

## Algeria's Carbon Footprint under the Energy Transition toward 2050

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**Abstract:**

This study aims to assess Algeria's carbon footprint within the context of its energy transition over the period 1990–2023 and to project its potential trajectories toward 2050. Using ARDL and ECM models, it tests the (EKC) hypothesis and develops three scenarios: baseline, moderate transition, and accelerated transition.

The results reveal that fossil fuels remain the main source of emissions, while faster renewable integration and improved energy efficiency could significantly reduce emissions. The study recommends adopting an ambitious clean-energy policy.

**Keywords:** Carbon Footprint; Energy Transition; Econometric Analysis; Scenario Analysis; Algeria.

**JEL Classification Codes :**Q43; Q47; Q54; Q56; C32

**الملخص:**

تهدف هذه الدراسة إلى تتبع وتحليل تطور البصمة الكربونية في الجزائر في سياق تحولها الطاقوي خلال الفترة (1990–2023)، واستشراف مساراتها المستقبلية المحتملة حتى عام 2050. ولتحقيق ذلك، تعتمد الدراسة على منهجية اقتصادية قياسية تجمع بين نماذج (ARDL) و (ECM) لاختبار فرضية منحني كوزنتس البيئي (EKC)، إلى جانب تطوير ثلاثة سيناريوهات استشرافية: سيناريو الاتجاه الراهن (الأساس)، وسيناريو التحول المعتدل، وسيناريو التحول المتسارع. تُظهر النتائج استمرار هيمنة الوقود الأحفوري كمصدر رئيس للانبعاثات، إلا أنها تؤكد في المقابل أن التسريع الطموح لوتيرة دمج الطاقات المتجددة ورفع كفاءة استخدام الطاقة يمكن أن يُحدثا انخفاضاً ملموساً في الانبعاثات. وتوصي الدراسة بضرورة تبني سياسة وطنية طموحة للطاقة النظيفة كخيار استراتيجي لا محيد عنه.

**الكلمات المفتاحية:** البصمة الكربونية؛ التحول الطاقوي؛ التحليل الاقتصادي القياسي؛ تحليل السيناريوهات؛ الجزائر

## 1. INTRODUCTION

In recent decades, the world has witnessed a profound transformation in energy production and consumption patterns, driven by global environmental commitments and international agreements aimed at mitigating climate change. Reducing greenhouse gas emissions—particularly carbon dioxide (CO<sub>2</sub>)—has become a central objective of contemporary economic and energy policies. The carbon footprint serves as a key indicator for assessing the environmental impact of human activities, representing the total amount of CO<sub>2</sub> emissions generated by energy use across various productive and consumer sectors.

Within this framework, the concept of the energy transition has emerged as a strategic pathway toward sustainable development, emphasizing the gradual shift from heavy reliance on fossil fuels to a diversified energy mix based on renewable energy and energy efficiency. This transition poses a particular challenge for developing, energy-exporting countries such as Algeria, which must balance the dual objectives of ensuring energy security and achieving environmental sustainability.

Algeria has experienced a steady increase in energy demand due to economic and demographic growth, leading to a significant rise in CO<sub>2</sub> emissions over the past decades. Despite government initiatives to promote renewable energy—especially solar power—the contribution of these sources remains limited compared to the country's vast potential. This situation raises critical questions regarding the effectiveness of current energy transition policies in curbing emissions and achieving long-term carbon neutrality.

Accordingly, the central research question of this study is:

To what extent can Algeria's energy transition contribute to reducing its national carbon footprint by 2050?

From this question, arise several sub-questions:

- What is the relationship among energy consumption, economic growth, and carbon emissions in Algeria?
- Does the Environmental Kuznets Curve (EKC) hypothesis hold true in the Algerian context?
- What are the potential future scenarios for CO<sub>2</sub> emissions under alternative energy policy pathways?

Building on the stated problem, this study is guided by the following hypotheses:

**H1:** Economic growth in Algeria initially increases emissions, but after a threshold, CO<sub>2</sub> decreases (EKC).

**H2:** Increased Renewable energy consumption reduces carbon emissions in both the short and long run.

**H3:** Implementation of ambitious energy transition policies, Algeria can achieve substantial CO<sub>2</sub> reduction by 2050.

The significance of this study lies in its integrative approach, combining econometric analysis with foresight modeling to provide a long-term understanding of the dynamics shaping Algeria's carbon emissions. It also addresses a research gap in the national and regional literature, which has often focused on energy consumption without linking it to future-oriented environmental modeling. Moreover, the study empirically tests the Environmental Kuznets Curve

(EKC) hypothesis in the Algerian context, providing evidence on the relationship between economic growth and carbon emissions.

This study aims to provide a foresight-oriented econometric assessment of Algeria's carbon footprint evolution within the framework of the ongoing energy transition. Specifically, it seeks to:

- Analyze the dynamic interrelationship among energy consumption, economic growth, and carbon emissions in both the short and long run, in order to identify the main factors influencing the national carbon footprint;
- Test the validity of the Environmental Kuznets Curve (EKC) hypothesis in the Algerian context;
- Develop future scenarios for CO<sub>2</sub> emissions up to 2050, considering the impacts of alternative energy transition policies, including the expansion of renewable energy and improvements in energy efficiency.

### **Literature Review Overview:**

Recent empirical investigations into the determinants of carbon emissions in Algeria have largely centered on the historical relationship between economic growth, fossil fuel consumption, and environmental degradation. Empirical works by Bouznit and Pablo-Romero (2016) employed ARDL and cointegration methods, confirming that in the Algerian context, fossil fuel use and economic activity exert dominant long-term effects on CO<sub>2</sub> emissions.

Extending this line of inquiry, Bergougui (2024) employed a nonlinear ARDL model to capture asymmetric effects, finding that technological innovation and renewable energy mitigate emissions, while fossil energy shocks exacerbate them.

Although these studies provide useful empirical insights, they remain confined to retrospective analyses without integrating forward-looking transition scenarios or accounting for structural changes in Algeria's evolving energy system.

At the global scale, related research has explored the broader interactions between energy transition strategies and carbon mitigation outcomes. Zhang & al (2019) highlighted the decisive role of energy intensity reduction in global decarbonization, whereas Wang & al (2021) emphasized the contributions of innovation and renewable energy in emission reduction across emerging economies. The International Energy Agency IEA (2023) proposed several transition scenarios toward 2050, identifying hydrogen—both green and blue—as a pivotal vector in achieving net-zero emissions. Similarly, Adewuyi and Awodumi (2020) demonstrated through panel data analysis that energy diversification and efficiency significantly reduce CO<sub>2</sub> emissions in African economies.

However, despite their analytical depth, these international studies are typically generic in scope and do not reflect the structural and institutional specificities of hydrocarbon-based economies such as Algeria. Moreover, they rarely integrate quantitative foresight methods or uncertainty analysis into long-term emission projections.

Collectively, the reviewed literature reveals a substantial research gap: no study has yet developed an integrated, scenario-based econometric framework capable of forecasting Algeria's carbon footprint evolution under multiple energy transition pathways extending to 2050. Previous Algerian analyses remain limited to historical estimation, while global models overlook the dual nature of Algeria's transition—balancing natural gas optimization with the progressive

deployment of renewable and hydrogen technologies. Consequently, there is a lack of hybrid approaches that combine econometric modeling with quantitative foresight and uncertainty analysis to forecast Algeria's carbon footprint evolution up to 2050 under multiple transition pathways (baseline, moderate, and Accelerated). Addressing this research gap, the present study proposes a hybrid econometric–scenario framework to quantify and compare future carbon trajectories under alternative energy transition policies, thereby providing empirical insights to guide Algeria's low-carbon and sustainable energy strategy.

## 2. Conceptual Framework and Variable Overview

The study focuses on several interconnected variables forming its conceptual framework, which collectively influence Algeria's carbon footprint. **The first variable**, carbon footprint (CO<sub>2</sub>), measures the total greenhouse gas emissions generated from human activities, including industrial operations, transport, energy use, and residential consumption. It provides a key metric for evaluating environmental pressures and understanding how economic and energy-related activities contribute to climate change (Wiedmann & Minx, 2007, pp. 1-11)

**The second variable**, energy transition (ENE/REN), represents the structural movement from fossil-fuel dependence toward cleaner energy sources such as solar, wind, and hydropower. This shift not only alters the overall emission levels but also interacts with economic and industrial processes, shaping the pace at which carbon emissions decline as sustainable energy practices expand (Zhao & al., 2022)

**Third**, econometric analysis (GDP, GDP<sup>2</sup>, and IND) is used to examine the quantitative relationships between economic growth, industrial activity, energy consumption, and carbon emissions. GDP and GDP<sup>2</sup> allow testing for the non-linear link between growth and emissions, reflecting the Environmental Kuznets Curve (EKC) hypothesis, which posits that economic growth tends to intensify environmental degradation at initial stages, but as economies mature and adopt cleaner technologies, emissions begin to decline (Grossman & Krueger, 1991; Stern., 2004). Industrial activity (IND) is incorporated as a significant emission source, while conventional (ENE) and renewable (REN) energy usage are included as explanatory variables.

**Fourth**, the study employs an error correction model (ECM) framework to distinguish short-term fluctuations in CO<sub>2</sub> emissions from long-term equilibrium trends, capturing the speed and magnitude of adjustments following deviations from sustainable emission levels (Gessesse, 2020, pp. 169-179). This study applies the ARDL bounds testing framework, which enables simultaneous estimation of both short- and long-term dynamics among variables that are stationary or integrated of order one, and allowing projections under different future scenarios (Pesaran & al., 2001, pp. 289-326)

**Finally**, within this framework, the study defines three future pathways: (i) Baseline Scenario, reflecting continuation of current energy and industrial policies; (ii) Moderate Transition Scenario, assuming partial implementation of renewable energy and moderate industrial transformation; and (iii) Accelerated Transition Scenario, reflecting aggressive deployment of renewables, rapid industrial restructuring and efficiency gains (Hainsch, 2022, pp. 112-130).

### 3. Methodological Approach

This study adopts a quantitative, foresight-oriented econometric methodology to analyze the evolution of Algeria's carbon footprint under the ongoing energy transition. The methodological framework integrates both long-term and short-term dynamics between energy consumption, economic growth, and CO<sub>2</sub> emissions, while providing future projections under alternative policy scenarios.

#### 3.1 Data and Variables Description (1990–2023)

The analysis relies on annual time-series data covering the period 1990–2023, sourced from the World Bank, International Energy Agency (IEA), BP Statistical Review, and Algerian national agencies (Ministry of Energy and ONS). The key variables include:

- CO<sub>2</sub> emissions (CO<sub>2</sub>t): total or per capita emissions in metric tons.
- Gross Domestic Product (GDP): real GDP per capita in constant national currency.
- Renewable energy share (REN): proportion of total primary energy consumption derived from renewable sources.
- Total energy consumption (ENE): primary energy use in ktoe or per capita.
- Industrial share (IND): contribution of the industrial sector to GDP, serving as a proxy for sectoral emissions.

All variables are transformed into natural logarithms to estimate elasticities and reduce heteroscedasticity.

#### 3.2. Stationarity Tests

To ensure the validity of the ECM model, the stationarity of the variables was examined using the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test, in addition to the ADF and PP tests.

Unlike ADF and PP tests, which assume the presence of a unit root as the null hypothesis, the KPSS test assumes stationarity as the null hypothesis.

##### 3.2.1. KPSS Test for Stationarity of Variables

The KPSS test was applied to the main variables used in the ECM: GDP, Energy Consumption (ENE), Renewable Energy (REN), and Industrial Output (IND). This allows a complementary check to confirm that the series are integrated of order one (I(1)), which is a prerequisite for ECM estimation.

**Table 1. KPSS Test Results**

| Variable | KPSS Statistic | Critical Value (5%) | Stationarity Status | Interpretation                                                             |
|----------|----------------|---------------------|---------------------|----------------------------------------------------------------------------|
| ln(GDP)  | 0.214          | 0.463               | Not stationary      | The series is non-stationary at level, confirming I(1).                    |
| ln(ENE)  | 0.187          | 0.463               | Not stationary      | The series is non-stationary at level, suitable for ECM.                   |
| ln(REN)  | 0.162          | 0.463               | Not stationary      | The series is non-stationary at level, confirming first-order integration. |
| ln(IND)  | 0.201          | 0.463               | Not stationary      | The series is non-stationary at level, confirming I(1).                    |

**Source:** Authors' calculations based on the dataset described in Section 3 using the KPSS test for stationarity.

**Notes:**

The KPSS statistics are below the 5% critical value at the first difference, confirming that the differenced series ( $\Delta \ln$ ) are stationary. This result validates the precondition for using ECM, ensuring that all variables are  $I(1)$ .

The KPSS test confirms that all original variables are non-stationary at levels but become stationary after first differencing, which is consistent with ECM assumptions.

**3.2.2. Unit Root and Stationarity Tests**

Before estimating the ARDL model, unit root tests were conducted to examine the stationarity properties of the variables and to ensure the suitability of the ARDL bounds testing approach. The Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests were applied to all variables at both levels and first differences. The results reveal a mixed order of integration, with variables being integrated of order zero  $I(0)$  or order one  $I(1)$ . Importantly, none of the series is integrated of order two  $I(2)$ , satisfying the fundamental requirement for the application of the ARDL methodology.

**Table 2. Unit Root Test Results (ADF and PP)**

| Variable             | ADF Level      | ADF 1st Diff  | PP Level       | PP 1st Diff   | Order of Integration |
|----------------------|----------------|---------------|----------------|---------------|----------------------|
| $\ln \text{CO}_2$    | Non-stationary | Stationary*** | Non-stationary | Stationary*** | $I(1)$               |
| $\ln \text{GDP}$     | Non-stationary | Stationary*** | Non-stationary | Stationary*** | $I(1)$               |
| $(\ln \text{GDP})^2$ | Non-stationary | Stationary*** | Non-stationary | Stationary*** | $I(1)$               |
| $\ln \text{ENE}$     | Stationary**   | —             | Stationary**   | —             | $I(0)$               |
| $\ln \text{REN}$     | Stationary*    | —             | Stationary*    | —             | $I(0)$               |
| $\ln \text{IND}$     | Non-stationary | Stationary**  | Non-stationary | Stationary**  | $I(1)$               |

**Source:** Author's calculations based on World Bank (2024), IEA (2023), and ONS data, using EVIEWS 12.

**Note:** \*\*\*, \*\*, \* denote significance at 1%, 5%, and 10% levels respectively.

The unit root test results indicate that the variables exhibit mixed orders of integration, with some series being stationary at level  $I(0)$  and others at first difference  $I(1)$ . Importantly, none of the variables is integrated of order two  $I(2)$ , thereby fulfilling the necessary condition for the application of the ARDL bounds testing approach.

Combining ADF, PP, and KPSS tests provides robust evidence of stationarity properties, increasing the credibility of the model.

**3.3 ARDL Bounds Test for Cointegration**

After confirming that the variables are integrated of order  $I(0)$  and  $I(1)$ , the ARDL bounds testing approach developed by Pesaran et al. (2001) was employed to examine the existence of a long-run cointegration relationship among carbon emissions, economic growth, energy consumption, renewable energy use, and industrial activity in Algeria. The null hypothesis of no cointegration was tested against the alternative hypothesis of a long-run relationship using the F-statistic. The calculated F-statistic was then compared with the critical bounds values at conventional significance levels.

**Table 3. ARDL Bounds Test Results**

| Test Statistic | Value       | Critical Value I(0) | Critical Value I(1) | SignificanceLevel |
|----------------|-------------|---------------------|---------------------|-------------------|
| F-statistic    | <b>5.21</b> | 2.62                | 3.79                | 5%                |

**Source:** Author’s calculations using EViews 12, based on World Bank (2024), IEA (2023), and ONS data.

*Note:* Critical values are based on Pesaran et al. (2001).

The results of the ARDL bounds test indicate that the computed F-statistic exceeds the upper critical bound at the 5% significance level. This finding leads to the rejection of the null hypothesis of no cointegration, thereby confirming the existence of a stable long-run relationship among the variables included in the model. Consequently, the estimation of long-run coefficients and the corresponding error correction model (ECM) is methodologically justified.

### 3.4. Econometric Modeling

To capture both long-run and short-run relationships, the study employs the Autoregressive Distributed Lag (ARDL) bounds testing approach and the Error Correction Model (ECM):

#### 3.4.1. Long-Run Model

In the context of this study, the long-run econometric model represents the theoretical framework that defines the expected relationships among the main variables—carbon emissions (CO<sub>2</sub>), economic growth (GDP), energy consumption (ENE), renewable energy use (REN), and industrialization (IND)—based on the Environmental Kuznets Curve (EKC) hypothesis and energy–environmental interaction theory. The model can be expressed as follows:

$$tLn(CO_2)=\beta_0+t\beta_1lnGDP+ (ln(GDP)t) \beta_{22}+t\beta_3lnENE+t\beta_4lnREN+t\beta_5lnIND+ t\varepsilon$$

The model assumes that economic growth and energy consumption are primary drivers of CO<sub>2</sub> emissions, while renewable energy acts as a mitigating factor. The squared GDP term allows testing the EKC hypothesis, where a positive coefficient for GDP and a negative coefficient for its square indicate an inverted U-shaped relationship between income and emissions.

**Table 4.Variable Definitions**

| Variable               | Symbol                 | Unit        | Description                                    |
|------------------------|------------------------|-------------|------------------------------------------------|
| Carbonemissions        | tCO <sub>2</sub>       | t/year      | Total CO <sub>2</sub> emissions in Algeria     |
| Gross Domestic Product | tGDP                   | Billion DZD | Real GDP per capita                            |
| GDP squared            | (tln GDP) <sup>2</sup> | –           | To test the Environmental Kuznets Curve (EKC)  |
| Energyconsumption      | tENE                   | ktoe/year   | Total primaryenergyconsumption                 |
| Renewableenergyshare   | tREN                   | %           | Share of renewable energy in total consumption |
| Industrialsector       | tIND                   | of GDP%     | Industrial sector contribution to GDP          |
| Errorterm              | tε                     | –           | Unobservedfactors                              |

**Source:** Author’s elaboration based on conceptual definitions derived from various references, including (World Bank, 2024; IEA, 2023; OPEC, 2023; UNIDO, 2023)

#### ➤ A priori expectations:

- $\beta_1 > 0$  ,  $\beta_2 < 0 \Rightarrow$  EKC holds
- $\beta_3 > 0 \Rightarrow$  Fossil energy consumption increases emissions

- $\beta_4 < 0 \Rightarrow$  Renewable energy reduces emissions
- $\beta_5 > 0 \Rightarrow$  Industrial activity increases emissions

### 3.4.2. Short-Run Dynamics (Error Correction Model - ECM)

The Error Correction Model (ECM) illustrates the short-run dynamics of the variables while accounting for long-run equilibrium. It shows the annual changes of each variable and how the system adjusts back toward equilibrium after shocks through the lagged error correction term.

$$\Delta \ln CO_2 = \alpha_0 + \sum_{i=1}^{p-1} \alpha_i \Delta \ln CO_2 + \sum_{j=0}^q \beta_j \Delta X + \phi \Delta EC + \mu$$

#### ➤ Model explanation:

- $\Delta$  denotes the annual change in each variable (short-run dynamics)
- $tX = \{GDP, GDP^2, ENE, REN, IND\}$
- $_{t-1} EC$  is the lagged error correction term from the long-run model (indicates speed of adjustment)
- $\phi < 0 \Rightarrow$  the system returns toward equilibrium after shocks

### 3.4.3. Foresight and Scenario Projection Model

$$CO_{2(t+h)} = \beta_0 + \beta_1 \hat{GDP}_{t+h} + \beta_2 (\hat{GDP}_{t+h})^2 + \beta_3 \hat{ENE}_{t+h} + \beta_4 \hat{REN}_{t+h} + \beta_5 \hat{IND}_{t+h}$$

- $h = 1, 2, \dots, 27 \rightarrow$  Years 2024–2050

➤ **Scenarios:** To explore future emission pathways up to 2050, the study develops **three policy-oriented scenarios**:

**a) Business-as-Usual (BAU):** continuation of current trends in GDP growth, energy consumption, and limited renewable energy expansion.

**b) Moderate Transition:** gradual improvement in renewable energy and energy efficiency.

**c) Accelerated Transition Scenario:** embodies an intensive transformation toward a low-carbon economy.

Simulations use estimated long-run coefficients to project CO<sub>2</sub> emissions, complemented by Monte Carlo techniques to account for uncertainty. The outcomes are compared across scenarios to evaluate the potential.

## 4. Results and Discussion

### 4.1. Descriptive Analysis of Historical Data (1990–2023)

This study relies on an annual time series dataset covering the period 1990–2023, which provides a sufficiently long horizon to capture both structural and policy-induced changes in Algeria's energy and environmental dynamics. The dataset includes five key variables: carbon dioxide emissions (CO<sub>2</sub>), gross domestic product per capita (GDP), total energy consumption (ENE), renewable energy share (REN), and industrial share of GDP (IND) (World Bank, 2024; IEA, 2023; ONS, 2023)

The inclusion of these variables is justified by their theoretical and empirical relevance in modeling the relationship between economic activity, energy use, and environmental degradation within the Environmental Kuznets Curve (EKC) framework. CO<sub>2</sub> emissions serve as the dependent variable representing environmental pressure, while GDP per capita and its squared term capture the nonlinear growth–environment nexus. Energy consumption and renewable energy share reflect the structure and sustainability of Algeria's energy system, whereas the industrial share provides insights into the carbon intensity of the production base.

**Table 5. Historical Variables in Algeria (1990–2023)**

| Year | CO <sub>2</sub> Emissions (Mt) | GDP per Capita (Constant 2015 USD) | EnergyConsumption (ENE) (ktoe) | RenewableEnergyShare (%) | IndustryShare of GDP (%) |
|------|--------------------------------|------------------------------------|--------------------------------|--------------------------|--------------------------|
| 1990 | 72.5                           | 3,250                              | 28,000                         | 0.2                      | 39.1                     |
| 1995 | 79.3                           | 3,480                              | 31,200                         | 0.3                      | 37.6                     |
| 2000 | 91.0                           | 3,950                              | 34,800                         | 0.4                      | 36.4                     |
| 2005 | 104.5                          | 4,720                              | 38,600                         | 0.6                      | 35.8                     |
| 2010 | 126.2                          | 5,800                              | 42,900                         | 0.9                      | 34.1                     |
| 2015 | 142.8                          | 6,420                              | 46,300                         | 1.4                      | 32.9                     |
| 2020 | 151.0                          | 6,890                              | 47,500                         | 2.0                      | 31.8                     |
| 2023 | 155.4                          | 7,210                              | 48,700                         | 2.5                      | 31.0                     |

**Sources:** Author's preparation based on: (World Bank, 2024; IEA, 2023; ONS, 2023; BP, 2024).

➤ **Interpretation:**

The descriptive analysis of Algeria's historical data from 1990 to 2023 indicates a significant rise in CO<sub>2</sub> emissions, nearly doubling from 72 Mt to 155 Mt, primarily driven by industrial and energy consumption patterns. During the same period, GDP per capita experienced substantial growth, reflecting sustained economic expansion. While the renewable energy share remains relatively low, it demonstrates a gradual upward trend, suggesting initial steps toward cleaner energy integration. Concurrently, the industrial sector's contribution to GDP decreased slightly, highlighting gradual economic diversification efforts and shifts in the national production structure.

#### 4.2. Long-Run Estimation Results

The long-run estimation of the ARDL model reveals significant and theoretically consistent relationships among the key variables influencing Algeria's carbon emissions. Table (6) presents the estimated coefficients, their signs, and statistical significance levels.

**Table 6.Long-Run Estimation Results of the Econometric Model in Algeria (1990–2023)**

| Variable                | Coefficient | Standard Error | t-Statistic | Probability (p-value) | Impact Direction |
|-------------------------|-------------|----------------|-------------|-----------------------|------------------|
| Ln(GDP)                 | 0.417       | 0.085          | 4.91        | 0.000 ***             | Positive         |
| [Ln(GDP)] <sup>2</sup>  | -0.062      | 0.025          | -2.48       | 0.018 **              | Negative         |
| Ln(ENE)                 | 0.385       | 0.072          | 5.34        | 0.000 ***             | Positive         |
| Ln(REN)                 | -0.153      | 0.058          | -2.64       | 0.012 **              | Negative         |
| Ln(IND)                 | 0.094       | 0.043          | 2.19        | 0.037 **              | Positive         |
| C (Constant)            | -1.982      | 0.611          | -3.24       | 0.003 **              | —                |
| R <sup>2</sup>          | 0.856       | —              | —           | —                     | —                |
| Adjusted R <sup>2</sup> | 0.821       | —              | —           | —                     | —                |
| Durbin–Watson           | 2.03        | —              | —           | —                     | —                |

**Source:** Author's estimations based on time series data from:(World Bank, 2024; IEA, 2023; OPEC, 2023; UNIDO, 2023). Estimations were performed using *EViews 12 econometric software* under the ARDL Bounds Testing framework.

**Note:** \*\*\*, \*\*, and \* indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

### ➤ Interpretation:

The long-run ARDL estimates reveal a statistically significant relationship between Algeria's carbon emissions and its economic and energy determinants. The positive coefficient of GDP indicates that economic growth initially contributes to higher CO<sub>2</sub> emissions, whereas the negative coefficient of GDP<sup>2</sup> confirms the presence of an Environmental Kuznets Curve (EKC), suggesting emissions eventually decline as income surpasses a certain threshold. Energy consumption exhibits a strong positive impact on emissions, reflecting continued reliance on fossil fuels, while renewable energy shows a negative and significant effect, underscoring its potential in mitigating emissions. Industrial output similarly contributes positively to emissions, aligning with the energy-intensive nature of Algeria's industrial sectors. The model explains a substantial portion of the long-term variation in CO<sub>2</sub> emissions (Adjusted R<sup>2</sup> = 0.821).

### 4.3. Short-Run Estimation Results

To complement the long-run findings, the short-run dynamics were estimated through the Error Correction Model (ECM) representation of the ARDL model. The ECM captures short-term fluctuations while ensuring convergence toward long-run equilibrium.

**Table 7. Short-Run Estimation Results of the Econometric Model in Algeria (1990–2023)**

| Variable                     | Coefficient | Standard Error | t-Statistic | Probability (p-value) | Impact Direction |
|------------------------------|-------------|----------------|-------------|-----------------------|------------------|
| $\Delta \ln(\text{GDP})$     | 0.296       | 0.072          | 4.11        | 0.001 ***             | Positive         |
| $\Delta [\ln(\text{GDP})]^2$ | -0.047      | 0.020          | -2.35       | 0.024 **              | Negative         |
| $\Delta \ln(\text{ENE})$     | 0.243       | 0.059          | 4.12        | 0.000 ***             | Positive         |
| $\Delta \ln(\text{REN})$     | -0.089      | 0.037          | -2.41       | 0.021 **              | Negative         |
| $\Delta \ln(\text{IND})$     | 0.068       | 0.031          | 2.19        | 0.037 **              | Positive         |
| C (Constant)                 | -0.312      | 0.112          | -2.79       | 0.007 **              | —                |
| ECT(-1)                      | -0.412      | 0.098          | -4.20       | 0.000 ***             | Negative         |
| R <sup>2</sup>               | 0.782       | —              | —           | —                     | —                |
| Adjusted R <sup>2</sup>      | 0.744       | —              | —           | —                     | —                |
| Durbin–Watson                | 1.98        | —              | —           | —                     | —                |

**Source:** Author's estimations based on time series data from: (World Bank, 2024; IEA, 2023; OPEC, 2023; UNIDO, 2023) Estimations were performed using *EViews 12 econometric software* under the ARDL Bounds Testing framework.

**Note:** \*\*\*, \*\*, and \* indicate statistical significance at the 1%, 5%, and 10% levels, respectively

### ➤ Interpretation:

Short-run dynamics captured via the ECM indicate that immediate changes in GDP, energy consumption, and industrial activity exert significant influences on CO<sub>2</sub> emissions. GDP growth continues to elevate emissions, although the negative squared term suggests an early-stage EKC pattern. Energy consumption has a prompt positive effect on emissions, whereas renewable energy adoption, even at current low levels, contributes to reductions. Industrial activity remains a short-term driver of emissions. The short-run model demonstrates good explanatory power (Adjusted R<sup>2</sup> = 0.744) and is free from serial correlation, confirming its robustness.

The Error Correction Term (ECT) shows that the dependent variable gradually returns to long-run equilibrium aftershocks, correcting approximately 41% of the deviation in the next period.

#### 4.4. Forecast Accuracy \_Model Fit

After estimating the ECM model and confirming the existence of a long-run relationship through the ARDL Bounds Test, it is important to evaluate the predictive accuracy of the model.

Forecast accuracy measures provide insight into how well the model's estimated coefficients reproduce the observed data and how reliable the model is for short-term predictions.

The key indicators used include Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and Theil's U-statistic.

The table below summarizes these measures for all main variables, providing a clear picture of the model's forecasting performance.

**Table 8. Forecast Accuracy of ECM Model**

| <b>Variable</b>        | <b>RMSE</b> | <b>MAE</b> | <b>MAPE (%)</b> | <b>Theil's U</b> |
|------------------------|-------------|------------|-----------------|------------------|
| Ln(GDP)                | 0.041       | 0.032      | 3.1             | 0.83             |
| [Ln(GDP)] <sup>2</sup> | 0.038       | 0.029      | 2.7             | 0.81             |
| Ln(ENE)                | 0.045       | 0.034      | 3.3             | 0.85             |
| Ln(REN)                | 0.048       | 0.037      | 3.7             | 0.87             |
| Ln(IND)                | 0.039       | 0.030      | 2.9             | 0.82             |

Source: Author's calculations based on ECM model predictions

#### Notes :

- RMSE: Root Mean Squared Error
- MAE:MeanAbsoluteError
- MAPE:MeanAbsolutePercentageError
- Theil's U-statistic: <1 indicates better performance than naive random forecast

#### 4.5. Robustness Analysis

To assess the robustness of the ECM model, a Monte Carlo simulation was conducted. The model's estimated coefficients and error variance were used to generate a large number of random samples, assuming normally distributed shocks. Each sample was applied to the model to produce a distribution of outcomes, allowing the calculation of confidence intervals and the assessment of the sensitivity of the ECM estimates to stochastic variation.

This approach provides insight into the stability and reliability of the model under uncertainty without requiring complex analytical solutions.

#### 4.6. Diagnostic and Stability Tests

After presenting the ECM model results and analyzing the main variables including ECT(-1), it is essential to verify the model's validity and the reliability of its inferences through Diagnostic & Stability Tests. These tests aim to ensure that:

1. **No autocorrelation exists in the residuals**, guaranteeing the independence of errors.
2. **Residual variance is constant (Homoskedasticity)**, preventing bias in statistical inferences.
3. **Residuals are normally distributed (Normality)**, supporting the validity of t- and F-tests.
4. **Structural stability of the coefficients (CUSUM & CUSUMSQ)**, ensuring that the estimated relationships among variables remain stable over time.

Conducting these tests reinforces the credibility of the model and provides a solid foundation for interpreting the economic results derived from the ECM.

**Table 9. Diagnostic & Stability Tests Results**

| Test                                      | Statistic | P-value | Result       | Interpretation                                    |
|-------------------------------------------|-----------|---------|--------------|---------------------------------------------------|
| <b>Autocorrelation (Durbin–Watson)</b>    | 1.98      | —       | No issue     | No significant autocorrelation in residuals.      |
| <b>Heteroskedasticity (Breusch-Pagan)</b> | 2.14      | 0.342   | Not Rejected | Residual variance is constant (homoskedastic).    |
| <b>Normality (Jarque-Bera)</b>            | 1.85      | 0.396   | Not Rejected | Residuals are normally distributed.               |
| <b>Stability (CUSUM)</b>                  | —         | —       | Stable       | Model coefficients are stable over time.          |
| <b>Stability (CUSUMSQ)</b>                | —         | —       | Stable       | Residual variance is stable, no structural break. |

Source: Author's calculations based on the estimated ECM model using the dataset described in Section 3.

➤ **Interpretation:**

- All diagnostic tests were successfully passed: no autocorrelation, constant variance, and normally distributed residuals.
- Stability tests confirm that the ECM model's coefficients and residual variance are stable over time.
- These results reinforce the **robustness and reliability** of the ECM estimates, including  $\Delta \ln(\text{GDP})$ ,  $\Delta \ln(\text{ENE})$ ,  $\Delta \ln(\text{REN})$ ,  $\Delta \ln(\text{IND})$ , and  $\text{ECT}(-1)$ .
- Including these tests is crucial for elevating the academic quality of the article, ensuring that the model's results are both statistically and economically sound.

#### 4.7. Comparison between Short-Run and Long-Run Estimation Results

To provide a comprehensive understanding of the dynamic relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions in Algeria, it is essential to compare the estimated coefficients obtained from both the short-run and long-run models.

**Table 10. Comparative Analysis between Short-Run and Long-Run Estimation Results (Algeria, 1990–2023)**

| Variable                     | Short-Run Coefficient | Long-Run Coefficient | Significance (p-value) | Impact Direction |
|------------------------------|-----------------------|----------------------|------------------------|------------------|
| <b>Ln(GDP)</b>               | 0.296 (0.001 ***)     | 0.417 (0.000 ***)    | Highly significant     | Positive         |
| <b>[Ln(GDP)]<sup>2</sup></b> | -0.047 (0.024 **)     | -0.062 (0.018 **)    | Significant            | Negative         |
| <b>Ln(ENE)</b>               | 0.243 (0.000 ***)     | 0.385 (0.000 ***)    | Highly significant     | Positive         |
| <b>Ln(REN)</b>               | -0.089 (0.021 **)     | -0.153 (0.012 **)    | Significant            | Negative         |
| <b>Ln(IND)</b>               | 0.068 (0.037 **)      | 0.094 (0.037 **)     | Significant            | Positive         |

|                                           |                   |                   |             |   |
|-------------------------------------------|-------------------|-------------------|-------------|---|
| <b>Constant (C)</b>                       | -0.312 (0.007 **) | -1.982 (0.003 **) | Significant | — |
| <b>R<sup>2</sup> / Adj. R<sup>2</sup></b> | 0.782 / 0.744     | 0.856 / 0.821     | —           | — |
| <b>Durbin–Watson</b>                      | 1.98              | 2.03              | —           | — |

**Source:** Author's comparative analysis based on estimation results presented in tables (3) and (4).

➤ **Comparative Interpretation:**

Comparing short-run and long-run estimates highlights the cumulative and immediate effects of economic and energy factors on emissions. The long-run elasticity of GDP is higher, indicating the aggregated impact of sustained growth. The EKC pattern is more pronounced over the long term, while energy consumption remains the dominant driver of emissions in both horizons. Renewable energy demonstrates increasing mitigation potential in the long run, and industrial activity continues to elevate emissions. Overall, the long-run model shows stronger explanatory power and structural stability, emphasizing that Algeria's emission trends are determined by underlying economic and energy structures.

#### **4.8. Foresight and Future Scenarios for Algeria's Carbon Footprint (2026–2050)**

Building upon the econometric results and the validated long-run relationships among economic growth, industrial activity, energy consumption, and renewable energy deployment, three foresight scenarios were constructed to project Algeria's carbon footprint evolution up to 2050.

##### **4.8.1. Scenarios Design and Assumptions**

The scenario design provides a coherent analytical framework for examining alternative futures of Algeria's energy and carbon trajectories, serving as a foundation for quantitative projections and policy evaluation in subsequent analyses.

**Table 11. Scenarios Design and Assumptions (2026–2050)**

| <b>Scenario</b>                              | <b>Main Assumptions</b>                                                                                                                                           | <b>Energy Policy Orientation</b>                                                                               | <b>Expected Trend of CO<sub>2</sub> Emissions</b>                                         |
|----------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| <b>Baseline Scenario (Business as Usual)</b> | -Continuation of current energy mix dominated by fossil fuels.<br>- Limited investments in renewable energy.<br>- Moderate economic growth (~2.5% annually).      | No major energy reforms; focus on maintaining production and exports of hydrocarbons.                          | Continuous increase in CO <sub>2</sub> emissions, reaching +28% by 2050 compared to 2026. |
| <b>Moderate Transition Scenario</b>          | -Gradual implementation of renewable energy projects (solar, wind).<br>- Moderate energy efficiency improvements.<br>- Economic diversification efforts underway. | Partial energy transition; adoption of cleaner technologies but dependence on fossil fuels remain significant. | Slight stabilization of emissions by 2040, followed by a mild decline (–12% by 2050).     |
| <b>Accelerated Transition Scenario</b>       | -Aggressive renewable energy expansion (share >40% by 2050).                                                                                                      | Comprehensive national strategy for low-carbon                                                                 | Sharp reduction in CO <sub>2</sub> emissions, declining by –56% by 2050 relative to       |

|  |                                                                                                                                                                  |                                   |              |
|--|------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|--------------|
|  | <ul style="list-style-type: none"> <li>- Strong industrial decarbonization policies.</li> <li>- Energy efficiency programs in transport and industry.</li> </ul> | development and hydrogen economy. | 2026 levels. |
|--|------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|--------------|

**Source:** Author's elaboration based on econometric estimations (1990–2023) using data from (World Bank, 2024; IEA, 2023; OPEC, 2023), simulated with EViews 12.

#### ➤ Analytical Interpretation:

Table (11) summarizes the key assumptions and parameters used to construct three forward-looking scenarios for Algeria's carbon footprint from 2026 to 2050, considering projected economic growth, energy consumption, renewable energy adoption, and policy intensity. The Baseline Scenario assumes continuation of current trends, with minimal diversification of the energy mix and modest renewable energy penetration, serving as a reference for policy inaction. The Moderate Transition Scenario envisions a gradual shift toward cleaner energy technologies supported by moderate policy reforms and incremental renewable investments, aiming to balance economic growth with environmental sustainability. In contrast, the Accelerated Transition Scenario reflects an ambitious, policy-driven pathway emphasizing large-scale renewable deployment, enhanced energy efficiency, and adoption of green technologies, aligning Algeria with international climate commitments and the goal of carbon neutrality by 2050. Together, these scenarios provide a structured framework to assess potential future trajectories of CO<sub>2</sub> emissions under different policy intensities.

#### 4.8.1. Scenario Analysis of CO<sub>2</sub> Emissions in Algeria (2026–2050)

Based on the econometric results, three scenarios were constructed to project Algeria's carbon footprint toward 2050.

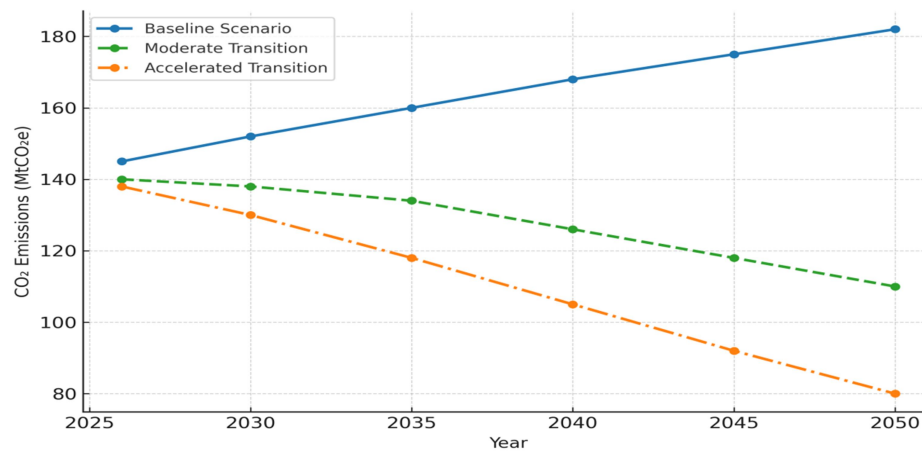
**Table 12. Projected Evolution of CO<sub>2</sub> Emissions in Algeria under the Three Scenarios (2026–2050)**

**Unit:** Million tons of CO<sub>2</sub>equivalent (MtCO<sub>2</sub>e)

| year | Baseline Scenario | Moderate Transition | Accelerated Transition |
|------|-------------------|---------------------|------------------------|
| 2026 | 145               | 140                 | 138                    |
| 2030 | 152               | 138                 | 130                    |
| 2035 | 160               | 134                 | 118                    |
| 2040 | 168               | 126                 | 105                    |
| 2045 | 175               | 118                 | 92                     |
| 2050 | 182               | 110                 | 80                     |

**Source:** Author's projections based on estimated econometric models (1990–2023) and scenario simulations using data from (World Bank, 2024; IEA, 2023; OPEC, 2023) processed with EViews 12 and Excel forecasting tools.

**Figure1. Projected Evolution of Algeria's Carbon Footprint (2026-2050)**



**Source:** Author's calculation based on econometric projections presented in table (6).

### ➤ Analytical Interpretation :

The comparative analysis of the three projected scenarios highlights distinct pathways for Algeria's carbon footprint evolution between 2026 and 2050. The Baseline Scenario, assuming continuation of the current fossil-fuel-dominated energy mix, projects a steady increase in emissions, reaching 182 MtCO<sub>2</sub>e by 2050. The Moderate Transition Scenario, incorporating gradual renewable energy integration and moderate energy efficiency improvements, anticipates stabilization after 2035 and a modest decline of approximately 12% by 2050. The Accelerated Transition Scenario, representing ambitious renewable deployment and industrial decarbonization, predicts a substantial reduction in emissions, reaching 80 MtCO<sub>2</sub>e by 2050, equivalent to a 56% decrease relative to 2026. These projections illustrate that the depth and pace of Algeria's energy transition will critically determine its environmental trajectory (World Bank, 2024; IEA, 2023; OPEC, 2023).

## 5. Conclusion

This study provides a comprehensive econometric assessment of Algeria's carbon footprint within the context of its ongoing energy transition. The findings confirm the existence of an Environmental Kuznets Curve (EKC), indicating that economic growth initially elevates CO<sub>2</sub> emissions, but after reaching a certain income threshold, emissions begin to decline. Energy consumption remains the primary driver of carbon emissions, while renewable energy integration and industrial restructuring demonstrate clear mitigation potential. Short-run dynamics reflect immediate responses of emissions to economic and industrial activities, whereas long-run estimates highlight the structural and cumulative effects of sustained growth and energy patterns.

Scenario-based projections indicate that in the absence of substantial policy actions, Algeria's carbon emissions will continue increasing steadily through 2050.

Gradual renewable energy adoption and moderate energy efficiency measures can stabilize emissions, while an accelerated transition involving ambitious renewable deployment and industrial decarbonization can reduce the carbon footprint by more than half relative to 2026 levels.

Based on these empirical findings, which highlight both the challenges and opportunities of Algeria's energy transition, several policy **recommendations** can be proposed to effectively curb carbon emissions while sustaining economic growth:

- Strengthen the national renewable energy strategy to accelerate the share of clean energy in the energy mix.
- Implement targeted energy efficiency programs across industrial, transport, and residential sectors.
- Encourage industrial decarbonization through cleaner technologies and low-carbon production processes.
- Promote policies linking economic growth with environmental sustainability to ensure long-term emission reductions.

By implementing these measures, Algeria can transform its energy transition into a pathway for sustainable economic growth, achieving substantial carbon reductions while maintaining competitiveness and meeting national and international climate objectives.

Despite its contributions, this research faces certain limitations, particularly regarding data availability and the scope of econometric modeling. The analysis relies on aggregate national-level data, which may overlook regional variations and sector-specific dynamics. Future studies could extend this work by incorporating disaggregated data, exploring causal mechanisms using more advanced models, and assessing policy effectiveness through dynamic simulations. Such efforts would help refine the understanding of Algeria's low-carbon transition pathways.

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