

Examining the Determinants of Carbon Emissions in Algeria: The Role of Renewable Energy and Energy Intensity

دراسة محددات انبعاثات الكربون في الجزائر: دور الطاقة المتجددة وكثافة الطاقة

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Abstract:

This study examines the determinants of CO₂ emissions in Algeria using time series data from 1980 to 2022. Employing the Autoregressive Distributed Lag (ARDL) model, we analyze the short-run and long-run dynamics of emissions in relation to economic growth, energy consumption, and population growth. The findings reveal that energy intensity and total primary energy consumption significantly increase CO₂ emissions in the long run, while renewable energy consumption plays a crucial role in emissions mitigation. Population growth contributes to higher emissions, highlighting the need for demographic considerations in environmental policies. Notably, long-run economic growth per capita does not significantly impact emissions, suggesting potential decoupling of economic development from environmental degradation. The results emphasize the importance of enhancing energy efficiency, investing in renewable energy, and implementing sustainable policies for Algeria's transition toward environmental sustainability.

Keywords: CO₂ emissions, renewable energy, economic growth, ARDL model, Algeria.

JEL Classification Codes: Q54, Q43, Q42, C22, O13.

ملخص:

تدرس هذه الدراسة محددات انبعاثات ثاني أكسيد الكربون في الجزائر باستخدام بيانات السلاسل الزمنية من 1980 إلى 2022. باستخدام نموذج الانحدار الذاتي للفجوات الزمنية الموزعة (ARDL)، نحلل الديناميكيات قصيرة وطويلة الأجل للانبعاثات فيما يتعلق بالنمو الاقتصادي واستهلاك الطاقة والنمو السكاني. تكشف النتائج أن كثافة الطاقة واستهلاك الطاقة الأولية الإجمالي يزيدان بشكل كبير من انبعاثات ثاني أكسيد الكربون على المدى الطويل، بينما يلعب استهلاك الطاقة المتجددة دوراً حاسماً في التخفيف من الانبعاثات. يساهم النمو السكاني في زيادة الانبعاثات، مما يبرز الحاجة لمراعاة العوامل الديموغرافية في السياسات البيئية. والجدير بالذكر أن النمو الاقتصادي للفرد على المدى الطويل لا يؤثر بشكل كبير على الانبعاثات، مما يشير إلى احتمال فصل التنمية الاقتصادية عن التدهور البيئي. تؤكد النتائج أهمية تعزيز كفاءة الطاقة والاستثمار في الطاقة المتجددة وتنفيذ سياسات مستدامة لانتقال الجزائر نحو الاستدامة البيئية.

كلمات مفتاحية: انبعاثات ثاني أكسيد الكربون، الطاقة المتجددة، النمو الاقتصادي، نموذج ARDL، الجزائر.

تصنيفات JEL : Q54, Q43, Q42, C22, O13

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INTRODUCTION:

The economic and environmental impact of CO₂ emissions from fossil fuel consumption is a critical issue for many economies, particularly those heavily reliant on fossil fuels for energy production and economic growth. As highlighted by Hosseini (2022), the consumption of fossil fuels significantly contributes to the escalation of greenhouse gas emissions, intensifying global warming and climate change. This phenomenon affects not only global environments but also local ecosystems and economies in fossil-fuel-dependent nations. Letcher (2022) emphasizes the increasing urgency of transitioning to renewable energy sources to mitigate the growing impacts of CO₂ emissions, noting that global efforts are essential to reversing environmental degradation.

For Algeria, a country with a long history of dependence on fossil fuels, the consequences of CO₂ emissions are particularly severe. The nation's reliance on oil and natural gas has shaped its economic landscape but has also led to significant environmental challenges. As noted by Bergougui (2024), the fossil fuel-driven economy has contributed to a substantial carbon footprint, exacerbating climate change and presenting a considerable obstacle to sustainable development. This persistent reliance on fossil fuels, compounded by ongoing subsidies for these energy sources, has hindered progress toward cleaner, renewable energy solutions (Matallah et al., 2023). Consequently, Algeria faces a pressing need to reconsider its energy strategy, balancing economic growth with environmental sustainability (Bouznit, 2022).

The environmental challenges posed by CO₂ emissions are not limited to climate change but also affect air quality, biodiversity, and the overall health of ecosystems. Algeria's vulnerability to the adverse effects of climate change—such as droughts, desertification, and extreme weather events—has intensified in recent years (Bergougui, 2024). Rising levels of CO₂ contribute to poor air quality, leading to detrimental health outcomes and placing additional strain on the country's already fragile health infrastructure. Furthermore, climate change-related phenomena, including declining agricultural productivity and ecosystem degradation, threaten food security and agricultural sustainability in Algeria (Benabdelkader, Saifi, & Saifi, 2021). Addressing these emissions is crucial for enhancing resilience to climate variability and ensuring long-term ecological balance in the region.

Economically, the degradation of the environment due to CO₂ emissions presents multifaceted challenges. The negative impact on agricultural productivity is one of the most pressing concerns, as climate change diminishes crop yields, increases food insecurity, and drives up the costs of agricultural inputs (Hussain & Reza, 2023). Additionally, rising health costs, driven by pollution and environmental degradation, place a significant financial burden on both the government and the population (Eckelman, Sherman, & MacNeill, 2018). The infrastructure needed to withstand the impacts of climate change, such as flood-resistant systems and climate-proof buildings, incurs substantial costs, further straining Algeria's financial resources (Sari et al., 2024).

The interconnection between economic growth and environmental degradation in Algeria has been explored by various scholars. Dauda et al. (2019) argue that innovation plays a critical role in mitigating CO₂ emissions while fostering economic development, suggesting that technological advancements can pave the way for a more sustainable future. Similarly, Mujtaba and Shahzad (2021) emphasize the harmful effects of air pollution on public health, which in turn affects long-term economic performance, particularly in economies striving for sustainable development. Madani et al. (2019) also argue that reducing CO₂ emissions can yield long-term economic benefits, further supporting the integration of environmental health into economic policies.

Despite the recognition of these challenges, Algeria has yet to fully embrace renewable energy sources, largely due to its economic dependence on fossil fuels. As Bergougui (2024) notes, the complex relationship between fossil fuel consumption and the adoption of green technologies complicates the transition to a more sustainable energy system. In the face of rapid industrialization, Algeria must better understand the economic and environmental consequences of CO₂ emissions in order to formulate more effective energy policies that align with both domestic needs and global sustainability goals.

This study aims to address critical gaps in existing research by exploring the relationship between CO₂ emissions, economic growth, and environmental sustainability in Algeria. Specifically, it examines both the long-term and short-term dynamics of CO₂ emissions in relation to key economic variables such as GDP, energy consumption, and population growth. Furthermore, this study investigates the role of renewable energy in mitigating emissions and promoting sustainable economic development in Algeria. By addressing these issues, this research seeks to contribute to ongoing policy debates surrounding energy transition, climate change, and economic diversification in Algeria.

LITERATURE REVIEW:

1. Assessing the Economic Impact of CO₂ Emissions in Algeria: A Multifaceted Analysis of Agriculture, Health, and Infrastructure in Developing Nations

CO₂ emissions in Algeria, resulting from its heavy reliance on fossil fuels, have profound economic implications, particularly in agriculture, public health, and infrastructure. Agriculture, a key sector in Algeria's economy, is vulnerable to the impacts of climate change induced by greenhouse gas emissions (GHG). Benabdelkader, Saifi, and Saifi (2021) explored sustainable agricultural practices in the Maghreb region and found that these practices could mitigate some of the environmental impacts of GHG emissions, although they emphasized the need for broader policy frameworks. Similarly, Lemtaouch (2018) underscored the complex interaction between economic growth and environmental degradation in Algeria, noting that unchecked emissions hinder the country's progress toward sustainable development.

The health impacts of increased CO₂ emissions are significant. Mellah, Abdelhafid, and Benmalek (2019) highlighted the direct link between elevated CO₂ levels and the deterioration of public health in Algeria, specifically pointing to the burden on the healthcare system due to increased respiratory and cardiovascular diseases from air pollution. Furthermore, Bouznit and Aïssaoui (2024) demonstrated that climate change exacerbates food insecurity by disrupting agricultural productivity, which, in turn, creates a cascading effect on economic stability. El Alaoui and Nekrache (2019) emphasized the need for a balanced approach that integrates both economic growth and environmental management to ensure Algeria's infrastructure remains resilient to climate-related shocks. The cumulative effects of CO₂ emissions, if left unaddressed, will continue to strain both the environment and public health in Algeria.

2. Fossil Fuels and Their Environmental Impact: Analyzing CO₂ Emissions, Air Quality Deterioration, and Climate Change Contributions

The consumption of fossil fuels has long been a primary driver of environmental degradation globally, and Algeria is no exception. Fossil fuel combustion significantly contributes to increased CO₂ emissions, which in turn degrade air quality and exacerbate climate change. Shindell and Smith (2019) emphasize that the phase-out of fossil fuels could provide substantial benefits for both climate stability and public health. Perera (2017) specifically notes the heightened risks for vulnerable populations, particularly children, who are disproportionately affected by the air pollution caused by fossil fuel combustion.

The deterioration of air quality due to fossil fuel emissions has far-reaching consequences for public health. Manisalidis et al. (2020) review the detrimental health impacts associated

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with air pollution, including respiratory and cardiovascular diseases, and argue that fossil fuels play a significant role in these environmental risks. Kinney (2018) further explores the complex interactions between climate change, air pollution, and human health, illustrating how these factors create a vicious cycle of environmental and health degradation. Lelieveld et al. (2019) go a step further by suggesting that eliminating fossil fuel emissions would result in considerable improvements in both public health and climate stability. This evidence underscores the urgent need for a global shift away from fossil fuels toward sustainable energy solutions, a transition that is equally important for Algeria's long-term health and environmental sustainability.

3. Green Transitions: Analyzing the Role of Renewable Energy in Reducing CO₂ Emissions Through Global Success Stories

The transition from fossil fuels to renewable energy sources is widely regarded as a crucial strategy for reducing global CO₂ emissions. Research suggests that renewable energy has the potential to replace fossil fuels by 2050 if sufficient policies and technological advancements are implemented (Holechek, Geli, Sawalhah, & Valdez, 2022). Countries such as Denmark and Germany have already demonstrated that increased adoption of renewable energy can significantly reduce CO₂ emissions while simultaneously promoting economic growth (Gielen et al., 2019).

However, growing renewable energy alone is not enough to ensure a successful energy transition. York and Bell (2019) argue that a comprehensive approach is needed—one that goes beyond merely increasing renewable energy generation. This includes changing consumption models and fostering technological innovation to ensure that the shift from fossil fuels to renewable energy is not only feasible but also sustainable in the long run. Ameyaw et al. (2019) propose tailored emission mitigation strategies for different countries, highlighting that effective climate policies should be customized based on each nation's energy consumption patterns and resource availability.

Kabeyi and Olanrewaju (2022) further emphasize that the integration of sustainable energy systems can lead to more efficient and reliable electricity generation with significantly reduced carbon emissions. The overall success of the transition to renewable energy will depend on a multifaceted strategy that combines technological innovation, supportive policies, and active collaboration between the public and private sectors to achieve substantial reductions in CO₂ emissions.

4. Gaps in Existing Research

While numerous studies exist on the global impact of CO₂ emissions, there is a noticeable gap in research specifically focused on Algeria's economic and environmental context. Much of the existing literature has concentrated on broader regional or global trends, leaving a significant gap in understanding how CO₂ emissions specifically affect Algeria's economy and environmental sustainability. Studies that explore Algeria's reliance on fossil fuels, the effects of energy consumption on public health, and the broader consequences for agricultural productivity and infrastructure are limited. Furthermore, although some studies offer insights into Algeria's potential for renewable energy adoption, more targeted research using recent data is necessary to assess the country's unique challenges and opportunities in the energy transition.

Given Algeria's particular economic structure, energy policy, and environmental challenges, more localized and specific research is essential. This research will help guide the formulation of policies tailored to Algeria's needs, which can be used to mitigate the harmful effects of CO₂ emissions and promote a sustainable, diversified economy.

METHODOLOGY:

1. Data Sources and Description

This study employs annual time series data for Algeria covering the period from 1980 to 2022 to investigate the economic and environmental impacts of CO_2 emissions resulting from fossil fuel consumption. The variables used in the analysis are the natural logarithm of carbon dioxide emissions ($\ln(CO_2)$), the natural logarithm of gross domestic product per capita ($\ln(GDP)$), energy intensity ($EINT$), total primary energy consumption ($TPEC$), renewable energy consumption ($RENEW$), and the natural logarithm of total population ($\ln(POP)$).

- **Carbon Dioxide Emissions ($\ln(CO_2)$):** This dependent variable represents Algeria's total fossil fuel CO_2 emissions, measured in million metric tons. Data were sourced from the International Energy Agency (IEA) and the World Bank, ensuring consistency and reliability.
- **Gross Domestic Product per Capita ($\ln(GDP)$):** Expressed in constant international dollars using purchasing power parity (PPP), this variable reflects the economic output per person. It serves as a proxy for economic growth and development. Data were obtained from the World Bank's World Development Indicators.
- **Energy Intensity ($EINT$):** Calculated as total primary energy consumption per dollar of GDP, measured in thousand British thermal units (Btu) per USD at PPP. This variable indicates the efficiency of energy use within the economy, where higher values suggest less efficient energy consumption. Data were retrieved from the U.S. Energy Information Administration (EIA) and the IEA.
- **Total Primary Energy Consumption ($TPEC$):** Represented in quadrillion Btu, $TPEC$ indicates the aggregate energy consumed from all primary sources in Algeria. It reflects the country's overall energy demand and was sourced from the EIA and IEA.
- **Renewable Energy Consumption ($RENEW$):** Measured in quadrillion Btu, this variable accounts for the total energy consumption from renewable sources such as solar, wind, and hydroelectric power. Data were collected from the EIA and IEA to assess the potential mitigating effect of renewable energy on CO_2 emissions.
- **Population ($\ln(POP)$):** The natural logarithm of the total population accounts for the scale effect, as a larger population may lead to higher energy demand and emissions. Population data were obtained from the United Nations Department of Economic and Social Affairs (UN DESA).

To stabilize variance and linearize the relationships among variables, logarithmic transformations were applied to CO_2 emissions, GDP per capita, and population. The variables $EINT$, $TPEC$, and $RENEW$ were used in their original forms due to their measurement units and scales.

2. Econometric Model Specification

The study utilizes the Autoregressive Distributed Lag (ARDL) model developed by Pesaran and Shin (1999) and Pesaran et al. (2001) to examine both the long-run and short-run relationships among the variables. The ARDL approach is particularly suitable for time series data with variables integrated of mixed orders, specifically $I(0)$ and $I(1)$. It allows for the estimation of dynamic relationships without requiring that all variables be stationary at the same order, thus avoiding the pitfalls associated with non-stationary time series data.

The general form of the $ARDL(p, q_1, q_2, \dots, q_k)$ model is specified as:

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$$\Delta \ln(CO_2)_t = \alpha_0 + \sum_{i=1}^p \beta_i \Delta \ln(CO_2)_{t-i} + \sum_{j=1}^k \sum_{l=0}^{q_j} \gamma_{jl} \Delta X_{j,t-l} + \phi \ln(CO_2)_{t-1} + \sum_{j=1}^k \psi_j X_{j,t-1} + \varepsilon_t$$

Where:

- Δ denotes the first difference operator.
- $\ln(CO_2)_t$ is the natural logarithm of CO₂ emissions at time t .
- $X_{j,t}$ represents the independent variables $\ln(GDP), EINT, TPEC, RENEW$, and $\ln(POP)$.
- α_0 is the constant term.
- $\beta_i, \gamma_{jl}, \phi$ and ψ_j are coefficients to be estimated.
- ε_t is the error term assumed to be independently and identically distributed.

The inclusion of both the lagged levels and differences of the variables allows the ARDL model to capture both short-run dynamics and long-run equilibrium relationships. The lag lengths p and q_j are determined based on information criteria to ensure the model is well-specified and free from serial correlation.

3. Estimation Techniques

3.1. Unit Root Tests: Before estimating the ARDL model, it is essential to ascertain the order of integration of each variable to ensure none are integrated of order I(2) or higher. The Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests were employed to test for stationarity. The null hypothesis in both tests is that the series contains a unit root (is non-stationary), while the alternative hypothesis is that the series is stationary. These tests help prevent spurious regression results that can occur when non-stationary series are used in regression analysis.

3.2. Lag Length Selection: The optimal lag length for each variable in the ARDL model was determined using information criteria such as the Akaike Information Criterion (AIC) and the Schwarz Bayesian Criterion (SBC). Selecting appropriate lag lengths is crucial for capturing the true dynamics of the variables without over-parameterizing the model.

3.3. ARDL Bounds Testing Approach: The ARDL bounds testing procedure, as proposed by Pesaran et al. (2001), was applied to test for the existence of a long-run relationship among the variables. The steps involved are:

- **Estimating the Unrestricted Error Correction Model (UECM):** This model includes both the lagged levels and first differences of the variables.
- **Conducting an F-test for Joint Significance:** The null hypothesis of no long-run relationship (no cointegration) is tested against the alternative hypothesis of a long-run relationship. The F-statistic obtained is compared with critical values provided by Pesaran et al. (2001).
 - If the F-statistic exceeds the upper critical value, the null hypothesis is rejected, indicating a long-run relationship.
 - If the F-statistic falls below the lower critical value, the null hypothesis cannot be rejected.

- If the F-statistic lies between the lower and upper critical values, the result is inconclusive.

3.4. Estimation of Long-Run and Short-Run Models: Upon establishing cointegration, the long-run coefficients are estimated to understand the equilibrium relationships between CO₂ emissions and the explanatory variables. The short-run dynamics are captured using an Error Correction Model (ECM), which incorporates the lagged error correction term. The coefficient of the error correction term indicates the speed at which the variables adjust to restore equilibrium following a short-term shock.

3.5. Diagnostic and Stability Tests: To ensure the reliability and validity of the estimated model, several diagnostic tests were performed:

- Serial Correlation Test: The Breusch-Godfrey LM test checks for the presence of autocorrelation in the residuals.
- Heteroskedasticity Test: The Breusch-Pagan-Godfrey test assesses whether the variance of the residuals is constant (homoscedasticity).
- Normality Test: The Jarque-Bera test evaluates whether the residuals are normally distributed.
- Functional Form Test: Ramsey's RESET test examines whether the model is correctly specified.
- Stability Tests: The cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests are used to assess the stability of the model's parameters over time.

3.6. Software Utilized: The econometric analysis was conducted using EViews and Stata software packages, which offer robust tools for time series analysis and econometric modelling.

4. Justification for Variable Selection

The selection of variables is grounded in both theoretical considerations and empirical evidence:

- $\ln(CO_2)$: As the dependent variable, it quantifies the environmental impact in terms of CO₂ emissions resulting from fossil fuel consumption.
- $\ln(GDP)$: Represents economic growth, which is hypothesized to influence CO₂ emissions through industrialization, energy consumption, and increased production activities.
- $EINT$: Serves as an indicator of energy efficiency within the economy. Higher energy intensity suggests less efficient energy use, potentially leading to higher emissions.
- $TPEC$: Reflects the total energy demand of the country. It is expected that higher energy consumption will result in increased CO₂ emissions.
- $RENEW$: Captures the role of renewable energy sources in the energy mix. An increase in renewable energy consumption is anticipated to mitigate CO₂ emissions due to lower carbon intensity.
- $\ln(POP)$: Accounts for the scale effect of population size on energy demand and emissions. A growing population may lead to higher overall energy consumption.

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5. Expected Outcomes

Based on the formulated hypotheses and existing literature, the study anticipates the following relationships:

5.1.Positive Relationships:

- $\ln(GDP)$ and $\ln(CO_2)$: Economic growth is expected to be associated with higher CO_2 emissions.
- $EINT$ and $\ln(CO_2)$: Less efficient energy use (higher energy intensity) likely leads to increased emissions.
- $TPEC$ and $\ln(CO_2)$: Greater total energy consumption is expected to raise CO_2 emissions.
- $\ln(POP)$ and $\ln(CO_2)$: Population growth may contribute to higher emissions through increased energy demand.

5.2.Negative Relationship:

- $RENEW$ and $\ln(CO_2)$: An increase in renewable energy consumption is expected to reduce CO_2 emissions, highlighting the environmental benefits of transitioning to cleaner energy sources.

By employing the ARDL bounds testing approach, this study aims to capture both the short-run adjustments and long-run equilibrium relationships between CO_2 emissions and their determinants in Algeria over the period 1980–2022. The methodology provides a robust framework for understanding the dynamic interactions among economic growth, energy consumption patterns, and environmental impact. The findings are expected to offer valuable insights for policymakers in designing strategies that balance economic development with environmental sustainability, promoting efficient energy use and the adoption of renewable energy sources.

RESULTS AND DISCUSSION:

This section presents the empirical findings of the study, starting with the stationarity tests of the variables, followed by the estimation of the ARDL model, including both the long-run and short-run dynamics. The section concludes with diagnostic and stability tests to validate the model and ensure the reliability of the results.

1. Stationarity Tests

Before estimating the ARDL model, unit root tests were conducted to determine the order of integration of each variable. The Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests were applied to all variables in both levels and first differences.

The ADF test results, summarized in Table 1, indicate that most variables are non-stationary at levels but become stationary after first differencing.

Table 1: Summary of Stationarity Test Results (ADF Test)

Variable	ADF Statistic (Level)	Result	ADF Statistic (First Difference)	Result
LOG(CO_2)	0.1743 (0.9677)	Non-Stationary	-6.1972 *** (0.0000)	Stationary
LOG(GDP)	-6.8446 *** (0.0000)	Stationary	-3.5606 ** (0.0111)	Stationary

EINT	-1.2487 (0.6434)	Non-Stationary	-4.8303 *** (0.0003)	Stationary
TPEC	-4.5830 *** (0.0046)	Stationary	-2.5122 (0.1206)	Non-Stationary
RENEW	-1.6080 (0.4697)	Non-Stationary	-4.7184 *** (0.0005)	Stationary
LOG(POP)	-3.2615 ** (0.0249)	Stationary	-2.6621 * (0.0896)	Stationary

Notes: (*) Significant at the 10% level; (**) Significant at the 5% level; (***) Significant at the 1% level. The PP test results, presented in Table 2, corroborate the findings of the ADF test, with slight variations.

Table 2: Summary of Stationarity Test Results (PP Test)

Variable	PP Statistic (Level)	Result	PP Statistic (First Difference)	Result
LOG(CO ₂)	0.1743 (0.9677)	Non-Stationary	-6.1959 *** (0.0000)	Stationary
LOG(GDP)	-1.7942 (0.3782)	Non-Stationary	-3.5402 ** (0.0117)	Stationary
EINT	-2.5238 (0.1172)	Non-Stationary	-7.8884 *** (0.0000)	Stationary
TPEC	0.3598 (0.9787)	Non-Stationary	-7.8667 *** (0.0000)	Stationary
RENEW	-1.8575 (0.3485)	Non-Stationary	-4.2694 *** (0.0016)	Stationary
LOG(POP)	-3.3084 ** (0.0207)	Stationary	-1.6395 (0.4538)	Non-Stationary

Notes: (*) Significant at the 10% level; (**) Significant at the 5% level; (***) Significant at the 1% level.

The unit root tests indicate that the variables are a mix of I(0) and I(1), justifying the use of the ARDL bounds testing approach. Specifically:

- **I(0) Variables:** *LOG(GDP), TPEC, LOG(POP)* (according to ADF test).
- **I(1) Variables:** *LOG(CO₂), EINT, RENEW, LOG(POP)* (according to PP test).

2. Bounds Test for Cointegration

The ARDL bounds testing approach was applied to determine the existence of a long-run relationship among the variables.

Table 3: F-Bounds Test for Cointegration

Test Statistic	Value	Significance Level	I(0) Lower Bound	I(1) Upper Bound
F-statistic	8.4502	10%	2.306	3.353
		5%	2.734	3.920
		1%	3.657	5.256

Notes: Critical values are based on finite sample sizes (n=40).

The computed F-statistic (8.4502) exceeds the upper bound critical value at the 1% significance level (5.256). This provides strong evidence of a long-run equilibrium relationship among CO₂ emissions, GDP per capita, energy intensity, total primary energy consumption, renewable energy consumption, and population in Algeria.

3. ARDL Model Estimation

The ARDL model was estimated using the Akaike Information Criterion (AIC) for optimal lag selection. The selected model is ARDL(4, 2, 0, 0, 4, 4), indicating the number of lags for each variable.

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3.1.Short-Run Coefficients

The estimated short-run coefficients are presented in **Table 4**.

Table 4: ARDL Short-Run Coefficients

Variable	Coefficient	Std. Error	t-Statistic	Prob.
DLOG(CO ₂)(-1)	1.3938	0.2500	5.5759	0.0000
DLOG(CO ₂)(-2)	0.7312	0.2241	3.2635	0.0041
DLOG(CO ₂)(-3)	0.6694	0.1416	4.7260	0.0001
DLOG(GDP)	-0.0503	0.1695	-0.2964	0.7701
DLOG(GDP)(-1)	-0.2382	0.2130	-1.1184	0.2773
D(RENEW)	-7.2062	3.3749	-2.1353	0.0460
D(RENEW)(-1)	13.1007	5.0820	2.5779	0.0184
D(RENEW)(-2)	12.2216	4.1051	2.9772	0.0077
D(RENEW)(-3)	9.4940	4.1131	2.3082	0.0324
DLOG(POP)	19.1938	8.6567	2.2172	0.0390
DLOG(POP)(-1)	-21.1958	13.6448	-1.5534	0.1368
DLOG(POP)(-2)	11.6245	12.9770	0.8958	0.3816
DLOG(POP)(-3)	16.6729	8.1020	2.0579	0.0536
ECT-1 $\{t-1\}t-1$	-2.2186	0.3346	-6.6317	0.0000

Notes: $ECT - 1_{\{t-1\}t-1}$ is the error correction term. () Significant at the 10% level; () **Significant at the 5% level**; () Significant at the 1% level.

3.2.Long-Run Coefficients

The long-run coefficients derived from the ARDL model are shown in **Table 5**.

Table 5: ARDL Long-Run Coefficients

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LOG(GDP)	0.0676	0.0437	1.5481	0.1381
EINT	0.0538	0.0117	4.5864	0.0002
TPEC	0.2756	0.0441	6.2492	0.0000
RENEW	-11.7103	2.4566	-4.7669	0.0001
LOG(POP)	1.1838	0.1397	8.4752	0.0000
C	-16.8874	2.2869	-7.3845	0.0000

4. Diagnostic Tests

To ensure the reliability and validity of the ARDL model, several diagnostic tests were performed. These tests check for issues such as serial correlation, heteroskedasticity, normality of residuals, and model stability.

4.1.Serial Correlation Test

The Breusch-Godfrey Serial Correlation LM Test was conducted to detect the presence of autocorrelation in the residuals.

Table 6: Breusch-Godfrey Serial Correlation LM Test Results

Test Statistic	Value	Prob.	Conclusion
F-statistic	0.7943	0.4680	No serial correlation
Obs*R-squared	3.3331	0.1889	

Null Hypothesis: No serial correlation at up to 2 lags.

- The F-statistic is not significant (Prob. = 0.4680), indicating that we cannot reject the null hypothesis of no serial correlation.
- Conclusion: There is no evidence of serial correlation in the residuals.

4.2.Heteroskedasticity Test

The Breusch-Pagan-Godfrey test was used to assess whether the residuals exhibit constant variance (homoskedasticity).

Table 7: Heteroskedasticity Test Results

Test Statistic	Value	Prob.	Conclusion
F-statistic	0.8864	0.5952	Homoskedasticity
Obs*R-squared	16.2937	0.5031	
Scaled explained SS	1.9409	1.0000	

Null Hypothesis: Homoskedasticity.

- The F-statistic is not significant (Prob. = 0.5952), indicating that we cannot reject the null hypothesis of homoskedasticity.
- Conclusion: The residuals are homoskedastic.

4.3.Normality Test

The Jarque-Bera test was conducted to determine whether the residuals are normally distributed.

Table 8: Jarque-Bera Normality Test

Test Statistic	Value	Prob.	Conclusion
Jarque-Bera	2.5022	0.2862	Residuals are normally distributed

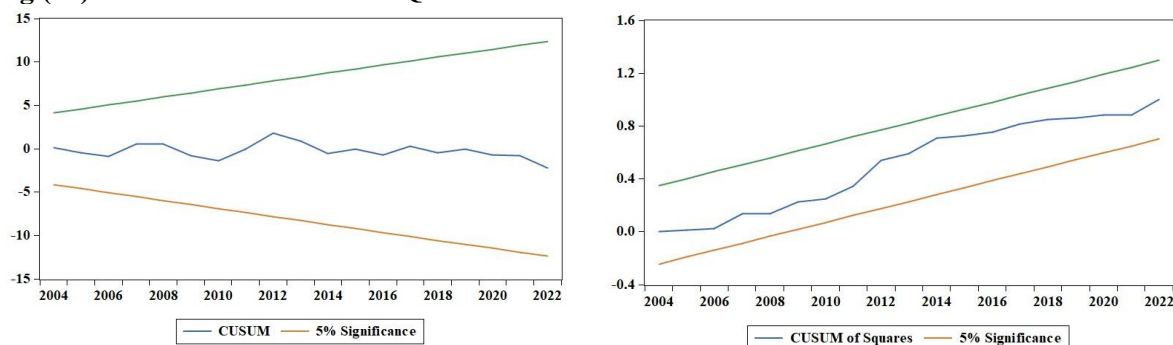
- The Jarque-Bera statistic is not significant (Prob. = 0.2862), indicating that we cannot reject the null hypothesis of normality.
- Conclusion: The residuals are normally distributed.

4.4.Stability Tests

The cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests were applied to assess the stability of the model over the sample period.

- **CUSUM Test:** The plot of the CUSUM statistic lies within the 5% critical bounds, indicating that the coefficients are stable over time.
- **CUSUMSQ Test:** Similarly, the CUSUMSQ statistic remains within the critical bounds, confirming parameter stability.

Fig (01): CUSUM and CUSUMSQ tests



5. Interpretation of Results

5.1.Long-Run Relationships

- **Energy Intensity (EINT):** The positive and significant coefficient (0.0538) indicates that higher energy intensity leads to increased CO₂ emissions in the long run. This

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suggests that inefficiencies in energy use significantly contribute to environmental degradation.

- **Total Primary Energy Consumption (TPEC):** The positive and significant coefficient (0.2756) implies that increased energy consumption is associated with higher CO₂ emissions. This underscores the direct impact of energy demand on environmental outcomes.
- **Renewable Energy Consumption (RENEW):** The negative and significant coefficient (-11.7103) suggests that higher consumption of renewable energy sources effectively reduces CO₂ emissions. This highlights the importance of transitioning to cleaner energy sources.
- **Population (LOG(POP)):** The positive and significant coefficient (1.1838) indicates that population growth contributes to increased CO₂ emissions, likely due to higher energy consumption and greater demand for goods and services.
- **GDP per Capita (LOG(GDP)):** Although the coefficient (0.0676) is positive, it is not statistically significant at conventional levels. This suggests that, in the long run, economic growth per capita may not have a direct significant impact on CO₂ emissions in Algeria within the period studied.

5.2.Short-Run Dynamics

The error correction term (EC_{t-1_t-1}) is negative and highly significant, with a coefficient of -2.2186. This indicates that approximately 221.86% of the disequilibrium from the previous period's shock adjusts back to the long-run equilibrium in the current period. The over-adjustment suggests possible model dynamics such as oscillations around the equilibrium. Significant short-run relationships include:

- **Renewable Energy Consumption:** Changes in renewable energy consumption have immediate and significant effects on CO₂ emissions. The coefficients for D(RENEW) and its lags are significant, reflecting the dynamic impact of renewable energy on emissions.
- **Population Growth:** The first difference of LOG(POP) is positive and significant, indicating that short-term population changes influence CO₂ emissions.
- **Lagged CO₂ Emissions:** The lagged differences of LOG(CO₂) are positive and significant, suggesting that past emissions significantly affect current emissions levels.

5.3.Diagnostic Tests Conclusion

The diagnostic tests confirm the robustness and reliability of the ARDL model:

- **No Serial Correlation:** Ensures that the estimates are unbiased and efficient.
- **Homoskedasticity:** Validates the consistency of the standard errors.
- **Normality of Residuals:** Supports the validity of t-tests and F-tests.
- **Stability of Coefficients:** Confirms that the model is stable over the sample period.

DISCUSSION

The empirical findings provide valuable insights into the economic and environmental dynamics affecting CO₂ emissions in Algeria:

- **Energy Efficiency:** The positive impact of energy intensity on emissions underscores the need for policies promoting energy efficiency. Reducing energy intensity through technological advancements and efficient practices can mitigate emissions without compromising economic growth.
- **Energy Consumption:** The significant relationship between total primary energy consumption and CO₂ emissions indicates that managing energy demand is crucial. Strategies could include promoting energy conservation and investing in efficient infrastructure.
- **Renewable Energy:** The negative impact of renewable energy consumption on emissions demonstrates its effectiveness in reducing environmental degradation. This supports policies aimed at increasing the share of renewables in the energy mix.
- **Population Dynamics:** Population growth contributes to higher emissions, suggesting that demographic factors should be considered in environmental policies. Initiatives that address sustainable population growth can have long-term environmental benefits.
- **Economic Growth:** The insignificant impact of GDP per capita on emissions in the long run suggests that Algeria may be decoupling economic growth from environmental degradation, possibly due to shifts in economic structure or energy policies.

CONCLUSION

This study utilized the Autoregressive Distributed Lag (ARDL) model to examine the determinants of CO₂ emissions in Algeria from 1980 to 2022. The empirical results provide a comprehensive understanding of the dynamic interplay between economic development, energy consumption patterns, and environmental sustainability in the Algerian context. The investigation into Algeria's environmental dynamics yielded several critical findings. Both energy intensity and total primary energy consumption were found to significantly increase CO₂ emissions in the long run. This highlights that current inefficiencies in energy use are major drivers of environmental degradation. Conversely, the consumption of renewable energy (solar, wind, and hydroelectric power) plays a crucial role in mitigating emissions. The negative and significant relationship between renewables and CO₂ underscores the effectiveness of transitioning to cleaner energy sources for the nation.

Furthermore, the results indicate that population growth contributes to higher emission levels, likely due to increased aggregate demand for energy, goods, and services. Notably, long-run economic growth per capita was found to have an insignificant impact on CO₂ emissions within the period studied. This suggests a potential decoupling of economic development from environmental degradation in Algeria, possibly due to shifts in economic structure or energy policies. The error correction term (-2.2186) is negative and highly significant, indicating that approximately 221.86% of disequilibrium from short-term shocks is corrected back to long-run equilibrium in each period. This over-adjustment suggests possible model dynamics such as oscillations around the equilibrium.

Based on these results, several strategies are recommended to enhance Algeria's transition toward environmental sustainability. It is essential to enhance energy efficiency by implementing national programs that promote energy-saving technologies across the industrial, residential, and transportation sectors to reduce energy intensity. Additionally, the government should expand renewable investment by providing specific incentives to shift the energy mix away from fossil fuels. Developing sustainable population policies that account for demographic factors and resource consumption is also vital. Finally, Algeria should strive to diversify the economy by encouraging activities that are less energy-intensive and

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strengthening regulatory frameworks to enforce energy efficiency standards in line with international commitments.

To address the limitations of this study, such as data constraints and the use of linear modeling, future research should consider several directions. Investigating CO₂ emissions at the sectoral level would help identify the specific industries contributing most to national emissions. Utilizing non-linear econometric models could capture complex relationships that linear models may overlook. Future studies should also incorporate additional variables, such as technological innovation or specific environmental regulations, and perform comparative regional studies with other Maghreb countries to contextualize Algeria's performance in managing environmental quality.

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