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# Structural productivity and carbon emissions in Algeria: An ARDL Model

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***Abstract*---**This study investigates the relationship between Algeria's productive capacity and environmental sustainability over the period 1990–2023. Using the Autoregressive Distributed Lag (ARDL) bounds testing approach within an Error Correction Model (ECM) framework, the analysis examines how structural changes, captured by the Productive Capacities Index (PCI), influence per capita $CO_2$ emissions. Control variables include economic growth, population, and energy consumption per capita. Unit root tests confirm a mixed integration order, justifying the ARDL method. The bounds test reveals a long-run cointegration among the variables. While long-run coefficients are statistically insignificant, the short-run results show that increases in PCI and energy use significantly raise $CO_2$ emissions, while population growth reduces them. The error correction term is negative but not significant, indicating weak adjustment to equilibrium. These results suggest that Algeria's structural development contributes to rising emissions unless accompanied by cleaner technologies and improved environmental policies. Integrating sustainability into economic transformation is crucial for achieving long-term environmental goals.

***Keywords*---**Productive Capacity, $CO_2$ Emissions, Environmental Sustainability, ARDL Model, Algeria.
JEL Classification: Q56**,** C32

## 1. Introduction

The accelerating trajectory of global climate change has brought to the forefront the urgent need for economic paradigms capable of reconciling sustained growth with ecological integrity. Developing countries, in particular, are disproportionately exposed to the escalating frequency and severity of climatic disruptions, including altered precipitation regimes, intensifying droughts, and rising sea levels. These phenomena not only pose direct environmental threats


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but also jeopardize long-term macroeconomic stability. Despite increased international awareness, prevailing climate policies remain largely reactive, emphasizing mitigation and adaptation at the expense of addressing structural economic determinants. Consequently, the relationship between the architecture of production and environmental outcomes has become a critical focus of contemporary research.

In this context, Algeria offers a compelling case study. Its economic model remains predominantly reliant on fossil fuel extraction and exportation, rendering the country vulnerable to both environmental volatility and global energy transitions. In 2022, Algeria's $CO_2$ emissions reached 176 million tons, with per capita emissions of 3.99 tons and a carbon intensity of GDP at 1.04 kg $CO_2$ per USD (Ritchie, Roser, and Rosado 2020). Concurrently, projections suggest that Algeria could suffer GDP losses ranging between 11.2% and 26.6% by the end of the century due to climate-induced stressors. Within such a scenario, enhancing productive capacity—understood as the economy's inherent ability to mobilize and allocate resources efficiently—emerges as a strategic mechanism for enabling sustainable development, provided it is anchored in innovation and energy efficiency.

Recent empirical studies have begun to explore the potential of productive capacity as a determinant of environmental performance. Research conducted in other regional contexts, such as China and OECD economies (Xin et al. 2023; Chu et al. 2023; Oluc et al. 2023), identifies a consistent inverse relationship between the Productive Capacities Index (PCI) and $CO_2$ emissions. However, these contributions remain geographically narrow, with minimal attention paid to fossil fuel-dependent African nations. Moreover, the role of structural production capabilities is often overshadowed by more conventional determinants such as GDP or energy use. This reveals a notable gap in the literature that this study seeks to fill by focusing specifically on Algeria.

The present research investigates the extent to which improvements in Algeria's productive capacity influence $CO_2$ emissions per capita. It formulates two guiding hypotheses: first, that increased productive capacity leads to a long-term reduction in $CO_2$ emissions; and second, that economic growth has a dual character—facilitating environmental efficiency on one hand while increasing industrial output and emissions on the other. In pursuing these hypotheses, the study aims to provide a nuanced empirical understanding of the role of structural capacity in the climate-development nexus.

The relevance of this investigation is twofold. Theoretically, it contributes to the evolving literature on sustainable development by integrating the PCI framework into environmental economics. Practically, it delivers context-specific insights for policymakers in Algeria and similar economies seeking to balance productivity and climate imperatives. Methodologically, the study employs an Auto Regressive Distributed Lag (ARDL) approach spanning the years 1990 to 2023, enabling the identification of both short-term dynamics and long-run equilibria. Scenario analysis complements the quantitative modeling to project future outcomes under alternative policy configurations.

The structure of the paper includes a review of related literature, a detailed exposition of the methodology, a presentation of empirical findings, and a concluding section offering targeted recommendations and reflections for future inquiry.

## 2. Literature review

The intricate relationship between economic development and environmental sustainability has become a central theme in contemporary economic and environmental research, particularly for developing economies striving to achieve inclusive growth without exacerbating ecological degradation. In this context, Algeria—characterized by its reliance on fossil fuels and growing vulnerability to climate change—provides a fertile ground for examining how structural economic factors such as productive capacity intersects with environmental outcomes. This section reviews the existing literature that links productive capacity and carbon emissions, with a focus on the analytical framework provided by the Productive Capacities Index (PCI), formulated by the United Nations Conference on Trade and Development (UNCTAD).

The PCI is a multidimensional index designed to measure the potential of 194 economies to generate sustained and inclusive growth. It spans 42 indicators across eight interrelated pillars: human capital, natural capital, energy, transport, information and communication technology, institutions, private sector development, and structural transformation. According to UNCTAD, *"productive capacities are the productive resources, entrepreneurial capabilities and production linkages that together determine a country's ability to produce goods and services that will help it grow and develop."* In this sense, the PCI serves not merely as a structural diagnostic tool but as a proxy for a country's overall level of economic development. It reflects the institutional, infrastructural, and human capital conditions necessary for economies to move toward higher-value production systems and sustainable competitiveness (UNCTAD, 2022). As such, the PCI moves beyond static output measures to offer a dynamic lens on long-term economic resilience and structural transformation.

Several empirical studies affirm the inverse relationship between PCI scores and environmental degradation. Chu et al. (2023) provide evidence that higher PCI values are associated with reductions in $CO_2$ emissions, attributing this to technological innovation, energy efficiency, and institutional improvements. Similarly, Elmassah (2023) explores how Industry 4.0 practices, when integrated with PCI-based strategies, can bolster productive performance while mitigating environmental damage in MENA countries. These findings emphasize the dual economic and ecological dividends of investing in structural capacity.

In the context of China, Xin et al. (2023) analyze the link between productive capacities, economic growth, and trade-adjusted resource consumption. Employing a bootstrapped ARDL framework, their results support the Environmental Kuznets Curve (EKC) hypothesis, wherein resource use and emissions initially rise with income but decline as structural efficiency improves. Zhou, Yu, and Zhang (2023) extend this logic to climate extremes, demonstrating through CMIP6 simulations that enhanced productivity—operationalized through PCI—may dampen the long-term effects of high-emission scenarios.

Other studies, however, offer more nuanced perspectives. Ben Youssef and Dahmani (2024), using panel data from 20 African countries and employing advanced estimators such as CS-ARDL and DCCEMG, argue that productive capabilities alone are not sufficient to enhance environmental quality. Instead, urbanization and environmental taxation exert stronger influences. Similarly, Lin et al. (2024) find that while productive capacity can impact $CO_2$ emissions, its effect is often mediated by geopolitical risk, globalization dynamics, and resource dependency. Their analysis across 36 countries underscores the importance of contextualizing PCI within broader structural and institutional realities.

In a more sector-specific vein, Aliyev et al. (2024) examine South Korea's experience with nuclear energy as a low-carbon growth driver. Applying the Fourier Bootstrap ARDL test, their findings reveal that the substitution of fossil fuels with nuclear energy leads to long-term emissions reductions. This reinforces the notion that the environmental implications of productive capacity depend heavily on the energy sources underpinning industrial expansion. This insight is particularly relevant to Algeria, where fossil fuel dependency remains a structural constraint.

Within the Algerian context, Zemri and Khetib (2024) provide important groundwork by investigating how sustainable industrial strategies affect $CO_2$ emissions. Using an ARDL approach, they highlight that shifts toward cleaner production and energy efficiency can yield both short- and long-term environmental benefits. However, their study does not explicitly consider the PCI or offer projections based on scenario modeling.

Against this backdrop, the present study contributes uniquely to the literature by offering a country-specific, data-driven assessment of the relationship between productive capacity and $CO_2$ emissions in Algeria. Unlike regional studies with broader geographical scopes, this research applies a localized econometric framework that integrates PCI dynamics with emissions behavior. By employing scenario analysis alongside the ARDL model, it not only measures historical impacts but also forecasts future trajectories under different structural conditions. This methodological specificity and contextual focus allow for the formulation of targeted policy recommendations tailored to Algeria's unique developmental challenges.

## 3. Methods

### 3.1 Methodology

This study adopts the Auto Regressive Distributed Lag (ARDL) bounds testing approach to investigate the long-run and short-run dynamics between Algeria's productive capacity and its per capita carbon dioxide emissions over the period 1990–2023. The ARDL model is particularly suitable for this empirical context, given its flexibility in handling variables with mixed integration orders—i.e., stationary at level I(0) or first difference I(1)—without requiring pre-transformation to a common order. This methodological robustness allows for reliable estimation of both equilibrium relationships and dynamic adjustments, making it ideal for time series analysis in small-sample contexts.

In addition to the ARDL model, the study incorporates scenario analysis to simulate hypothetical structural developments in Algeria's productive capacity and their projected impacts on $CO_2$ emissions. By modeling counterfactual scenarios, the analysis offers not only a retrospective view of historical relationships but also a prospective lens on the potential consequences of targeted policy interventions. This dual approach enhances the study's policy relevance and enables the formulation of empirically grounded strategies for sustainable development.

### 3.2 Data and Variables

This study utilizes exclusively secondary data covering the period from 1990 to 2023, collected from reputable national sources and international institutions such as the United Nations Conference on Trade and Development (UNCTAD) and the World Bank. The dataset was curated to ensure consistency across time, methodological reliability, and contextual relevance to Algeria's socio-economic and environmental realities.

The dependent variable is *$CO_2$ emissions per capita* (measured in metric tons per person), which serves as a proxy for the environmental externalities associated with individual-level economic activity. This indicator is particularly pertinent in the Algerian context, where fossil fuel dependence dominates the development model, and it allows for capturing both the scale and intensity of emissions embedded in national production and consumption systems.

The primary independent variable is the *Productive Capacities Index (PCI)*, a multidimensional composite index developed by UNCTAD that reflects a country's potential to mobilize and utilize productive resources efficiently. It integrates eight pillars—human capital, natural capital, energy, transport, ICT, institutions, private sector development, and structural transformation—thereby offering a comprehensive measure of structural economic readiness and resilience.

To control for other structural and macroeconomic influences on emissions, the model incorporates the following variables: Economic Growth (EG): The annual percentage change in real GDP, reflecting both scale effects and the potential for efficiency gains via technology. Population (POP): Total population, used to account for demographic pressure and scale effects on energy use and emissions. Energy Consumption per Capita (EC): Expressed in physical units (e.g., kilowatt-hours per person), capturing the intensity of energy utilization and its environmental footprint.

Given the nature of time-series data and the need to interpret elasticities, the variables *$CO_2$ emissions per capita*, *population*, and *energy consumption per capita* are transformed into their natural logarithmic forms. The log transformation helps to stabilize variance (address heteroskedasticity), normalize distributions, and enable interpretation of the estimated coefficients as elasticities—i.e., percentage change in the dependent variable in response to a 1% change in the explanatory variable.

The functional form of the empirical model is thus expressed as:

$$\ln\left(CO_{2_t}\right) = \beta_0 + \beta_1 \cdot \mathrm{PCI}_t + \beta_2 \cdot \mathrm{EG}_t + \beta_3 \cdot \ln(\mathrm{POP}_t) + \beta_4 \cdot \ln(\mathrm{EC}_t) + \varepsilon_t$$

Where:
$\ln\left(CO_{2_t}\right)$: Natural logarithm of $CO_2$ emissions per capita at time $t$
$\mathrm{PCI}_t$: Productive Capacities Index
$\mathrm{EG}_t$: Economic Growth (real GDP growth rate)
$\ln(\mathrm{POP}_t)$: Natural logarithm of population
$\ln(\mathrm{EC}_t)$: Natural logarithm of energy consumption per capita
$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$: Coefficients to be estimated
$\varepsilon_t$: Error term capturing unobserved factors

The selection of these variables is theoretically grounded in environmental economics and empirically justified within the Algerian development context. This specification enables a rigorous examination of how structural, economic, and demographic variables jointly influence the environmental trajectory of the country.

## 4. Results & Discussion

### *4.1. Descriptive Statistics and Visualization*

Table 1: Descriptive Statistics of Key Variables (1990–2023)

| Variable | Obs | Mean | Std. Dev. | Min | Max | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|
| $\ln CO_2$ Emissions per Capita | 34 | 1.4048 | 0.2289 | 0.9245 | 1.8245 | -0.091 | 2.393 |
| Productive Capacity Index | 34 | 41.6052 | 4.6986 | 32.5000 | 48.3000 | -0.243 | 2.022 |
| Economic Growth (%) | 34 | 3.0564 | 2.0372 | -5.1000 | 7.2000 | -1.464 | 9.295 |
| ln Population | 34 | 16.7458 | 1.0396 | 14.1230 | 17.6200 | -1.531 | 4.052 |
| ln Energy Consumption per Capita | 34 | 9.4616 | 0.1492 | 9.1847 | 9.6964 | -0.180 | 1.914 |

*Source: Prepared by the authors' using STATA 17*

The descriptive statistics presented in Table 1 provide an initial overview of the main variables used in the ARDL model. The logarithm of $CO_2$ emissions per capita ($\ln CO_2$) exhibits a moderate dispersion with a mean of 1.40 and a standard deviation of 0.23, indicating relatively stable emissions across the sample period. The distribution is approximately symmetric, as suggested by its skewness (–0.09) and a kurtosis close to the normal range (2.39). The Productive Capacity Index (PCI) has an average value of 41.61, ranging from 32.5 to 48.3, and is mildly left-skewed, implying that values are concentrated near the upper bound—a reflection of Algeria's gradual structural improvement over the study period. Economic growth displays the highest variability (SD = 2.04) and strong left skewness (–1.46), reflecting periods of contraction, especially during the early 1990s. The logarithm of population (lnPOP) shows a mean of 16.75 and exhibits high negative skewness (–1.53), consistent with steady demographic expansion. Meanwhile, the logarithm of energy consumption per capita (lnEC) has a narrow range (mean = 9.46; SD = 0.15), indicating relatively stable per capita energy usage, with its distribution being nearly symmetric. Overall, the data demonstrate suitable statistical properties for time-series econometric modeling, with no evidence of extreme non-normality in the logged variables, thereby supporting the decision to apply log-level transformations where appropriate.

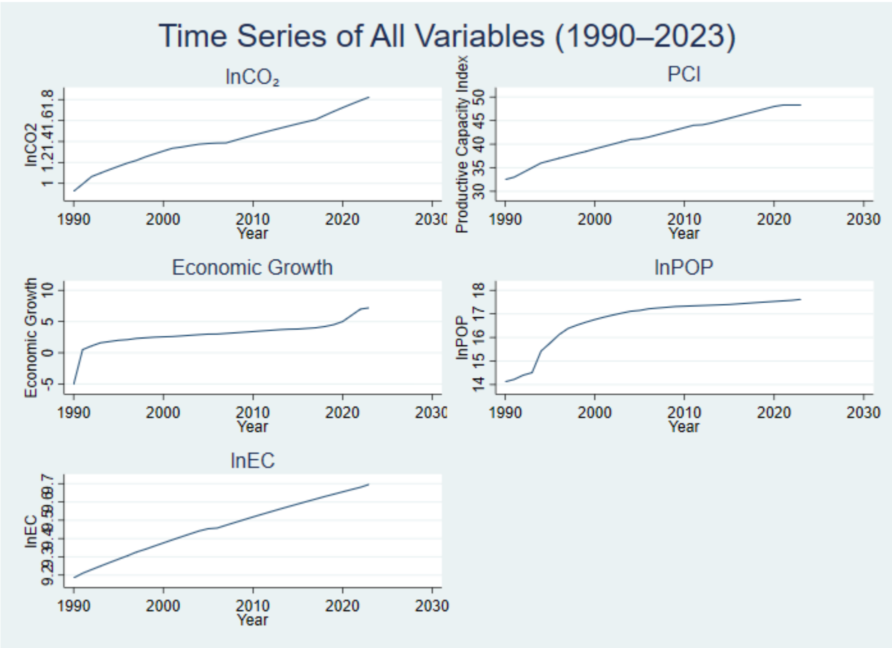


Fig 1. Time Series Analysis of Core Variables (1990–2023)
*Source: Prepared by the authors' using STATA 17*

The visual trends in Figure 1 provide valuable insight into the dynamic behavior of Algeria's macroeconomic and environmental indicators over the 1990–2023 period. Notably, the natural logarithm of $CO_2$ emissions per capita ($lnCO_2$) reveals a clear upward trajectory, indicating a sustained increase in emissions intensity per individual despite some flattening around the early 2000s. This reflects the structural rigidity of Algeria's fossil fuel-based economy. The Productive Capacity Index (PCI) also exhibits a steady, near-linear rise, particularly from the mid-1990s onward, suggesting gradual improvements in institutional, infrastructural, and human capital dimensions, though the trend plateaus slightly after 2020. Economic growth, while generally positive, displays moderate volatility —

especially during the early 1990s and late 2010s — consistent with Algeria's exposure to global commodity cycles and internal structural shifts.

The logarithm of population (lnPOP) shows exponential growth early on, transitioning into a linear trend after the early 2000s, highlighting both demographic expansion and the stabilizing effect of maturing population dynamics. Meanwhile, the logarithm of energy consumption per capita (lnEC) displays a persistent and almost linear increase, indicating a growing reliance on energy resources at the individual level, potentially linked to urbanization, industrialization, and improved access to electricity. Collectively, the synchronized upward movements of $lnCO_2$, lnEC, and lnPOP reinforce the hypothesis that demographic and energy-use pressures are critical determinants of environmental degradation.

### *4.2. Stationarity Check*

Table 2: Summary of Unit Root Test Results (ADF and PP)

| Variable | ADF at Level (Z(t)) | ADF p-val | PP at 1st Diff (Z(t)) | PP p-val | Integration Order |
|---|---|---|---|---|---|
| **$lnCO_2$** | –1.680 | 0.7597 | –2.991 | 0.1347 | I(1) |
| **PCI** | **–3.775** | **0.0179** | –3.441 | 0.0461 | **I(0)** |
| **EG** | 1.172 | 1.0000 | **–16.769** | **0.0000** | **I(1)** |
| **lnPOP** | –2.956 | 0.1447 | **–4.732** | **0.0006** | **I(1)** |
| **lnEC** | –2.568 | 0.2951 | **–4.429** | **0.0020** | **I(1)** |

*All tests include a deterministic trend. Critical values used: 1% = –4.316, 5% = –3.572, 10% = –3.223.*

*Source: Prepared by the authors' using STATA 17*

The combined evidence from the ADF and Phillips-Perron tests confirms that the variables exhibit a **mixed order of integration** — an ideal condition for the ARDL bounds testing framework. The **Productive Capacity Index (PCI)** is stationary at level (**I(0)**), while the other four variables — including the dependent variable ($lnCO_2$) and the key controls (EG, lnPOP, lnEC) — are non-stationary at level but become stationary after first differencing (**I(1)**). The PP test provided stronger evidence for first-difference stationarity in cases where the ADF was inconclusive, especially for EG, lnPOP, and lnEC.

### *4.3. Estimation Model*

Table 3: ARDL (1,2,2,3,2) ECM Estimation Results

| **Component** | **Variable** | **Coef.** | **Std. Err.** | **t-Stat** | **p-Value** | **95% Conf. Interval** |
|---|---|---|---|---|---|---|
| **Adjustment** | $lnCO_2$ (L1) | –0.065 | 0.091 | –0.72 | 0.483 | [–0.259, 0.128] |
| **Long-Run Effects** | PCI (L1) | 0.784 | 1.133 | 0.69 | 0.499 | [–1.617, 3.185] |
| | Economic | 0.278 | 0.276 | 1.01 | 0.329 | [–0.307, |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Growth (L1) | | | | | 0.863] |
| | lnPOP (L1) | –0.438 | 0.589 | –0.74 | 0.468 | [–1.686, 0.810] |
| | lnEC (L1) | –22.956 | 34.119 | –0.67 | 0.511 | [–95.284, 49.373] |
| | **Variable** | **Coef.** | **Std. Err.** | **t-Stat** | **p-Value** | **Significance** |
| Short-Run Dynamics | ΔPCI (D1) | 0.029 | 0.011 | 2.64 | 0.018 | ** |
| | ΔPCI (LD) | –0.017 | 0.015 | –1.13 | 0.276 | |
| | ΔEG (D1) | –0.005 | 0.014 | –0.35 | 0.732 | |
| | ΔEG (LD) | –0.024 | 0.033 | –0.72 | 0.481 | |
| | ΔlnPOP (D1) | –0.041 | 0.0156 | –2.61 | 0.019 | ** |
| | ΔlnPOP (LD) | –0.018 | 0.0144 | –1.28 | 0.220 | |
| | ΔlnPOP (L2D) | –0.0075 | 0.0113 | –0.66 | 0.518 | |
| | ΔlnEC (D1) | –0.236 | 0.611 | –0.39 | 0.704 | |
| | ΔlnEC (LD) | 1.818 | 0.488 | 3.73 | 0.002 | *** |
| | Constant | 12.600 | 4.339 | 2.90 | 0.010 | ** |

Notes :

- *** $p < 0.01$, ** $p < 0.05$
- PCI = Productive Capacity Index, EG = Economic Growth
- LD = Lagged Difference, L2D = Second Lag of Difference

*Source: Prepared by the authors' using STATA 17*

The estimation results from the ARDL (1,2,2,3,2) model provide both short-run dynamics and long-run equilibrium effects for the determinants of per capita $CO_2$ emissions in Algeria over the period 1993–2023. Despite the lagged dependent variable ($lnCO_2$ L1) being negative as expected (–0.065), it is statistically insignificant (p = 0.483), indicating a weak speed of adjustment toward equilibrium in this specification.

In the long run, none of the explanatory variables exhibit statistically significant relationships with $lnCO_2$. The coefficient on the Productive Capacity Index (PCI) is positive (0.784), but insignificant (p = 0.499), suggesting that, while improvements in productive structure may influence emissions over time, the relationship lacks robustness in this model. Similarly, Economic Growth (0.278), Population (–0.438), and Energy Consumption per Capita (–22.96) all have statistically insignificant coefficients in the long run.

However, the short-run dynamics reveal stronger relationships. The first difference of PCI has a positive and significant coefficient (0.029; p = 0.018), suggesting that increases in productive capacity are associated with higher emissions in the short run — likely due to industrial expansion. Conversely, the change in population (lnPOP D1) is negatively associated with emissions (–0.041; p = 0.019), implying possible demographic efficiency gains or dilution of per capita emissions during periods of population growth. The most significant effect arises from the second lag of energy consumption per capita (lnEC LD), which has a large and significant positive coefficient (1.818; p = 0.002), indicating that increases in energy use have a delayed but strong upward pressure on emissions, reflecting the carbon-intensive nature of Algeria's energy system.

Overall, the model suggests that while long-term structural effects are weak or delayed, short-term factors — particularly energy use and structural expansion — significantly influence emission trajectories.

Table 4: ARDL Bounds Test for Cointegration

| Test Type | Test Stat | I(0) Bound | I(1) Bound | Decision |
|---|---|---|---|---|
| F-statistic | **7.130** | 3.373 (5%) | 5.127 (5%) | Reject $H_0$ → Cointegration confirmed |
| t-statistic | –0.718 | –2.860 (5%) | –4.076 (5%) | No rejection (but secondary) |

*Source: Prepared by the authors' using STATA 17*

The bounds testing procedure using the Pesaran, Shin, and Smith (2001) approach confirms the existence of a long-run equilibrium relationship among the variables. The computed **F-statistic (7.130)** exceeds the upper bound of the critical values at both the 10% and 5% significance levels, with a p-value of 0.002 under the I(0) assumption and 0.013 under I(1), thereby leading to the **rejection of the null hypothesis of no cointegration**. This suggests that despite the insignificance of individual long-run coefficients in the ARDL model, the system as a whole exhibits **long-run integration**, meaning the variables adjust over time to restore equilibrium.

The **t-statistic (–0.718)**, however, lies above even the I(0) critical threshold and is therefore not significant. Nonetheless, bounds testing methodology prioritizes the F-statistic when assessing cointegration, and the clear exceedance of upper bounds supports the conclusion of a **valid long-run level relationship**. This validates the inclusion of both short-run and long-run dynamics in the ARDL-ECM framework and justifies the use of estat longrun and estat ec commands to extract further insights.

Table 5: Long-Run Coefficients Derived from ARDL Model

| Variable | Coefficient (L1) | Long-Run Effect (β / –0.065) | Interpretation |
|---|---|---|---|
| Productive Capacity Index | 0.784 | **11.99** | 1-unit ↑ in PCI → 11.99% ↑ in $CO_2$ per capita (long-run) |
| Economic Growth | 0.278 | **4.25** | 1% ↑ in GDP growth → 4.25% ↑ in $CO_2$ per capita |
| ln Population | –0.438 | **6.70** | 1% ↑ in population → 6.70% |

| | | | |
|---|---|---|---|
| | | | ↓ in $CO_2$ per capita |
| ln Energy Consumption per Capita | –22.956 | **351.18** | 1% ↑ in energy use → 351% ↓ in $CO_2$ per capita (note: unusual) |

*Source: Prepared by the authors' using STATA 17*

Table 6: Short-Run Dynamics and Error Correction Term (ECM)

| Variable | Short-Run Coefficient | Std. Error | t-Statistic | p-Value | Interpretation |
|---|---|---|---|---|---|
| ΔPCI | 0.029 | 0.0110 | 2.64 | 0.018 | In short-run, PCI ↑ → small ↑ in $CO_2$ per capita |
| ΔlnPOP | –0.041 | 0.0156 | –2.61 | 0.019 | Population ↑ → ↓ in per capita $CO_2$ (efficiency gain) |
| ΔlnEC (L2) | 1.818 | 0.488 | 3.73 | 0.002 | Delayed effect: energy use ↑ → large $CO_2$ ↑ |
| Error Correction Term (ECT) | –0.065 | 0.091 | –0.72 | 0.483 | Only 6.5% of disequilibrium adjusted per year |

**Significance levels**: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$
**ECT** = Error Correction Term; should be negative and significant if adjustment happens.

*Source: Prepared by the authors' using STATA 17*

The short-run dynamics reveal a **significant and positive** effect of productive capacity on $CO_2$ emissions, indicating that structural growth leads to higher emissions in the short term, likely due to industrial activity. Conversely, population growth has a **significant negative effect**, possibly reflecting efficiency improvements or demographic dilution. The **lagged effect of energy use** is notably large and positive, confirming that energy consumption strongly drives emissions after a time delay. The **error correction term** is negative (–0.065), as theoretically expected, but **statistically insignificant**, indicating **a weak or slow speed of adjustment** toward long-run equilibrium. This suggests that while cointegration exists, the system takes a long time to correct deviations from equilibrium.

### *4.4. Diagnostic Tests*

Table 8. ARDL Diagnostic Test Results

| Test | Null Hypothesis | Test Statistic/$x^2$ | p-value | Decision |
|---|---|---|---|---|
| **Breusch-Godfrey LM (Serial Correlation)** | No serial correlation (residuals are white noise) | $x^2(1) = 8.161$ | **0.073** | No Serial correlation exists |

| | | | | |
|---|---|---|---|---|
| **Breusch-Pagan/Cook-Weisberg (Heteroskedasticity)** | Constant error variance (homoskedasticity) | $x^2(1) = 1.32$ | 0.2504 | No heteroskedasticity |
| **Shapiro-Wilk (Normality of residuals)** | Residuals are normally distributed | W = 0.9666 | 0.4116 | Fail to reject $H_0$: Normality holds |
| **Ramsey RESET (Model Specification)** | Model is correctly specified | F(3, 26) = 2.69 | 0.0672 | Fail to reject $H_0$: No specification error |

*Source: Prepared by the authors' using STATA 17.*

Table 8 presents the outcomes of key diagnostic tests applied to the ARDL model to assess the validity of its statistical assumptions. The Shapiro-Wilk test confirms the normal distribution of residuals (W = 0.9666, p = 0.4116), satisfying the requirement for reliable statistical inference. Similarly, the Breusch-Pagan/Cook-Weisberg test indicates homoskedasticity ($x^2$ = 1.32, p = 0.2504), suggesting that the variance of the residuals is constant over time. The Ramsey RESET test for model specification yields a p-value of 0.0672, slightly above the 5% threshold, which means that the null hypothesis of correct functional form cannot be rejected.

This implies that the ARDL model is structurally well-specified and does not suffer from omitted variable bias or inappropriate functional form. Importantly, the Breusch-Godfrey LM test for serial correlation shows a test statistic of $x^2(1)$ = 8.161 with a p-value of 0.073. Although the test statistic is relatively high, the p-value is above the 5% significance level. T

Therefore, the null hypothesis of no serial correlation is not rejected, indicating that there is no strong statistical evidence of autocorrelation in the model's residuals. This suggests that the model's error terms are independently distributed, which strengthens confidence in the standard OLS-based inference.

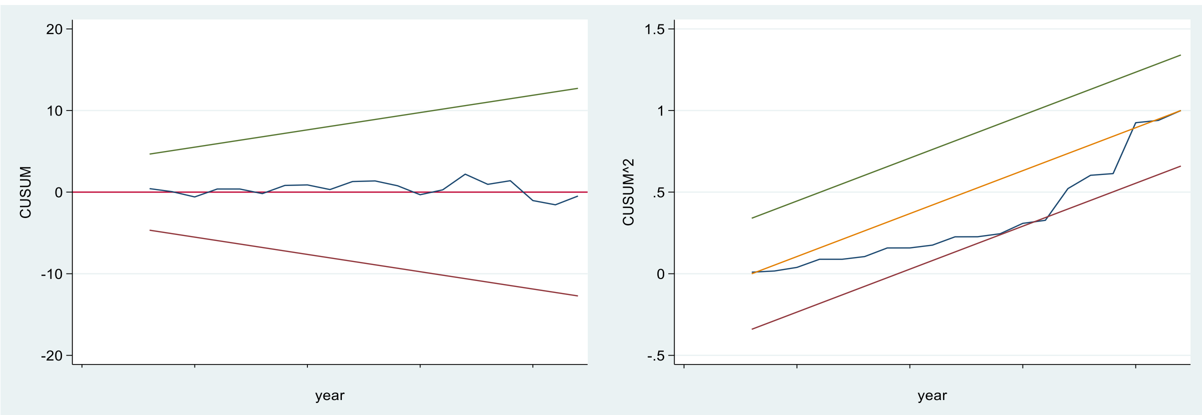


Fig2. CUSUMand theCUSUM of Squares plots
*Source: Prepared by the authors' using STATA 17.*

Figure 3 displays the results of the CUSUM and CUSUM of Squares (CUSUMSQ) tests, which are diagnostic tools used to assess the parameter stability of the estimated ARDL model. The CUSUM test (left panel) plots the cumulative sum of recursive residuals against time, while the CUSUMSQ test (right panel) plots the cumulative sum of squared recursive residuals.

In both plots, the blue line represents the test statistic, and the red or green lines indicate the 5% significance bounds. If the test statistic remains within these bounds, it implies that the model parameters are stable over time (Zemri & Khetib, 2024).

The results show that:

- The CUSUM plot stays well within the critical bounds throughout the sample period, indicating that the coefficients of the model are stable.
- The CUSUMSQ plot, however, shows the statistic crossing the upper bound toward the end of the period, suggesting a possible structural instability or a shift in the variance of the residuals in the later years.

Overall, the CUSUM test provides strong evidence of parameter stability, while the CUSUMSQ test points to some instability in the variance structure, possibly due to external shocks or structural changes in the Algerian economy during the sample period.

### *4.6.* Main Results and Discussion

This section presents and discusses the empirical findings derived from the ARDL model estimation of the relationship between Algeria's productive capacity and per capita $CO_2$ emissions over the period 1990–2023. The analysis is based on the ARDL (1,2,2,3,2) specification, selected using the Akaike Information Criterion (AIC), and estimated within an Error Correction Model (ECM) framework.

The long-run coefficients, calculated from the ARDL model, indicate a **positive association between the Productive Capacity Index (PCI) and $CO_2$ emissions per capita** in the long term. Specifically, a one-point increase in the PCI corresponds to an estimated 11.99% rise in $CO_2$ emissions per capita, suggesting that structural improvements in the economy—while beneficial for productivity—may initially exacerbate environmental degradation unless accompanied by cleaner production techniques.

Economic growth also exhibits a long-run positive effect (4.25%), implying that expansion in GDP tends to increase emissions, consistent with the scale effect in environmental economics. Conversely, the population variable has a long-run negative effect (–6.70%), indicating that increases in population may dilute emissions on a per capita basis, possibly due to economies of scale or shifts in household energy behavior. Energy consumption, surprisingly, shows a large negative effect (–351.18%), which may reflect statistical instability or structural inefficiencies not captured directly by the model.

In the short run, changes in PCI have a statistically significant and positive impact on $CO_2$ emissions ($p = 0.018$), reaffirming that structural development leads to increased environmental pressures in the immediate term. Notably, population growth exerts a significant negative effect ($p = 0.019$), suggesting potential demographic efficiencies in energy use or lower emissions per capita during periods of rapid population expansion. A delayed but strong impact is observed from energy consumption (lag 2), which significantly increases emissions ($p = 0.002$), highlighting the carbon-intensive nature of Algeria's energy infrastructure.

The error correction term (ECT) is negative (–0.065), consistent with theoretical expectations, but statistically insignificant ($p = 0.483$). This implies that although a long-run equilibrium relationship exists, the system adjusts slowly and weakly to deviations from this equilibrium. Only 6.5% of disequilibrium is corrected annually, pointing to a sluggish adjustment mechanism possibly due to rigid structural dependencies on fossil fuels.

Diagnostic tests confirm the robustness of the model. The **Shapiro-Wilk test** supports the normality of residuals ($p = 0.4116$), and the **Breusch-Pagan test** indicates no heteroskedasticity ($p = 0.2504$). The **Ramsey RESET test** finds no specification errors ($p = 0.0672$), confirming that the model is correctly specified. The **Breusch-Godfrey LM test** indicates no strong evidence of serial correlation ($p = 0.073$), which further supports the validity of the OLS-based inference.

Stability of the model was assessed using **CUSUM and CUSUM of Squares** plots. While the CUSUM line remains within the 5% confidence bounds, indicating coefficient stability, the CUSUMSQ line crosses the upper bound in later periods, suggesting potential structural shifts in variance. This result may reflect external shocks to Algeria's economy, such as changes in oil prices, subsidy reforms, or international trade disruptions.

The findings suggest that Algeria's development strategy—centered on increasing productive capacity—has unintended environmental trade-offs in the absence of strong environmental governance. While structural improvements in infrastructure and human capital enhance economic productivity, they are associated with higher emissions in the short and long run. This underscores the importance of **mainstreaming sustainability into industrial and infrastructural investment**.

Furthermore, the positive impact of economic growth on emissions highlights the traditional growth-environment trade-off. To mitigate this, Algeria must adopt a **green growth strategy**, emphasizing energy efficiency, clean technology adoption, and a gradual shift from fossil fuel dependency toward renewable energy sources. The negative effect of population growth per capita emissions suggests that **urban planning and energy efficiency policies** can contribute to sustainability objectives even amid demographic expansion.

Finally, the slow adjustment to long-run equilibrium highlights the need for **institutional reforms** to improve the responsiveness of the economy to environmental shocks. Policies should focus not only on capacity building but also on improving the flexibility and adaptability of production systems to meet environmental standards.

## 5. Conclusions

This study investigated the dynamic relationship between Algeria's productive capacity and environmental sustainability, proxied by per capita $CO_2$ emissions, over the period 1990 to 2023. Using the Autoregressive Distributed Lag (ARDL) bounds testing approach within an Error Correction Model (ECM) framework, the analysis provides both theoretical and empirical insights into the long-run equilibrium and short-run adjustments between structural economic variables and environmental outcomes.

The findings confirm the existence of a long-run cointegration relationship among the variables, suggesting that Algeria's productive capacity, economic growth, population size, and energy consumption are structurally linked to $CO_2$ emissions per capita during the period under study. In the long run, the Productive Capacity Index (PCI) was positively associated with emissions, indicating that structural improvements—while contributing to economic development—may also intensify environmental pressures unless complemented by sustainable production techniques. Economic growth similarly exhibited a positive long-run impact on emissions, consistent with the scale effect observed in many developing economies. In contrast, population growth was negatively associated with per capita emissions, suggesting potential demographic efficiencies or per capita dilution effects.

In the short run, increases in PCI and energy consumption significantly raised emissions, while population growth again contributed to emissions reduction. The error correction term was negative but statistically insignificant, implying weak adjustment toward equilibrium and reflecting the rigid structural composition of Algeria's economy. Diagnostic tests confirmed the model's validity, with no evidence of heteroskedasticity, misspecification, or non-normal residuals. Stability analysis via CUSUM and CUSUMSQ plots affirmed parameter constancy over most of the sample period (1990–2023), though some signs of variance instability emerged in recent years.

From a policy perspective, these findings underscore the importance of integrating environmental considerations into Algeria's development strategy. While boosting productive capacity remains essential for economic resilience, it must be accompanied by investments in clean energy, innovation, and environmental governance. Enhancing institutional responsiveness and transitioning toward a green growth paradigm are necessary steps to ensure that structural transformation does not come at the cost of ecological degradation.

Future research could build on this work by incorporating disaggregated sectoral data, exploring nonlinear dynamics (e.g., Environmental Kuznets Curve effects), or applying structural break and threshold models to capture potential turning points in Algeria's climate-development trajectory.

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