

ECONOMIC GROWTH, ENERGY CONSUMPTION AND CARBON DIOXIDE EMISSIONS IN ROMANIA: AN ARDL ASSESSMENT OF THE ENVIRONMENTAL KUZNETS CURVE HYPOTHESIS

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Abstract:

The Environmental Kuznets Curve (EKC) hypothesis, originally introduced by Grossman and Krueger in 1991, proposes an inverted U-shaped relationship between economic growth and environmental degradation, suggesting that environmental pressure tend to worse in early stages of development before gradually improving as income level rise. The multidisciplinary nature of EKC research integrates environmental economics, energy studies, sustainability science and econometrics methodology, focusing on the relations between economic development and environmental degradation. At the same time, EKC research has emerged as a globally interconnected scientific field, supported by academic contributions from both developed and emerging economies. This reflects the worldwide relevance of the issue of harmonizing economic growth with the imperatives of ecological sustainability and highlights the increasingly important role of international partnerships in advancing environmental economics research. This study investigates the long-run and short-run relationships between economic growth, energy consumption, and carbon dioxide (CO₂) emissions in Romania over the period 1990–2023 by employing the Autoregressive Distributed Lag (ARDL) approach. The empirical findings reveal a stable long-run relationship in which energy consumption is the main driver of CO₂ emissions, while no robust evidence is found to support either the conventional or the N-shaped Environmental Kuznets Curve (EKC) hypothesis.

Key words: *Environmental Kuznets Curve, EKC, Inverted-U-shape, ARDL, Romania*

1. Introduction

Climate change and environmental degradation have intensified interest in understanding the relationship between economic growth and carbon dioxide (CO₂)

emissions. Driving from classic Kuznets Curve, initially designed to study the relationship between income per capita and income inequality, Environmental Kuznets Curve (EKC) describes the relationship between economic development and environmental quality, considering that there is an inverted U-shaped relationship between per capita income and environmental quality, starting from the idea that once GDP per capita increases, indicators of environmental degradation appreciation increase in an initial phase, but at some point (Turning Point - TP) they will begin to decrease once GDP per capita growth indicates a higher level of development.

When the dependent variable is carbon emission per capita, studies refer to as Carbon Kuznets Curve (CKC) hypothesis (Liddle, 2015). Another EKC approach considers energy (energy consumption per capita) as the dependent variable, in which case it is referred to as the Energy Kuznets Curve (EnKC) (Khatatbeh, 2026).

In the specialized literature (Leal, 2022) the relationship between CO₂ emissions and GDP is the most frequently analysed, driving CO₂ emission as the most often used environmental indicator. However, empirical evidence remains inconclusive, particularly for transition economies who's economic and energy systems have undergone profound structural transformations. Romania represents a relevant case for examining EKC hypothesis, due to its transition from a centrally planned to a market economy, accession to the European Union, and increasing commitment to climate neutrality objectives. During the last three decades, the country has experienced sustained economic growth alongside significant changes in its energy sector, raising important questions regarding the interaction between economic development, energy consumption, and environmental quality

2. Literature review

2.1. Conceptual evolution of the Environmental Kuznets Curve (EKC): From the traditional model to the N-shaped curve

The Environmental Kuznets Curve (EKC) transfers the logic of Kuznets's (1955) income-inequality hypothesis to the relationship between economic development and environmental pressure. Early empirical studies reported that several indicators of local air and water pollution first deteriorated and then improved as income rose (Grossman & Krueger, 1995; Selden & Song, 1994; Shafik, 1994). This pattern was formalized as an inverted U-shaped relationship: at low-income levels, industrial expansion and intensive resource use generate a dominant scale effect; at intermediate levels, production shifts toward less material-intensive activities; and at higher income levels, cleaner technologies, stronger institutions, and demand for environmental quality may produce composition and technique effects large enough to reduce emissions. The turning point therefore represents a conditional balance among competing forces, rather than an automatic consequence of growth.

In this context, the descending segment of the traditional EKC has been interpreted as evidence of environmental decoupling. Relative decoupling occurs when environmental pressure grows more slowly than economic output, whereas absolute decoupling requires

emissions to decline while income continues to increase. The N-shaped hypothesis questions the long-term stability of this process (Tapio, 2005).

Several mechanisms have been proposed to explain this trajectory. Environmental quality can behave as a normal or superior good, encouraging stricter regulation once basic needs are met; structural transformation can move output from heavy industry toward services; and technological progress can lower pollution intensity (Dinda, 2004, 2005). Andreoni and Levinson (2001) show that an EKC may also emerge from increasing returns to pollution abatement, while the Green Solow model links declining emissions intensity to technological progress (Brock & Taylor, 2010). These explanations imply different policy levers. A fall in territorial emissions may reflect effective decarbonization, but it may also reflect the relocation of pollution-intensive production through trade.

The traditional EKC has consequently faced substantial methodological criticism. Estimated shapes and turning points are sensitive to the pollutant, sample, time horizon, functional form, and treatment of unobserved heterogeneity (de Bruyn et al., 1998; Harbaugh et al., 2002; Stern et al., 1996). Stern (2004) further argues that results can be distorted by simultaneity, omitted variables, non-stationarity, and income polynomials that impose a common path on different countries. Long-run OECD evidence confirms that the relationship may change across historical periods (Churchill et al., 2018). Evidence from 182 countries is similarly heterogeneous: Azam et al. (2025) find support for the conventional EKC in only 84 cases. Thus, the inverted U is a testable hypothesis, not a universal development law.

A prominent extension is the N-shaped EKC, usually represented by a cubic income term with positive, negative, and positive coefficients. After the first turning point, emissions decline, but beyond a second threshold they increase again. This rebound may occur when the scale effects of affluent consumption outpace efficiency gains, when urban and transport systems remain locked into carbon-intensive infrastructure, or when technological and regulatory improvements reach diminishing returns. Panel quantile evidence reported by Allard et al. (2018) indicates that the N-shape varies across the emissions distribution, while Awan and Azam (2022) identify it for several G20 economies. Mahmood et al. (2021) also show that the curve's form changes when energy sources are modeled separately. The conceptual evolution from an inverted U to an N-shaped specification therefore shifts attention from a single income threshold to the durability of environmental improvement and provides a stronger rationale for testing both quadratic and cubic income effects in country-specific studies.

2.2. The energy dimension in EKC dynamics: Conventional fuel consumption versus renewable solutions

Energy is a principal transmission channel between income growth and environmental pressure. In the early development phase, higher output requires more electricity, heat, and transport, and systems dominated by coal, oil, and natural gas translate this scale effect into carbon emissions. Aggregate energy use, however, conceals changes in both energy intensity and the energy mix. An economy can consume more energy while reducing emissions if efficiency improves and low-carbon sources expand;

conversely, efficiency gains may be offset when fossil-fuel demand continues to rise. Suri and Chapman (1998) emphasize the joint roles of growth, trade, and energy, while Richmond and Kaufmann (2006) show that turning points for energy use and carbon emissions are neither identical nor consistently observed. The EKC turning point is therefore conditional on the energy system rather than on income alone.

The empirical literature increasingly separates conventional from renewable energy. For OECD countries, Shafiei and Salim (2014) report that non-renewable energy increases emissions, whereas renewable energy reduces them. Comparable results are obtained for EU economies by Bölük and Mert (2014) and Dogan and Seker (2016a), and for the United States by Dogan and Ozturk (2017). Bilgili et al. (2016) find that renewable energy reduces carbon emissions while preserving an EKC-type relationship, and Ben Jebli et al. (2016) show opposite effects for renewable and non-renewable consumption once trade is considered. Zoundi (2017) likewise finds a mitigating renewable-energy effect. These findings support treating renewables as a technique and composition channel that can strengthen the curve's descending segment. Nevertheless, intermittency, storage and grid constraints, embodied carbon, and rebound in total demand can weaken short-run gains; nuclear and other low-carbon sources may also alter the relationship (Menyah & Wolde-Rufael, 2010). Consequently, fossil-energy dependence tends to steepen the ascending segment of the EKC and delay its first turning point, whereas renewable energy and green electricity can reduce the emissions intensity of economic activity, flatten the pollution trajectory, and strengthen the descending segment of the curve.

Country-specific and structurally flexible models reinforce the need for energy disaggregation. For Turkey, Pata (2018) finds that renewable energy, urbanization, financial development, and structural breaks affect the estimated EKC. In Romania, Shahbaz et al. (2013) identify energy consumption as a central driver of carbon emissions within a long-run EKC framework. Mahmood et al. (2021) obtain N-shaped relationships for several primary and fossil-energy specifications in Egypt, showing that the second turning point can depend on the energy source. Using time-varying parameters for Jordan, Khatatbeh et al. (2026) distinguish the energy–income nexus from the emissions–income nexus and show that coefficients evolve with structural and policy conditions. Azam et al. (2025) find a generally positive contribution of energy use to emissions across a large global sample, although the EKC itself is far from universal. These studies demonstrate that GDP growth alone is insufficient to improve environmental quality when the energy system remains dependent on fossil fuels; lasting decoupling requires a structural transformation of energy production and consumption.

Taken together, renewable expansion can facilitate decoupling, while dependence on conventional fuels can postpone, flatten, or reverse the declining EKC segment. For Romania, an empirical model should control at least for renewable energy consumption and, where data permit, distinguish fossil or non-renewable energy from total energy use. Interaction terms, structural breaks, or time-varying coefficients could capture differences before and after grid modernization or policy reform. This specification avoids attributing energy-sector changes to income alone and permits a direct test of whether Romania follows a stable inverted U, an N-shaped path, or no common EKC pattern.

2.3. Comparative analysis at the global and regional levels: OECD economies, EU member states and emerging countries

In the academic literature, the behaviour and shape of the environmental Kuznets curve (EKC) vary significantly depending on the level of development and institutional rigor of the analysed regions. In the case of developed economies in the OECD area and the European Union, the dynamics of the EKC are marked by an accelerated pace of emission decoupling. Reference studies focused on the OECD group emphasize that the adoption of environmental technologies, trade in green goods and trade openness play a decisive role in reducing the carbon footprint (Dogan & Seker, 2016b; Gozgor, 2017; Apergis & Payne, 2012). Furthermore, the impact of economic globalization, the national financial structure and population aging act as major predictors of environmental quality in these highly industrialized countries (Zilio & Recalde, 2011; Wang et al., 2019; Koçak & Şarkgüneşi, 2018). In the context of the new technological wave, the interaction between financial digitalization and ecological innovation directly influences the shape of the curve, favouring its decreasing phase (Jahanger et al., 2021b; Saqib et al., 2022). At the level of the European Union, empirical evidence reflects a systemic concern for long-term sustainability and climate neutrality. Analyses show that achieving decarbonization targets requires deep structural reforms in waste management, the promotion of green entrepreneurship and the large-scale integration of renewable energy (Adebayo et al., 2021; Sharif et al., 2023; Zambrano-Monserrate et al., 2022). However, the complexity of the correlation between ecological footprint and economic performance indicates that simply increasing energy efficiency is not enough without adequate regulation of the common market (Destek et al., 2020; Alola et al., 2019; He et al., 2021).

In contrast, emerging countries face distinct environmental risks during rapid convergence stages. Studies in developing economies demonstrate that massive foreign direct investment flows, coupled with trade liberalization, can exacerbate environmental degradation, validating the "Pollution Haven Hypothesis" (Al-Mulali et al., 2015; Bakhsh et al., 2017; Gill et al., 2018). Even though technology transfers attempt to change the slope of the curve, reliance on conventional fuel sources increases environmental pressure and delays the decline in emissions (Usman et al., 2020; Saboori et al., 2016). Thus, major governance discrepancies between OECD and emerging economies determine asymmetric trajectories of the environmental Kuznets curve at the global level.

2.4. Particularities of the EKC in Romania and identification of the need for scientific research in the field.

The analysis of ecological sustainability and the dynamics of greenhouse gas emissions in the Central and Eastern European (CEE) region requires an analytical framework adapted to the historical, political and post-communist economic specificities of these states. In these economies undergoing structural transition from a deeply centralized system to a market economy, the initial trajectory of environmental degradation was marked by structural anomalies in relation to Western economies. In the 1990s, the collapse of the heavy industry sector and forced deindustrialization led to a sharp decrease

in the aggregate level of pollution (Adams et al., 2019; Jiang et al., 2021). However, this decline was not a direct result of the implementation of proactive energy efficiency or sustainability policies, but rather a by-product of the economic collapse and severe macroeconomic restructuring (Adebayo & Rjoub, 2023; Ben Jebli et al., 2022). With the start of the European integration process and alignment with global value chains, the accelerated pace of economic convergence in the region has reignited the classic tensions between economic expansion and environmental quality (Zhao et al., 2021; Ike et al., 2023). This highly complex interaction between financial sector dynamics, rapid physical capital accumulation, and European institutional regulations has generated a strongly nonlinear evolution of ecological degradation at the regional level (Zhao & Yang, 2021; Sharif et al., 2024).

Although Romania is directly subject to strict European directives on climate neutrality and accelerated energy transition, its individual ecological trajectory remains insufficiently explored in the specialized literature. In the vast majority of global or macro-regional empirical studies, the data related to Romania are treated and analysed almost exclusively as a simple component of extended groups of emerging countries or large European samples (Apergis, 2010; Alola et al., 2018; Destek et al., 2019). Such a collective methodological approach tends to homogenize econometric results and mask major structural gaps, vulnerabilities and national particularities of the Romanian economy. Specific elements that are not integrated or less highlighted include the historical coal-dependent energy mix, the low absorption of clean technologies of the latest generation, or the limited efficiency of fiscal decentralization reforms and environmental taxation (Usman et al., 2020; He et al., 2023; Kirikkaleli & Adebayo, 2021). In addition, pollutant spillover phenomena and regional development asymmetries accentuate the complexity of modelling the national ecological trajectory (Liang et al., 2018; Acheampong et al., 2021; Shen et al., 2024).

Therefore, there is an acute and clear need for dedicated scientific studies grounded in the realities of the national economy. This article aims to contribute to reducing the significant methodological and theoretical deficit in the regional literature by conducting a stand-alone case study focused on Romania. Implementing an econometric methodology designed to test the validity of the U shape and of the new theory of the N-shaped environmental Kuznets Curve represents a valuable original contribution. Our study provides a nuanced perspective on how national income growth and the transition to renewable sources influence long-term environmental degradation, providing policymakers with robust empirical evidence to underpin real economic decoupling strategies (Jahanger et al., 2021a; Churchill et al., 2021; Radulescu et al., 2022).

Previous studies on testing the EKC hypothesis in the case of Romania (Shabaz et al. 2013), (Neagu, 2018) used either the classic model of the relationship between CO₂ emissions, GDP and energy consumption (Shabaz, 2013) or a more complex version of it (Neagu, 2019), by replacing the classic GDP per capita variable with the Economic Complexity Index (ECI) and the “energy intensity” variable, as main determinant of carbon emissions. The first study, conducted by Shabaz provides empirical evidence supporting the Environmental Kuznets Curve hypothesis for Romania, and the existence of long run relationship between economic growth, energy consumption and energy pollutants. Energy

consumption was identified as the primary driver of CO₂ emissions, providing a positive and statistically significant effect on environmental degradation. Romania's declining emission level was due the post 1990 economic restructuring process, technological modernisation and the harmonisation of environmental regulations with the European Union Standards. The positive role of financial development and democratic institutional reforms in facilitating investments in cleaner technologies and promoted environmental sustainability must also be emphasized.

The second study, conducted by Neagu (2019) examines the EKC hypothesis for a panel data framework at the UE level, as well as for simple time series of individual countries. At the 25 European Union level, the results confirm an inverted U-shaped relationship between CO₂ emissions, economic complexity and energy intensity. But at the individual level, the EKC hypothesis based on cointegrating panel regression incorporating ECI was validated only in six cases: Belgium, France, Italy, Finland, Sweden and the United Kingdom. Although Romania recorded one of the most substantial increases in economic complexity among EU member state, it has not yet reached a level capable of generating a statistically significant reduction of carbon emissions.

2.5 Methodological Framework

The EKC hypothesis can be tested either for a single country or for a group of countries. Most authors (Akbostancı et al., 2009), (Chenyang, 2017) (Saboori, 2012) define the EKC hypothesis as a relationship between income and environmental quality, using the quadratic function (for the inverted U shape hypothesis) or the third-order polynomial (for the N shape hypothesis):

$$E = f(Y; Y^2, Z) \quad (1)$$

or

$$E = f(Y; Y^2, Y^3, Z) \quad (2)$$

Where E is an environmental indicator, Y is an income and Z represents other explanatory variables that may influence environmental degradation, such as international trade, energy consumption, technological progress and demography (Dinda, 2004), (Shen, 2006) .

The time series model is formulated as following (Dinda, 2004):

$$E_t = \alpha + \beta_1 Y_t + \beta_2 Y_t^2 + \beta_3 Y_t^3 + \epsilon_t \quad (3)$$

The panel data model is formed similarly:

$$E_{it} = \alpha_{it} + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \beta_3 Y_{it}^3 + \epsilon_{it} \quad (4)$$

Most empirical evidence for EKC are using cross-sectional panel data, using the following model (Dinda 2003):

$$E_{it} = \alpha_{it} + \beta_1 Y_{it} + \beta_2 Y_{it}^2 + \beta_3 Y_{it}^3 + \beta_4 Z_{it} + \epsilon_{it} \quad (5)$$

In these models, E is an environmental indicator, Y is an income and Z relates to other explanatory variables on environmental degradation; i indicates the country samples, t indicates the time, α_i is constant, ϵ_{it} is the standard error term and β is the coefficient of the explanatory variables.

In the specialized literature, the logarithmic version of the variables is often used (Pao et al., 2011), (Saboori et al., 2012), (Shahbaz et al., 2013), (Stern, 2004):

$$\ln E_{it} = \alpha_i + \beta_{1t} \ln Y_{it} + \beta_{2t} (\ln Y_{it})^2 + \epsilon_{it} \quad (6)$$

The model is designed for Time-series and panel data, where i indicates the country samples, t indicates the study period, α_i represents the fixed effect, ϵ_{it} is the standard error term, β_{1t} and β_{2t} denote the estimated coefficients.

Considering the values of the β coefficient the following relations between environment and economic development can be found (Daniil, 2023), (Dinda, 2003) (Leal, 2022):

(i)	$\beta_1 = \beta_2 = \beta_3 = 0$	A flat pattern and no significant relationship
(ii)	$\beta_1 > 0$ and $\beta_2 = \beta_3 = 0$	A positive (increasing) linear relationship
(iii)	$\beta_1 < 0$ and $\beta_2 = \beta_3 = 0$	A negative (decreasing) linear relationship
(iv)	$\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 = 0$	A quadratic inverted U-shaped relationship and the existence of the EKC
(v)	$\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 = 0$	A quadratic U-shaped relationship
(vi)	$\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 > 0$	A cubic N-shaped relationship
(vii)	$\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 < 0$	A cubic inverted N- shaped relationship

While the EKC is valid only in case (iv), the turning point (TP) can be determinate as

$$TP = - \frac{\beta_1}{2\beta_2} \quad (7)$$

In case of a cubic relationship is cubic and non-zero coefficients are non-zero, there two turning points can be determined.

Starting from these basic equations, variations of these equations can be found in the specialized literature, depending on the environmental indicator chosen, one or more explanatory variables and respectively the use or not of the logarithmic form of the variables.

Regarding the selection of the variables (Leal, 2022), for environmental indicators, beside Co2 emissions, Ammonium, Nitrous Oxide, PM_{2.5} emissions, Sulphur Dioxide emissions, Greenhouse Gases (GHG), Carbon Monoxide, Nitrous Oxide (N₂O or NO₂), Sulphur Dioxide (SO₂), Wastewater Discharge, Water Consumption or pollution, Solid Waste, were also been used.

While GDP is the most frequent economic indicator used in EKC relationship, Gross Regional Product (GRP), Foreign Direct Investment (FDI), Gross Value Added (GVA), Gross State Product, income inequality has also been used.

As dependent variable (Avazdahandeh &Tash, 2026) CO₂ emission, Energy use, Greenhouse gas emissions or Deforestation rate were used, while as the independent variable GDP per capita, Energy consumption, Forest area, Agriculture activities (Agricultural area, Forestry and fishing, Value Added per worker), Foreign direct investment, Trade openness, Economic growth, Renewable energy consumption are the most commonly used.

Considering the additional variables, Energy consumption is considered the most common variable added to the EKC estimations, taking into account renewable and non-renewable energy consumption; Oil, Coal, Biomass, Hydroelectricity or Agricultural energy consumption; Nuclear electricity output; Electricity production from non-renewable sources; Renewable electricity production; Energy Intensity; Energy price; Energy efficiency; Electrification; Energy taxes and Energy innovation. Beside energy, Economic, Environment, Technology, and Sociodemographic variables have been included in EKC model.

Due to all these variables, in specialized literature, EKC has numerous approaches, models, methods and econometric procedures of determination. Fully Modified Ordinary Least Square (FMOLS); Autoregressive Distributed Lag (ARDL) Ordinary Least Square (OLS) and Dynamic Ordinary Least Square (DOLS) are the most used methods.

Empirical studies examining the environmental Kuznets Curve (EKC) hypothesis across individual countries and country groups have yielded mixed findings (Leal, 2022). Therefore, evidence of an inverted U-shaped relationship at the aggregate level does not necessarily indicate that the EKC hypothesis is valid for every country included in the sample.

3. Methodology

This study aims to empirically assess the validity of the Environmental Kuznets Curve in case of Romania. It investigates whether the relationship between economic growth, measured by GDP per capita and environmental degradation, proxied by carbon dioxide (CO₂) emissions per capita, as well as energy consumption per capita follows the nonlinear inverted U-shaped pattern predicted by the EKC frameworks.

The empirical investigation relies on annual data spanning the period 1990-2023, as this represents the longest time interval for which complete and comparable data are available for all variables employed in the econometric analysis. All variables have been sourced from the World Bank's World Development indicators (WDI) database.

The model considers carbon dioxide (CO₂) emissions per capita (measured in metrics tons per capita) as dependent variable. The explanatory variables include real GDP per capita (constant 2015 US dollars), its squared term to capture the potential nonlinear relationship implied by the Environmental Kuznets Curve (EKC) hypothesis, and energy use per capita (measured in kilograms of oil equivalent per capita), which is incorporated as a control variable, to account for the impact of energy consumption on

environmental quality. All variables are transformed into natural logarithms prior to estimation.

The empirical analysis is conducted using an Autoregressive Distributed Lag (ARDL) model (Bölük, 2015), performed using EViews 10 Enterprise Edition, including unit root testing, ARDL estimation, bounds testing for cointegration and long-run coefficient estimation.

The present paper follows the time series, natural logarithm quadratic form model, largely used in the EKC literature, to test the EKC hypothesis in the case of Romania.

$$\ln CO_2 = f(\ln GDP, (\ln GDP)^2, \ln ENERGY) \quad (9)$$

$$\ln E_{it} = \alpha_i + \beta_{1t} \ln Y_{it} + \beta_{2t} (\ln Y_{it})^2 + \beta_{3t} \ln(z) + \epsilon_{it} \quad (10)$$

Considering the abovementioned dependent and independent variables, the model is:

$$\ln CO_{2t} = \alpha_i + \beta_{1t} \ln GDP_t + \beta_{2t} (\ln GDP_t)^2 + \beta_{3t} \ln(EN) + \epsilon_{it} \quad (11)$$

Where:

- The environmental indicator: CO_2 - Carbon dioxide (CO_2) per capita (t CO_2 /capita)
- The income indicator: GDP per capita (constant 2015 US dollars),
- The explanatory variables on environmental degradation: EN- Energy use (kg of oil equivalent per capita);
- t indicates the time: 1990-2023
- α_i is constant,
- ϵ_{it} is the standard error term
- β is the coefficient of the explanatory variables.

The analytical procedure involved the following main steps (Shahbaz et al, 2013), (Acaravci & Ozturk, 2010): testing the stationarity of variables using the Augmented Dickey - Fuller (ADF) and Phillips - Perron (PP) unit root tests; estimating the optimal ARDL model based on the Akaike Information Criterion (AIC); examining the existence of a long-run equilibrium relationship through the ARDL Bounds Test; and estimating the long-run coefficients and the associated Error Correction Model (ECM), followed by a series of post-estimation diagnostic and stability tests to assess the adequacy and robustness of the estimated model.

4. Results/findings

Table 1 reports the descriptive statistics for the logarithmic series of carbon dioxide emissions ($\ln CO_2$), real gross domestic product ($\ln GDP$) and energy consumption ($\ln EN$) for Romania over the period 1990–2023. The mean value indicates that the average logarithmic level of carbon dioxide emissions, real gross domestic product and energy consumption are 1.559, 7.498 and 8.821, respectively. The standard deviations indicate that energy consumption ($\ln EN$) exhibits the highest variability (0.367),

suggesting substantial changes over the sample period. Carbon dioxide emissions (LNCO₂) display a moderate degree of dispersion (0.179), whereas GDP (LNGDP) has the lowest variability (0.113) indicating a comparatively more stable evolution throughout the study period.

Table 1. Descriptive statistics of variables

	LNCO ₂	LNGDP	LNEN
Mean	1.558981	7.498092	8.820622
Median	1.523000	7.475055	8.878212
Maximum	2.090773	7.890347	9.420668
Minimum	1.304458	7.364804	8.308716
Std. Dev.	0.178610	0.113214	0.366716
Skewness	0.944976	1.375429	0.101775
Kurtosis	3.548455	5.422870	1.578626
Jarque-Bera	5.486352	19.03649	2.920793
Probability	0.064366	0.000073	0.232144
Sum	53.00536	254.9351	299.9011
Sum Sq. Dev.	1.052756	0.422972	4.437871
Observations	34	34	34

Source: Authors' using EViews

Table 2. The Correlation Matrix

Correlation	LNCO ₂	LNGDP	LNEN
LNCO ₂	1.000000		
LNGDP	-0.717367	1.000000	
LNEN	0.959693	-0.545700	1.000000

Source: Authors' using EViews

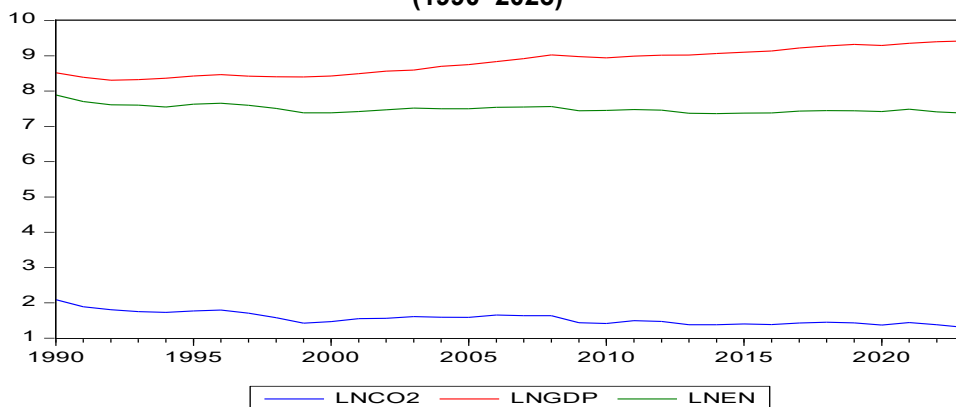
Table 2 presents the Pearson correlation coefficients between the three logarithmic series used in the model. LNCO₂ and LNEN exhibit a very strong positive correlation ($r = 0.9597$), indicating that carbon dioxide emissions and energy consumption move closely together over the sample period. This finding is consistent with the theoretical expectation that energy consumption, especially when derived from fossil fuel sources, is the main proximate driver of CO₂ emissions. LNCO₂ and LNGDP exhibit a moderately strong negative correlation ($r = -0.7174$), suggesting that, over the sample period as a whole, higher levels of economic output were associated with comparatively lower emissions. LNGDP and LNEN exhibit a moderate negative correlation ($r = -0.5457$), which reflect structural changes in the Romanian economy over the period 1990 - 2023, such as improvements in energy intensity, a gradual shift towards a more service-oriented economic structure, and gains in energy efficiency, that allowed economic output to increase, while energy consumption followed a comparatively more moderate or divergent trajectory across parts of the sample.

Figure 1 illustrates the evolution of the logarithmic series over the study period. Real GDP (LNGDP) exhibits a clear upward trend, reflecting sustained economic growth. In contrast, carbon dioxide emissions (LNCO₂) show an overall declining trend, while energy consumption (LNEN) remains relatively stable with only minor fluctuations.

The ARDL bounds testing approach of cointegration is developed by Pesaran (Pesaran et al., 2001). Considering that ARDL bounds testing approach can be used only if the order of integration of any of the variables is not greater than 1, it is necessary to test

for unit root to ensure that all the variables satisfy the underlying assumptions of the ARDL bounds testing approach.

Figure 1. Time Trends of the Study Variables: LNCO₂, LNGDP, and LNEN (1990–2023)



**Tabel 3. Unit Root Test Results
(Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP))**

Variable	Augmented Dickey–Fuller ADF (Level)		Phillips–Perron PP (Level)		Augmented Dickey–Fuller ADF (First Difference)		Phillips–Perron PP (First Difference)		Integration Order
	Statistic	p-value	Statistic	p-value	Statistic	p-value	Statistic	p-value	
LNCO ₂	-3,3483	0.0767	-3,9113	0.0228**	-4,5599	0.0052***	-7,6789	0.0000***	I(1)
LNGDP	-2,9239	0.1687	-4,1036	0.0146**	-4,2895	0.0096***	-4,3521	0.0083***	I(1)
LNGDP ²	-2,9319	0.1664	-4,089	0.0151**	-4,3225	0.0089***	-4,3662	0.0080***	I(1)
LNEN	-3,269	0.0897	-4,1594	0.0128**	-4,9263	0.0020***	-7,312	0.0000***	I(1)

Source: Authors' using EViews

Notes: Critical values (constant and trend): 1% = - 4.27; 5% = - 3.56; 10% = - 3.21.

*** Significant at the 1% level; ** Significant at the 5% level.

The ADF results indicate first-difference stationarity, while the PP test suggests level stationarity for several variables. No variable is integrated of order two (I(2)); therefore, the ARDL bounds testing approach is appropriate.

The stationarity proprieties of the variables were examined using both Argumented Dickey–Fuller (ADF) and Philips_Perron (PP) unit root tests, reported in Table no 3. The Argumented Dickey–Fuller (ADF) indicates that all variables (LN CO₂, LNGDP, LNGDP² and LNEN) are non-stationary in levels at the 5% significance level. However, the null hypothesis of a unit root is rejected for all variables after first differencing. Therefore, all variables are integrated of order one I(1), satisfy the precondition for the application of the ADRL bounds testing approaches. The PP test suggests stationarity at levels for all variables. Neither test indicates that any variable is integrated of order 2, I(2), therefore the Autoregressive Distributed Lag (ARDL) modelling approach proposed by Pesaran was employed to investigate the short-run and long-run dynamics among CO₂ emissions and

its determinants (economic growth and energy consumption) in Romania, testing for a potential Environmental Kuznets Curve effect.

Table 4. ARDL Short-Run Estimation Results

Dependent Variable: LNCO ₂				
Method: ARDL				
Sample (adjusted): 1991 2023				
Included observations: 33 after adjustments				
Maximum dependent lags: 2 (Automatic selection)				
Model selection method: Akaike info criterion (AIC)				
Dynamic regressors (2 lags, automatic): LNGDP LNGDP ² LNEN				
Fixed regressors: C				
Number of models evaluated: 54				
Selected Model: ARDL(1, 1, 1, 1)				
Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LNCO2(-1)	0.450129	0.169607	2.653953	0.0136
LNGDP	-4.497149	2.844040	-1.581254	0.1264
LNGDP(-1)	4.711589	2.927393	1.609483	0.1201
LNGDP ²	0.267399	0.161568	1.655029	0.1104
LNGDP ² (-1)	-0.285469	0.166487	-1.714662	0.0988
LNEN	1.080772	0.119802	9.021313	0.0000
LNEN(-1)	-0.426784	0.235240	-1.814253	0.0817
C	-4.545059	4.053388	-1.121299	0.2728
R-squared	0.979848	Mean dependent var		1.542866
Adjusted R-squared	0.974205	S.D. dependent var		0.154251
S.E. of regression	0.024774	Akaike info criterion		-4.350840
Sum squared resid	0.015344	Schwarz criterion		-3.988050
Log likelihood	79.78886	Hannan-Quinn criterion		-4.228772
F-statistic	173.6511	Durbin-Watson stat		1.908040
Prob(F-statistic)	0.000000			

Source: Authors' using EViews

The optimal lag structure was selected automatically according to the Akaike Information Criterion (AIC), most suitable for small sample data set, evaluating 54 candidate specifications, resulting in an ARDL (1,1,1,1) optimal model. Considering the 34 observations, the appropriate lag length of the variables for the sample was 2.

The estimated model demonstrates strong explanatory power, with a high R² of 0.980 and an adjusted R² of 0.974, indicating that 97.98% of the variation in CO₂ emissions is explained by the variables included in the model. The marginal difference between R² (0.980) and Adjusted R² (0.974) indicates that the explanatory power of the model is not substantially inflated by the number of estimated parameters, suggesting a reasonably well-specified model given the sample constraints

The overall model is highly significant (F-statistic = 173.65, $p < 0.000$), confirming the joint validity of the specification. The Durbin–Watson statistic (1.91) lies close to the benchmark value of 2, providing preliminary evidence against first-order residual autocorrelation.

The short-run estimation results reveal that energy consumption has a strong positive effect on carbon dioxide emissions. Specifically, the current-period coefficient of energy consumption is positive and highly statistically significant ($\beta = 1.081$, $p < 0.001$),

The result indicates that a 1% increase in energy consumption will immediately be led to an approximately 1.08% increase in CO₂ emissions with the same period, providing a near-unitary elasticity and underscoring the central role of energy use in driving emission outcomes. By contrast, neither GDP nor its squared term is statistically significant in the short-run specification.

The positive and statistically significant coefficient (LNCO₂ (-1) =0.450 (p=0.0136)) indicates that CO₂ emissions are persistent over time: the level of emissions from the previous year significantly influences the level of emissions from the current year, reflecting a degree of persistence or inertia in emissions levels. Neither the current nor the one-period lagged effect of economic growth on CO₂ emissions is statistically significant at conventional levels (p=0.1264 and p=0.1201), although the lagged coefficient approaches marginal significance. This suggests that the linear effect of GDP on emissions cannot be established with statistical confidence.

The current-period quadratic term (LNGDP², p=0.1104) is not statistically significant, but its one-period lag (LNGDP² (-1), p=0.0988) attains significance only at the 10% level.

The negative sign of the lagged quadratic coefficient (-0.285) is theoretically consistent with the inverted U-shaped relationship postulated by the Environmental Kuznets Curve (EKC) hypothesis. However, given that statistical significance is confident to the 10% threshold, the empirical evidence in support of the EKC hypothesis should be regarded as weak and inconclusive rather than robust.

Table 5. Bounds Test and Long-Run Estimates

Variable	Long-run Coefficient	Std. Error	t-Statistic	P-value
LNGDP	0.389981	1.521580	0.256300	0.7998
LNGDP2	-0.032862	0.086233	-0.381085	0.7064
LNEN	1.189349	0.138926	8.561000	0.0000
Constant	-8.265689	6.790433	-1.217255	0.2349
EC = LNCO ₂ - (0.3900*LNGDP -0.0329*LNGDP2 + 1.1893*LNEN -8.2657)				
F-Bounds Test		Null Hypothesis: No levels relationship		
Test Statistic	Value	Signif.	I(0)	I(1)
			Asymptotic: n=1000	
F-statistic	4.301029	10%	2.37	3.2
k	3	5%	2.79	3.67
		2.5%	3.15	4.08
		1%	3.65	4.66
Actual Sample Size	33		Finite Sample: n=35	
		10%	2.618	3.532
		5%	3.164	4.194
		1%	4.428	5.816
			Finite Sample: n=30	
		10%	2.676	3.586
		5%	3.272	4.306
		1%	4.614	5.966

Source: Authors' using EViews

To examine the existence of a long-run equilibrium relationship among the variables, the ARDL Bounds Testing procedure was applied. The results of the F-bounds test indicate that the computed F-statistic (4.301) exceeds the upper bound critical value $I(1)$ of 4.194 at both the 5% and of 3,532 at the 10% significance levels for finite-sample (the sample size $n=35$ is considered closely approximating the actual sample of 33 observations). Therefore, the null hypothesis of no levels relationship is rejected at the 5% significance level, providing statistical evidence of a long-run cointegrating relationship among variables. These findings validate the long-run coefficient estimates reported in the levels equation and confirms the appropriateness of the ARDL bounds testing. On the other side, it should be mentioned that, while the evidence of cointegration is robust at the 5% and 10% significance levels, it does not attain significance at the more stringent 1% threshold, even this pattern is not uncommon in small-sample applications.

The estimated long-run coefficients indicate that energy consumption emerges as the sole statistically significant determinant of long-run CO₂ emissions ($\beta = 1.189$, $p < 0.01$). A 1% increase in energy consumption is associated with an approximate 1.19% increase in emissions, *ceteris paribus*.

Regarding the Environmental Kuznets Curve hypothesis, the estimated coefficients of income and its squared term display the theoretically expected signs nominally consistent with the theoretical postulate of the Environmental Kuznets Curve (EKC). A positive linear coefficient ($\beta = 0.390$) followed by a negative quadratic coefficient ($\beta = -0.033$), implying an inverted-U relationship between income and emissions fail to attain conventional levels of statistical significance ($p = 0.799$ and $p = 0.706$, respectively). Consequently, the empirical evidence does not support the existence of a statistically robust EKC-type relationship for Romania during 1990-2023.

The Error Correction Coefficient is negative and statistically significant thereby confirming the existence of a stable long-run equilibrium relationship among LNCO₂, LNGDP, LNGDP2 and LNEC (ECM = -0,5499, $p < 0.01$). The level of the coefficient indicates that 55% of any short-run disequilibrium in CO₂ emissions is corrected within one year, implying a relatively rapid speed of adjustment.

To assess the adequacy, reliability and stability of the estimated ADRL model, a comprehensive set of post-estimation diagnostic tests was conducted, to examine whether the residuals follow a normal distribution, serial correlation, heteroskedasticity, white heteroskedasticity and conditional heteroskedasticity (ARCH effects). The results are presented in Table 6

Test 6. Post-estimation diagnostic tests

Diagnostic Test	Statistic Test	p-value	Decision
Jarque-Bera Normality	0,1	0,951	Residuals are normally distributed
Breusch-Godfrey LM	0,105	0,949	No serial correlation
Breusch-Pagan-Godfrey	16,304	0,023	Heteroskedasticity detected
ARCH LM	1,82	0,402	No ARCH effects
Ramsey RESET	2,021	0,168	Correct model specification

Source: Authors' using EViews

These tests evaluate whether the residuals satisfy the assumptions underlying the classical linear regression model and whether the estimated parameters remain stable throughout the sample period.

Overall, the post-estimation diagnostic analysis indicates that residuals are normally distributed, free from serial correlation and the model is correctly specified and structurally stable over the same period. While Breusch–Pagan–Godfrey test suggests the presence of heteroskedasticity, the ARCH LM test indicates the absence of conditional heteroskedasticity, and the remaining diagnostic tests confirm the overall robustness of the estimated specification.

The stability of the short-run and long-run coefficients are checked through the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests.

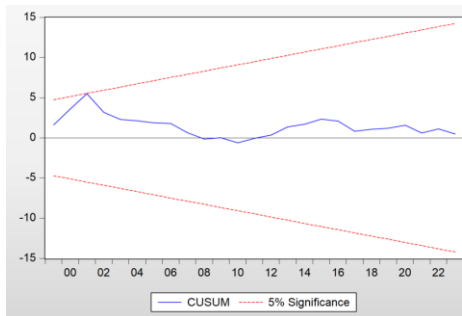


Figure 2. CUSUM test

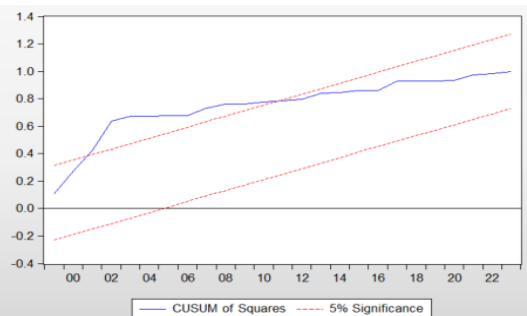


Figure 3. CUSUM of Squares (CUSUMSQ) test

Source: Authors' using EViews

The CUSUM test indicates parameter stability throughout the sample period, as the cumulative recursive residuals remain within the 5% critical bounds. However, the CUSUMSQ test reveals a temporary departure from the upper critical bound during the early part of the sample, suggesting the presence of limited parameter instability or variance shifts. This outcome is consistent with the evidence of heteroskedasticity reported by the Breusch-Pagan-Godfrey test and may reflect the structural economic transformations experienced by Romania during the transition period.

Therefore, the empirical findings reject the EKC hypothesis for Romania during the study period. Economic growth, by itself, does not appear to exert a statistically significant influence on carbon dioxide emissions, whereas energy consumption remains the dominant determinant of environmental degradation.

To assess the robustness of the baseline EKC specification, the model was extended by incorporating the cubic term of real GDP term to test the existence of an N-shaped Environmental Kuznets Curve.

Test 7. Long-run estimates including the cubic GDP term

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LNGDP	-73.80069	66.42228	-1.111083	0.2771
LNGDP2	8.294061	7.476566	1.109341	0.2778
LNGDP3	-0.311092	0.280315	-1.109794	0.2776
LNEN	1.274988	0.102103	12.48728	0.0000

Source: Authors' using EViews

The long-run estimates indicate that the coefficients associated with the linear, quadratic and cubic GDP terms are all statistically insignificant ($p > 0,05$). Moreover, the estimated signs (-/+/-) do not correspond to the theoretical pattern (+/-/+) required for an N-shaped EKC.

Therefore, the extended specification provides no empirical evidence supporting either the inverted U-shaped EKC or the N-shaped EKC hypothesis for Romania. The positive and statistically significant coefficient of energy consumption remains unchanged, confirming that energy use continues to be the main long-run determinant of CO₂ emissions.

5. Discussions

This study examined the relationship between economic growth, energy consumption and carbon dioxide emissions in Romania over the period 1990–2023, using the ARDL model. The research results highlighted the existence of a stable long-term relationship between the analysed variables; however, it does not support the Environmental Kuznets Curve (EKC) hypothesis, due to the lack of statistical significance of the coefficients. Even though the basic model was extended to the cubic polynomial form to examine the possibility of an N-shaped Environmental Kuznets Curve, all the estimated long-term coefficients were statistically insignificant. Moreover, their signs did not correspond to the theoretical configuration required for an N-shaped relationship. Therefore, neither the conventional inverted U-shaped EKC hypothesis nor its N-shaped extension are supported in the case of Romania, for the period 1990-2023.

These results align with those obtained by Neagu (Neagu, 2013): although at the level of the panel formed by 25 countries in the European Union the EKC hypothesis was validated, however, at the individual level, Romania was not among the countries in which this hypothesis was confirmed.

At the same time, the results differ from those obtained by Shahbaz (Shahbaz et al., 2013), whose research reveals that Environmental Kuznets curve (EKC) is found both in long-and-short runs in Romania, for the 1980-2010 period.

However, comparing the results should be done with caution: the time series cover different periods, the dependent or independent variables included in the study are not identical and the econometric models are either identical (ARDL in the case of the study conducted by Shahbaz (Shahbaz, 2013)) or different (FMOLS and DOLS in case of Neagu (Neagu, 2013), variables are measured in terms of relative or absolute level, all of these leading to significantly different results, this being one of the main aspects invoked by the EKC critics (Dinda, 2004), (Stern, 2004). Other econometric issues that can lead to different conclusions are related to heteroskedasticity, simultaneity, omitted variables bias, and cointegration issues. Different econometric tests and methods can generate different levels of statistical significance for coefficients, leading to opposing decisions regarding the validation or invalidation of hypotheses or models.

The results of the research indicate that carbon dioxide emissions, economic growth and energy consumption move together in the long term, despite the short-term fluctuations recorded in Romania. Deviations from the long-term equilibrium are gradually

corrected over time, suggesting that about half of any short-term imbalance is eliminated within a year.

The main finding of this study is that, in the long term, energy consumption is the dominant determinant of carbon dioxide emissions in Romania, any increases in energy consumption being associated with higher CO₂ emissions. This result is consistent with Romania's economic structure during the transition period, when fossil fuels continued to represent a substantial share of the national energy mix, despite the gradual expansion of renewable energy sources. Therefore, environmental quality seems to depend more strongly on changes in the energy system than on income growth.

Economic growth alone did not generate a statistically significant reduction in carbon emissions over the period under review, suggesting that environmental quality cannot be considered an automatic consequence of higher income levels, but rather depends on structural changes in production technologies, energy efficiency and environmental policies. Reducing carbon emissions in Romania therefore requires measures that primarily target the energy sector, rather than relying solely on economic growth.

Several limitations should be acknowledged. The analysis is based on annual observations covering the period 1990-2023, resulting in a relatively small sample size. Furthermore, the model only includes economic growth and energy consumption as explanatory variables. Future research could extend the analysis by incorporating variables such as renewable energy consumption, financial development, trade openness, technological innovation, institutional quality, or environmental policy indicators to gain a more comprehensive understanding of the factors.

A limitation of this study concerns data availability. Since official macroeconomic and environmental statistics are published with a lag by international databases, the analysis covers the period 1990–2023, representing the most recent year for which a complete and consistent data set was available at the time of the research. However, in the last 2 years Romania has undergone major transformations in terms of the forms of energy used: the exponential growth of solar panel users, the increase in the preference for electric or hybrid cars, the burden of reducing energy dependence as a result of the war in Ukraine and others, which are very poorly captured in the data available at the level of 2023. These changes generate effects both in terms of pollution and CO₂ emissions and on the energy used, variables used in the model in a dependent relationship.

Other aspects that must be taken into account from the perspective of the 1990-2023 analysed period are the following: with the accession to the European Union, Romania's energy policy aligned with that of the EU. Technological changes and economic development had a completely different development compared to the pre-accession period. Climate change and sustainable development objectives imposed homogeneous measures to reduce pollution and carbon emissions. Therefore, the moment 2007 represents the median value of the analysed time series, but in terms of the evolution of GDP, CO₂ emissions and energy used this moment had different and opposite meanings. Furthermore, aspects regarding international pollution must be taken into account, as Romania has a significantly extended border with countries that are not subject to EU regulations on pollution, and contamination can have a significant impact, especially regarding air pollution.

The period 2020-2023 included in the analysis represented major changes in consumption patterns and pollution. The lockdown period during the Covid pandemic affected transport and implicitly carbon emissions. The outbreak of the war in Ukraine, legislative changes regarding the energy market in Romania, the liberalization and respectively capping of energy prices influenced energy consumption, the type of energy consumed and implicitly the level of pollution. The lack of data for the recent period (2024-2025) means that the analysis does not fully capture the full effect of these events.

6. Conclusions

The empirical analysis of the relationship between economic growth, energy consumption and carbon dioxide (CO₂) emissions in Romania over the period 1990–2023, conducted using the ARDL method, confirmed the existence of a long-run equilibrium relationship between the variables, allowing the examination of both long-run effects and a short-run adjustment process.

The results highlighted that energy consumption exerts a positive and statistically significant impact on carbon dioxide emissions, emphasizing its central role in explaining environmental degradation in Romania.

The results of the short-run estimation show that energy consumption exerts a strong positive effect on carbon dioxide emissions, indicating that increases in energy use immediately translate into higher CO₂ emissions. By contrast, neither GDP nor its quadratic term are statistically significant in the short-run specification. The estimated long-run coefficients indicate that energy consumption remains the dominant determinant of carbon dioxide emissions in Romania. A 1% increase in energy consumption is associated with an approximately 1.19% increase in CO₂ emissions, holding other factors constant. Furthermore, 55% of short-run disequilibrium is eliminated within one year, reflecting a relatively rapid adjustment process.

Regarding the Environmental Kuznets Curve hypothesis, although the estimated coefficients show the theoretically expected signs, none of the coefficients is statistically significant. Therefore, although the estimated functional form is consistent with the conventional inverted U-shaped hypothesis, the empirical evidence is insufficient to confirm the existence of an Environmental Kuznets Curve for Romania during the period 1990–2023, both in the classical inverted U-shaped form and in the modern N-shaped approach.

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