln_{REC} appear to be stationary at the 1% level ($Z(t) = -5.586$ and -3.568 , respectively), while \ln_{EP} and \ln_{ET} remain statistically insignificant according to the ADF test. This mixed evidence does not allow for a definitive classification of all variables into clear integration orders. Rather than providing conclusive results, the unit root tests indicate a degree of uncertainty regarding the precise stochastic properties of the series. However, given the limited number of observations, the ADF test may suffer from low power; therefore, these results can still be considered acceptable when interpreted alongside subsequent tests and estimation methods.

Given this ambiguity, the choice of the ARDL framework is maintained primarily due to its relative flexibility in handling variables that are potentially integrated of different orders ($I(0)$ and $I(1)$). At the same time, it is important to emphasize that the pretesting results should not be interpreted as definitive proof of integration properties. Instead, they provide indicative guidance under conditions of limited data availability. Therefore, the subsequent ARDL estimations and cointegration analysis should be interpreted with caution. The small sample size and the limited power of unit root tests imply that the results may be sensitive to specification choices, and the findings should be viewed as suggestive rather than conclusive evidence regarding the underlying relationships among the variables.

4.3. ARDL model estimation results

After confirming that the data satisfy the conditions for applying the ARDL model through unit root testing, the study proceeds to estimate the ARDL model to examine the relationship among EP, ET, GDPpc, and REC. The model is specified in logarithmic form, allowing the estimated coefficients to be interpreted as elasticities, thereby capturing the relative impacts among variables.

Based on a maximum lag length of one and the small sample size (12 observations for the period 2011–2022), the estimation results indicate that the optimal model selected is ARDL(1,0,0,1). This implies that the dependent variable \ln_EP in the model with one lag, \ln_REC includes both its current value and one-period lag, while \ln_ET and \ln_GDPpc are included only in their contemporaneous forms.

Table 4. ARDL model estimation results (1,0,0,1)

Variable	Coef.	Std.Err	t-statistic	P-value
$\ln_EP(-1)$	-0.645	0.495	-1.30	0.240
\ln_ET	0.104	0.068	1.52	0.180
\ln_GDPpc	0.815	0.411	1.98	0.094
\ln_REC	0.422	0.235	1.79	0.123
$\ln_REC(-1)$	0.356	0.185	1.92	0.103
Constant	-7.132	2.198	-3.24	0.018
Obs.		12		
R-squared		0.4447		
Adj R-squared		-0.0181		
Root MSE		0.0439		

The ARDL estimation results indicate that the coefficient of the lagged dependent variable $\ln_EP(-1)$ is negative (-0.6456), but statistically insignificant at conventional levels. This suggests that past energy productivity tends to exert a negative influence on current energy productivity; however, the effect is not strong enough to be conclusively established within the sample.

Regarding the explanatory variables, the coefficient of \ln_ET is positive (0.1044), implying that environmental taxation tends to enhance energy productivity. Nevertheless, this coefficient is not statistically significant at the 10% level, indicating that the short-run impact of environmental taxes on energy productivity is not clearly evident. This result may reflect the lagged response of firms and the broader economy to environmental tax policies, as adjustments in technology and production behavior often require time to materialize.

The variable \ln_GDPpc has a relatively large positive coefficient (0.8158) and is statistically significant at the 10% level. This indicates that economic growth plays an important role in enhancing energy productivity. As GDP per capita increases, the economy needs greater resources to invest in advanced technologies, improve production processes, and enhance energy efficiency, thereby promoting higher energy productivity.

For \ln_REC , the coefficient of the contemporaneous term is 0.4220, while the coefficient of the one-period lag is 0.3565. Both coefficients are positive and statistically significant at the 10% level. These results suggest that renewable energy consumption has a positive impact on energy productivity, not only in the current period but also with spillover effects into the subsequent period. This reflects the role of renewable energy in improving overall energy efficiency by replacing less efficient and more polluting conventional energy sources.

The R-squared value of the model is 0.4447, suggesting that approximately 44.47% of the variation in energy productivity is explained by the independent variables in the model. Although this value is not particularly high, it is acceptable given the small sample size and the macroeconomic context, where many external factors beyond the model may influence the dependent variable.

4.4. The Error Correction Modeling (ECM)

To simultaneously examine both long-run and short-run relationships, the study further estimates the ARDL model in its ECM form using the *ec1* specification. The ECM results allow for a clear decomposition of long-run effects, short-run dynamics, and the speed of adjustment of the system when deviations from the long-run equilibrium occur.

The error correction term, represented by the coefficient of $\ln_EP(-1)$ in the adjustment (ADJ) component, is -1.6456 and statistically significant at the 5% level. The negative sign and statistical significance confirm the existence of a long-run equilibrium adjustment mechanism. The absolute value greater than one indicates a relatively rapid speed of adjustment, suggesting the presence of short-run overshooting. In other words, when energy productivity deviates from its long-run equilibrium, the system adjusts strongly to restore equilibrium in subsequent periods.

In the long-run relationship, the variables \ln_ET , \ln_GDPpc , and \ln_REC all exhibit positive coefficients. Among them, \ln_GDPpc and \ln_REC are statistically significant, suggesting that economic growth and renewable energy consumption are potentially important drivers of energy productivity over time. However, given that the Bounds test does not provide

strong evidence of cointegration, these long-run coefficients should be interpreted as tentative association rather than definitive equilibrium relationships.

Table 5. The ARDL–ECM result (ec1)

D.ln_EP	Coef.	Std. Err.	t	P>t	[95% Conf. Interval]	
ADJ						
ln_EP L1.	-1.645	0.495	-3.32	0.016	-2.857 -0.433	
Long-run						
ln_ET L1.	0.063	0.032	1.96	0.098	-0.015 0.142	
ln_GDPpc L1.	0.495	0.169	2.93	0.026	0.081 0.910	
ln_REC L1.	0.473	0.144	3.28	0.017	0.120 0.826	
Short-run						
ln_ET D1.	0.104	0.068	1.52	0.180	-0.064 0.273	
ln_GDPpc D1.	0.815	0.411	1.98	0.094	-0.190 1.821	
ln_REC D1.	0.422	0.235	1.79	0.123	-0.154 0.998	
_cons	-7.132	2.198	-3.24	0.018	-12.511 -1.752	
R-squared			0.671			
Adj R-squared			0.397			
Root MSE			0.043			

The positive coefficient of ln_ET indicates that environmental taxation may contribute to improving energy productivity in the long run. This reflects that environmental tax policies can incentivize firms to adopt more energy-efficient and environmentally friendly production practices; however, their effectiveness depends largely on tax rates, coverage, and complementary policy measures.

In the short-run dynamics, the coefficients of the first differences of ln_ET, ln_GDPpc, and ln_REC are all positive but not statistically significant. This suggests that short-term shocks in environmental taxation, income, and renewable energy consumption do not produce immediate or pronounced effects on energy productivity. This finding is consistent with the

nature of energy productivity, which typically responds slowly to policy and economic changes due to its dependence on long-term investments and technological innovation.

In summary, the ARDL and ECM estimation results reveal a dynamic relationship among energy productivity, environmental taxation, economic growth, and renewable energy consumption. While short-run effects remain limited and statistically insignificant, economic growth and renewable energy emerge as potential key drivers of energy productivity over time, whereas environmental taxation exerts a positive but modest influence that requires further strengthening through effective policy design.

The Bounds test method

To determine the existence of a long-run relationship among EP, ET, GDPpc, and REC, the study employs the Bounds cointegration test developed by [17]. This test is particularly suitable in the presence of variables with mixed orders of integration, provided that none of the variables is integrated of order two, I(2).

Table 6. The testing result (Bounds Test)

	10%		5%		1%		p-value	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
F	3.808	5.294	5.201	7.060	9.750	12.642	0.155	0.291
t	-2.643	-3.680	-3.162	-4.300	-4.395	-5.784	0.040	0.148
F	3.053							
t	-3.323							
H₀	There is no cointegration relationship.							

The Bounds test results indicate that the null hypothesis of no cointegration can not be rejected at conventional significance levels. This suggests that the evidence for a stable long-run equilibrium relationship among the variables is not strong enough. While the ECM results and long-run coefficients provide some indication of co-movement among the variables, these findings may not be interpreted as conclusive evidence of cointegration because of the studies using short time-series data, particularly with a limited number of observations in the 2010–2022 period. As such, the failure to reject the null hypothesis does not necessarily imply the absence of a long-run relationship but rather calls for cautious interpretation of the results.

Autocorrelation test for residuals

One of the key assumptions in time-series regression models is that the residuals are free from autocorrelation. To test this assumption, the study employs the Breusch–Godfrey LM test with a lag length of 1. The test results show that the Chi-square statistic is 10.573 with a p-value of 0.0011. At the 1% significance level, the null hypothesis of “no autocorrelation” is rejected. This indicates that the residuals of the ARDL model exhibit first-order autocorrelation.

Table 7. Autocorrelation test Breusch–Godfrey

	Chi-square	df	P-value
1	10.573	1	0.0011

Ho: No autocorrelation

The presence of autocorrelation in the residuals may stem from the dynamic nature of time-series data, particularly in the context of a small sample and macroeconomic variables that tend to follow cyclical patterns. If left unaddressed, this issue can lead to biased standard errors, thereby affecting the statistical inference of the estimated coefficients.

Adjusting the standard error using the Newey–West method

Since there is a presence of autocorrelation in the residuals. To address this issue and ensure the reliability of the estimation results, the Newey–West method was applied with a lag length of one. This approach provides robust standard errors that correct for both autocorrelation and heteroskedasticity in the error terms. Importantly, the use of Newey–West corrections does not eliminate the underlying issue of autocorrelation or fully resolve potential model misspecification. Rather, it adjusts the estimated standard errors to make statistical inference more robust in the presence of such problems. As a result, while the significance levels of the coefficients become more reliable, the possibility of residual dependence or omitted variable bias cannot be entirely ruled out.

The regression results with Newey–West standard errors show that the estimated coefficients retain their signs and relative magnitudes compared to the original ARDL model, suggesting a degree of consistency in the findings. Key variables, such as GDP per capita and renewable energy consumption, remain statistically significant, reinforcing their potential role in influencing energy productivity. However, these results should be interpreted with appropriate caution, given the small sample size and the remaining econometric limitations.

Table 8. Regression results with Newey–West standard errors

Variable	Coef	Std.err	t-statistic	P-value
ln_EP(-1)	-0.645	0.263	-2.45	0.050
ln_ET	0.104	0.059	1.75	0.131
ln_GDPpc	0.815	0.256	3.18	0.019
ln_REC	0.422	0.191	2.20	0.070
ln_REC(-1)	0.356	0.103	3.46	0.013
Constant	-7.132	1.060	-6.72	0.001
Obs			12	
F-statistic			3.83	
Prob > F			0.0664	

The coefficient of the lagged ln_EP remains negative and becomes statistically significant at the 5% level, indicating a meaningful short-run dynamic adjustment of energy productivity. The variable ln_GDPpc continues to exhibit a positive and statistically significant effect at the 5% level, reaffirming the important role of economic growth in enhancing energy productivity even after correcting the standard errors.

For ln_REC, both the contemporaneous and lagged coefficients are positive and statistically significant at the 10% to 5% levels, suggesting that renewable energy consumption has a positive and relatively stable impact on energy productivity. In contrast, ln_ET remains positive but statistically insignificant, indicating that the effect of environmental taxation is more likely to materialize in the long run rather than in the short run.

Overall, the application of robust standard errors strengthens the credibility of the empirical results, but it does not fully address all diagnostic concerns. Therefore, the findings should be viewed as reasonably robust but not definitive, and conclusions drawn from the model should remain appropriately qualified.

5. Conclusion and recommendations

This study aims to analyze the impact of key macroeconomic factors, including environmental taxation, GDP per capita, and renewable energy consumption, on energy

productivity in the context of a transition toward green growth and sustainable development. By employing time-series data and the ARDL approach combined with the ECM, the study provides a comprehensive assessment of the dynamic relationships among the variables in both the short and long run.

The estimation results indicate that energy productivity is influenced by economic and energy structure factors. In the short run, GDP per capita and renewable energy consumption have positive effects on energy productivity, highlighting the roles of economic growth and the transition toward cleaner energy sources in improving energy efficiency. The negative and statistically significant error correction term confirms the presence of an adjustment mechanism, whereby deviations from long-run equilibrium are gradually corrected over time.

In the long run, the estimated coefficients are consistent with theoretical expectations. GDP per capita continues to exert a positive effect, implying that economic development is associated with technological progress, improved production efficiency, and more efficient energy use. Renewable energy consumption has a positive and sustained impact on energy productivity, underscoring the critical role of energy transition in achieving green growth. Although environmental taxation does not show a clear short-run effect, its positive long-run coefficient suggests that it has the potential to incentivize more energy-efficient and environmentally friendly production and consumption behavior.

Diagnostic tests indicate that the ARDL model is generally appropriate for the dataset, despite the presence of residual autocorrelation. The use of Newey–West standard errors effectively addresses this issue and strengthens the reliability of the statistical conclusions. While the Bounds test does not provide strong evidence for a definitive long-run cointegration relationship, this result should be interpreted with caution given the small sample size and does not diminish the overall relevance of the findings.

Overall, the study achieves its objective of clarifying the relationships among economic factors, environmental policy, and energy transition in shaping energy productivity and provides empirical evidence to inform sustainable development policymaking.

Policy implications

First, the positive association between GDP per capita and energy productivity suggests that economic development may support improvements in energy efficiency. This implies that policies promoting growth in higher value-added and less energy-intensive sections could

potentially contribute to enhancing energy productivity. Nevertheless, the strength and stability of this relationship require further validation with more extensive data.

Second, the results indicate that renewable energy consumption is positively associated with energy productivity in both the short and long run. This finding provides tentative support for policies that encourage the expansion of renewable energy. However, the magnitude and persistence of this effect should be interpreted with caution, as the empirical evidence is based on a short time series and may be sensitive to model specification.

Third, environmental taxation shows a positive but statistically weak relationship with energy productivity. This suggests that environmental taxes may play a role in promoting more efficient energy use over time, although the current evidence does not allow for strong conclusions regarding their effectiveness. As such, any policy adjustments in this area should be considered carefully and in conjunction with complementary instruments such as technological support or regulatory measures.

More broadly, the findings highlight the potential importance of policy coordination across economic growth, energy transition, and environmental regulation. At the same time, the results underscore the need for further empirical research, particularly using longer time series or alternative methodologies, to better establish the robustness of these relationships before drawing firm policy conclusions.

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