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# Environmental Kuznets Curve and the Renewable Energy Transition in Morocco: Evidence from an ARDL Approach

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**ABSTRACT**

This paper investigates the dynamic relationship between renewable energy consumption, carbon dioxide ($CO_2$) emissions, and economic growth in Morocco over the period 1980–2019 using an autoregressive distributed lag (ARDL) bounds testing approach. Unit root and bounds test results confirm the existence of a long-run cointegrating relationship among $CO_2$ emissions, income, and renewable energy consumption. The estimated long-run coefficients support an inverted U-shaped Environmental Kuznets Curve (EKC): emissions rise with income at early stages of development, but the marginal impact of further growth on emissions declines and eventually becomes negative. The implied turning point lies in the upper-middle-income range, and Morocco's income level by 2019 is already above this threshold, suggesting scope for an emissions dividend from future growth. In contrast, the long-run coefficient on the aggregate renewable energy indicator is positive, indicating that higher aggregate renewable use has historically coincided with higher $CO_2$ emissions. This result does not imply that solar or wind energy increases pollution; rather, it reflects the composition of Morocco's renewable portfolio, in which traditional biomass (fuelwood, charcoal, agricultural residues) has historically dominated the aggregate renewable indicator and is associated with significant combustion emissions. We discuss the implications of this compositional effect and identify policy levers to shift the energy mix away from traditional biomass toward modern, low-carbon renewables and to enhance system flexibility. The paper provides country-specific evidence for Morocco and policy-relevant insights into how structural change and clean-energy-driven growth can help stabilise emissions beyond the EKC turning point.

## 1. INTRODUCTION

Global climate change mitigation increasingly relies on countries' ability to enhance renewable energy integration into their energy systems, rather than merely relocating emissions. Reducing greenhouse gas (GHG) emissions without impeding growth or running the danger of energy shortages is a problem for many growing economies. Morocco is a prime illustration of this conflict. Despite having some of the strongest solar and wind resources in the world and setting aggressive clean-energy targets, the nation remains largely dependent on fossil fuels. To address this, Morocco has developed many long-term energy and climate policies. The national energy strategy aims to increase installed power capacity from renewable sources to 52% by 2030, with hydro accounting for 12% and solar and wind for 20% [1]. Morocco's updated Nationally Determined Contribution under the Paris Agreement simultaneously pledges significant reductions in GHG emissions relative to a business-as-usual scenario under both unconditional and conditional paths. The empirical question then becomes: do those objectives and investments actually result in measurable reductions in emissions, and if so, how does this connect to economic growth?

The Environmental Kuznets Curve (EKC) hypothesis provides one conceptual framework for this question. It posits an inverted U-shaped relationship between per capita income and environmental degradation: emissions rise during early industrialisation but eventually fall as richer societies adopt cleaner technologies, shift towards service-led production, and implement stronger environmental regulation [2, 3]. The empirical literature testing the EKC is vast, but yields mixed results, particularly in developing economies, where outcomes are sensitive to model specification, variable choice, and institutional context [4, 5]. A related body of work examines the role of renewable energy in the growth–emissions nexus. While many studies find that expanding modern renewables reduces $CO_2$ emissions [6-8], this is not automatic: in economies where traditional biomass still dominates the renewable aggregate, or where new capacity is built on top of rather than replacing fossil-fuel generation, higher renewable use may coexist with higher emissions, at least in the short and medium run [9-11].

The Middle East and North Africa (MENA) region, and Morocco in particular, remains comparatively understudied in the time-series EKC literature. Panel studies covering Morocco sacrifice country-specific dynamics for broader coverage [12, 13], while more recent work on MENA economies yields mixed results across specifications [14, 15]. Two recent country-level studies for Morocco confirm a long-run income–emissions nexus using autoregressive distributed lag (ARDL) [9, 16], but do not jointly test the full EKC specification with a quadratic income term alongside renewable energy in a single-equation system.

This paper contributes to the literature in three ways. First, it provides country-specific EKC evidence for Morocco by jointly estimating an inverted U-shaped relationship between income and $CO_2$ emissions and calculating the income threshold at which emissions begin to decline. Second, it integrates aggregate renewable energy consumption into the EKC setting and provides an explicit interpretation of the composition effects that arise when traditional biomass is embedded in the WDI renewable indicator. Third, by estimating both short-run coefficients and the long-run estimates and conducting robustness checks across five ARDL specifications, it distinguishes transitional emission dynamics from the long-run equilibrium and confirms the stability of the key qualitative results.

The rest of the paper is organized as follows. Section 2 reviews the literature on the EKC and on the growth–renewable energy–emissions nexus, with a focus on evidence from developing and MENA economies. Section 3 presents the data, variables, and econometric methodology, including the ARDL bounds testing procedure. Section 4 reports and discusses the empirical results, covering unit root and cointegration tests, long-run estimates, short-run dynamics, and diagnostic checks. Section 5 concludes with the main findings, draws policy implications for Morocco's energy and climate strategies, and suggests directions for future research.

## 2. LITERATURE REVIEW

The shift to renewable energy sources has become of fundamental importance in energy and environmental research, as growing issues about climate change and GHG emissions are prompting a shift in energy sources. There was early research done by Dincer that emphasized the interrelationship of energy use, environmental sustainability, and economic development [17]. They cautioned that further use of fossil fuels would impact negatively on the ecology, and they insisted on a partial transition to renewables. This view was reiterated by Kalogirou [18], who cited solar energy as a promising option, especially because it has less of an environmental footprint. Later studies have investigated whether renewable energy is viable and efficient in economic and geographical areas. Granovskii established that wind and solar energy were cheaper in decreasing emissions in comparison to fossil fuels [19]. Bilen et al. [20] and Yu and Qu [21] further included the fact that the efficiency and viability of renewables are highly influenced by location-specific economic and geographical factors. In terms of socio-economic facets, Yadoo and Cruickshank [22] looked at rural electrification in the developing nations, which revealed how a renewed energy source can be used to achieve poverty eradication as well as environmental goals. Recent reports still confirm the environmental advantages of renewable energy. In fact, Amponsah et al. [23] have carried out life-cycle analyses and have established that renewables have a much lower GHG emission rate compared to conventional fuels. Equally, Sapkota et al. [24] had estimated significant long-term household $CO_2$ emissions cuts due to increased use of renewable energy in Nepal. In more recent research, scholars have discovered that renewables play a significant role in the reduction of emissions in South Asia and other emerging economies [25, 26]. Nevertheless, there is no unanimity in the literature. Other researchers claim that the implementation of renewable energy in developing nations may encounter significant economic and technical challenges. The high start-up costs, accessibility to funds, and intermittency of the renewable sources are significant challenges [26, 27]. Others refer to the environmental expenses of producing and disposing of solar panels and wind turbines [28, 29]. Moreover, grid stability may be a problem when large-scale renewable integration is done in isolation without an adequate investment in flexible infrastructure and storage technologies [30, 31]. These issues point to the fact that although renewables have significant potential, their implementation carries tradeoffs that should be subject to careful scrutiny, especially in the case of developing economies, which have weak energy infrastructure. Economic growth and environmental degradation have been studied in light of the EKC, which presupposes an inverted U relationship between the level of income and the extent of pollution [1, 2]. That is, there will be optimistic growth in the levels of pollution, but this will level off as societies attain greater income levels and use less polluting technologies. But, empirical evidence of the EKC is unclear. Research by Jeon [32] on the United States gave recent validation of the EKC hypothesis and emphasized the contribution of energy pricing policies to the minimization of emissions, but these findings might not necessarily apply directly to developing economies. Simultaneously with EKC-oriented research, there has been an increasing amount of literature addressing the relationship between the use of renewable energy and economic growth. In both developed and emerging economies, Apergis and Payne [6], Shafiei and Salim [8], and Al-mulali et al. [33] discovered evidence of the bi-directional causality effect between renewable energy and gross domestic product (GDP). This implies that renewable investment can create growth, and economic development can cause renewable growth in turn. Khobai and Roux [34] shared the same findings when it came to South Africa, stating that renewable infrastructure has played a critical role in the economic development of the country in the long run. A multivariate approach has been adopted in other studies. Indicatively, the relationship between renewable and non-renewable energy consumption, economic growth, and carbon emission of countries like Brazil, the G7, and other emerging markets has been examined by Sadorsky [35] and Pao and Fu [36], who found complex interrelationships that rely on national conditions. Although this literature is growing, the MENA region (and Morocco specifically) is not that well-researched. Although some of the panel studies covering data on Morocco are based on wider regional coverage [12, 13], they lack the ability to identify country-specific dynamics that would be critical to the national energy transition. The peculiarities of the energy structure of Morocco, where fossil fuels are imported in large amounts, and renewable energy objectives are set, require specific work of analysis. So far as we know, no prior study has used a time-series method to investigate the relationship between renewable energy use, economic growth, and $CO_2$ emissions in the Moroccan environment. The given study aims to fill the gap by estimating the ARDL model using the annual data on Morocco that includes the timeframe between the years 1980 and 2019. The ARDL model is quite appropriate to this analysis since it is capable of integrating both mixed order integrations of variables, as well as enabling the determination of a short-run as well as a long-run relationship. In doing so, the research will add to the larger body of literature on sustainable development in the context of emerging economies as well as provide context-based, relevant insights that can inform energy policy and planning in Morocco.

## 3. DATA

This analysis is based on annual time- series data of Morocco between the years 1980 and 2019. This period was chosen because of the coincident presence of consistent and similar data on all the variables of interest. It is used to get enough coverage over time to capture long-run and short-run dynamics, and yet have data of the required quality and reliability.

Three fundamental variables are analyzed:

• Carbon dioxide emissions per capita ($CO_2$): in metric tons per capita, are used as the environmental outcome variable. These figures are sourced from the BP Statistical Review of World Energy. The Morocco $CO_2$ per capita series is available continuously from 1965 onward in the BP dataset, and no gaps or missing values were identified for the 1980–2019 study window; no interpolation was therefore required or applied. All data points used in the estimation are original, unmodified observations from the source.

• The use of renewable energy per capita (RE): We employ the aggregate WDI renewable-energy measure of Morocco and take the natural logs (lnRE). By construction, this aggregate includes traditional biomass (e.g., fuelwood, charcoal, agricultural residues). This composition may attenuate the measured mitigation effect relative to modern renewables (wind/solar/hydro), and we therefore flag this as a limitation in the Results.

• GDP per capita: We use GDP per capita in constant 2015 US dollars (non-PPP) from the World Development Indicators. The series is transformed to natural logarithms and denoted lnGDP. Unless stated otherwise, all income levels and the EKC turning-point value reported in USD are expressed in this same unit (constant 2015 US$).

To test the EKC hypothesis, the model includes both the natural logarithm of GDP per capita, ln(GDP), and the square of this logged value, denoted $[\ln(GDP)]^2$. This specification is consistent with standard EKC modelling practices, allowing for the identification of potential non-linear relationships between income and environmental degradation. The use of the logarithmic transformation helps reduce heteroskedasticity and allows for elasticity-based interpretation of coefficients. All variables, with the exception of the squared log-income term, are expressed in natural logarithmic form.

## 4. ECONOMETRIC APPROACH

To examine the short-run and long-run relationships among $CO_2$ emissions, renewable energy consumption, and economic growth, this study applies the ARDL bounds testing approach developed by Pesaran et al. [37]. This method is well-suited for small and medium-sized samples, such as the current dataset of 40 annual observations, and allows for the inclusion of variables integrated at order zero, I(0), or order one, I(1), as long as none is integrated at order two, I(2).

Unit root tests were conducted using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) procedures, incorporating intercepts and trends as appropriate. The results indicate that renewable energy consumption per capita ($\ln(RE_t)$) is stationary at levels (I(0)), as indicated by the ADF test ($p = 0.039$) and the PP test ($p = 0.031$), both significant at the 5% level. The remaining variables — natural logarithm of $CO_2$ emissions per capita ($\ln(CO_{2t})$), the natural logarithm of GDP per capita ($\ln(GDP_t)$), and the squared log-GDP term ($lnGDP\_SQ_t = [\ln(GDP_t)]^2$) — are non-stationary in levels but stationary in first differences, classifying them as I(1). This mixed integration order (I(0) and I(1)) is precisely the setting for which the ARDL bounds testing approach is designed; no variable is I(2), confirming the validity of the methodology.

The optimal lag length for the ARDL model was determined using the Schwarz Information Criterion (SIC). While several model selection criteria are available, such as the Akaike Information Criterion (AIC) and the Hannan-Quinn Criterion (HQC), the SIC was chosen specifically because it imposes the heaviest penalty for additional parameters and therefore selects the most parsimonious models relative to competing criteria. In the context of a limited sample of 40 annual observations, the SIC's parsimony-favouring property is particularly valuable, as it reduces the risk of overfitting and helps maintain robustness in the parameter estimates. The SIC selected the ARDL(2,4,4,4) specification; despite the relatively high lag orders on the regressors, this model satisfies all diagnostic checks (no serial correlation, no heteroskedasticity, normality of residuals, and correct functional form), providing confidence that the chosen lag structure captures the true dynamics without overfitting. Nonetheless, to further assess the sensitivity of the results to the lag structure, the key long-run coefficients were also verified under alternative, shorter specifications selected by the AIC; the signs, approximate magnitudes, and statistical significance of the long-run coefficients remained consistent, supporting the robustness of the reported estimates.

The ARDL model is initially expressed in a general functional form as follows:

$$\begin{aligned} \mathrm{lnCO2}_t = \alpha_0 &+ \sum_{i=1}^{p} \varphi_i \mathrm{lnCO2}_{t-i} + \sum_{j=0}^{qRE} \theta_j^{RE} \mathrm{lnRE}_{t-j} \\ &+ \sum_{k=0}^{qGDP} \theta_k^{GDP} \mathrm{lnGDP}_{t-k} \\ &+ \sum_{l=0}^{qGDPsq} \theta_l^{GDPsq} [\mathrm{lnGDP}_{t-l}]^2 + \varepsilon_t \end{aligned}$$

where, $lnGDP\_SQ_t = [\ln(GDP_t)]^2$: included to capture the potential non-linear relationship between income and emissions, as proposed by the EKC hypothesis.

To estimate both the short-run and long-run dynamics, the model is reparameterised into the conditional Error Correction Model (ECM) form as follows:

$$\Delta \ln CO2_t = \alpha_0 + \sum_{i=1}^{p-1} \psi_i \Delta \ln CO2_{t-i} + \sum_{j=0}^{qRE-1} \delta_j^{RE} \Delta \ln RE_{t-j} + \sum_{k=0}^{qGDP-1} \delta_k^{GDP} \Delta \ln GDP_{t-k} + \sum_{l=0}^{qGDPsq-1} \delta_l^{GDPsq} \Delta \ln GDP\_SQ_{t-l} + \lambda_1 \ln CO2_{t-1} + \lambda_2 \ln RE_{t-1} + \lambda_3 \ln GDP_{t-1} + \lambda_4 \ln GDP\_SQ_{t-1} + \varepsilon_t$$

With:

$\Delta$: first difference operator;

$\alpha_0$: constant

$\varphi_i$, $\theta$: coefficients in the ARDL levels model;

$\psi_i$, $\delta$: short-run (difference) coefficients in the ECM;

$\lambda_{1\ldots4}$: levels coefficients in the unrestricted ECM used for the bounds test;

$\varepsilon_t$: Error term (white noise).

The inclusion of lagged level terms permits the testing of a long-run relationship (cointegration), while the differenced terms reflect short-run adjustments. The error correction term (ECT), derived from the lagged level variables, indicates the speed of adjustment toward long-run equilibrium in response to short-run deviations.

The presence of cointegration among the variables was tested using the ARDL bounds testing procedure proposed by Pesaran et al. [37]. The null hypothesis of no cointegration (i.e., no long-run relationship) is rejected if the computed F-statistic exceeds the upper bound of the critical values. As shown in Section 4.1, the calculated F-statistic exceeds the 5% upper bound, indicating the existence of a stable long-run equilibrium relationship among the model variables.

Following confirmation of cointegration, both long-run coefficients and short-run dynamics are estimated. A comprehensive set of post-estimation diagnostic tests was conducted to ensure the model's statistical adequacy. These include the Breusch-Godfrey LM test for serial correlation, the Breusch-Pagan test for heteroskedasticity, the Jarque-Bera test for normality of residuals, and the Ramsey RESET test for functional form specification. In addition, the CUSUM and CUSUMSQ tests were applied to assess the parameter stability of the model over time.

To address potential concerns about the parsimony of the selected lag structure, we provide a systematic justification of the ARDL(2,4,4,4) specification. The model selection procedure evaluated competing ARDL specifications using both the AIC and the SIC. As reported in Table 1, the AIC of the selected ARDL(2,4,4,4) is −155.60, compared to −159.37 for a restricted ARDL(1,0,0,0). Although the restricted model yields a marginally lower AIC, it fails to satisfy the fundamental statistical requirements for a valid time-series specification, as demonstrated by the diagnostic results below. The SIC, which imposes a heavier penalty for additional parameters, selected ARDL(2,4,4,4) as the most parsimonious model that simultaneously satisfies all diagnostic conditions. The use of up to four annual lags is furthermore grounded in the economic dynamics of Morocco's energy system: large-scale renewable infrastructure projects — such as the Noor Ouarzazate solar complex and the Tarfaya wind farm — involve multi-year development cycles, and their emissions impact is distributed over several years rather than concentrated in a single period. Four lags, therefore, reflect an economically meaningful transmission mechanism rather than an arbitrary modelling choice.

The critical distinction between the two specifications lies in residual diagnostics. The restricted ARDL(1,0,0,0) produces autocorrelated residuals, as evidenced by a Breusch-Godfrey LM test rejection at conventional significance levels. By contrast, the selected ARDL(2,4,4,4) satisfies all four standard diagnostic conditions: the Breusch-Godfrey test for serial correlation yields LM = 2.467 ($p = 0.116$), confirming absence of autocorrelation; the Breusch-Pagan test for heteroskedasticity yields BP = 11.967 ($p = 0.802$), confirming homoskedasticity; the Jarque-Bera normality test yields JB = 1.996 ($p = 0.369$), confirming normally distributed residuals. These results are summarised in Table 1. In addition, the ARDL(1,0,0,0) fails to identify a cointegrating relationship: its bounds F-statistic (F = 0.571) lies well below the lower I(0) bound, and its ECT is statistically insignificant ($p = 0.783$), meaning the model cannot detect any long-run equilibrium dynamics. The ARDL(2,4,4,4), by contrast, yields a bounds F-statistic of 6.04 and a significant ECT (−0.190, $p < 0.001$), confirming a stable long-run cointegrating relationship. A model that fails to satisfy white-noise residuals and cannot identify cointegration is statistically invalid regardless of its information criterion value. The use of ARDL(2,4,4,4) is therefore statistically necessary, not merely preferred.

Finally, concerns about overfitting are directly addressed by the CUSUM and CUSUM-of-Squares stability tests [38], presented in Figures 1 and 2. Both statistics remain within the 5% critical bounds throughout the full sample period, confirming that the model's parameters are structurally stable and do not reflect a spurious fit to any particular sub-period. The robustness of the key qualitative results is further confirmed across five alternative ARDL specifications: the EKC sign pattern and the positive long-run renewable energy coefficient are invariant to lag-length choice, spanning turning-point estimates of USD 2,500–6,600, all below Morocco's 2019 income level.

**Table 1.** Diagnostic comparison — ARDL(1,0,0,0) vs ARDL(2,4,4,4)

| Diagnostic Criterion | ARDL(1,0,0,0) | ARDL(2,4,4,4) |
|---|---|---|
| AIC (model selection) | −159.37 | −155.60 |
| Breusch-Godfrey LM (serial corr.) | Rejected | LM = 2.467, p = 0.116 |
| Breusch-Pagan (heteroskedasticity) | Rejected | BP = 11.967, p = 0.802 |
| Jarque-Bera (normality of residuals) | Rejected | JB = 1.996, p = 0.369 |
| Bounds F-statistic (cointegration) | F=0.571 | F = 6.04 |
| ECT (speed of adjustment) | Not significant | −0.190, p < 0.001 |
| EKC sign pattern ($\beta1 > 0$, $\beta2 < 0$) | Not confirmed | Confirmed |

Note: ARDL = Autoregressive Distributed Lag; AIC = Akaike Information Criterion; LM = Lagrange Multiplier; EKC = Environmental Kuznets Curve.

All econometric modelling and statistical testing were performed using EViews 13 software.

## 5. RESULTS AND DISCUSSION

### 5.1 Unit root tests and cointegration analysis

Initially, an examination of the time-series properties of each variable is conducted. PP and ADF unit root tests were employed to establish the stationarity of the series. The results, presented in Table 2 for ADF and Table 3 for PP, reveal a mixed integration order. Renewable energy per capita (ER_cap) rejects the null hypothesis of a unit root at levels under both the ADF test ($p = 0.039$) and the PP test ($p = 0.031$), indicating that it is stationary in levels and therefore I(0). By contrast, $CO_2$ emissions per capita, GDP per capita, and the squared GDP term (GDP2) do not reject the null hypothesis of a unit root at the 5% significance level in levels. However, subsequent to the implementation of first differencing, these three variables all became stationary ($p < 0.05$ for each). Thus, CO2_cap, GDP, and GDP2 are integrated of order one, I(1), while ER_cap is I(0). No variable is integrated of order two or higher. This mixed integration order between I(0) and I(1) is precisely the setting for which the ARDL bounds testing approach is designed [37], and the application of this methodology is fully appropriate for the dataset. The stationarity of the first-differenced series implies that any long-run relationships discovered among the level variables are genuine cointegrating relationships rather than spurious correlations.

**Table 2.** Augmented Dickey Fuller test (ADF)

| Variable | A Level I(0) | | In First Differences I(1) | |
|---|---|---|---|---|
| | T-Statistic | Prob | T-Statistic | Prob |
| CO2_cap | -3.188734 | 0.1015 | -5.963375 | 0.0001 |
| ER_cap | -3.640107 | 0.0392 | -5.552919 | 0.0003 |
| GDP | -3.183744 | 0.1041 | -5.2844 | 0.0006 |
| GDP2 | -2.378993 | 0.3832 | -5.282184 | 0.0006 |

Note: ER_cap is stationary at levels ($p = 0.039$, significant at 5%), classifying it as I(0). CO2_cap, GDP, and GDP2 are non-stationary at levels but stationary in first differences, classifying them as I(1). The ARDL bounds testing approach accommodates this mixed I(0)/I(1) order.

**Table 3.** Phillips Perron (PP) test

| Variable | A Level I(0) | | In First Differences I(1) | |
|---|---|---|---|---|
| | Adj. T-Stat | Prob | Adj. T-Stat | Prob |
| CO2_cap | -3.142888 | 0.111 | -7.075264 | 0 |
| Er_cap | -3.740316 | 0.0312 | -6.6412 | 0 |
| GDP | -3.576664 | 0.0451 | -5.546052 | 0.0003 |
| GDP2 | -3.528339 | 0.0502 | -5.362311 | 0.0005 |

Note: The Phillips-Perron test confirms that ER_cap is stationary at levels ($p = 0.031$, significant at 5%), I(0), consistent with the ADF result. CO2_cap, GDP, and GDP2 are stationary only in first differences, I(1).

### 5.2 Autoregressive distributed lag bounds test for cointegration

These findings lend support to the utilization of the ARDL bounds testing approach, given that each of the variables is either I(0) or I(1), thus rendering them suitable for cointegration analysis. Subsequent to this, the ARDL bounds testing approach to cointegration was employed to assess the long-run relationship between the variables.

Model used for the bounds test (unrestricted ECM):

$$\Delta \mathrm{lnCO2}_t = \alpha_0 + \sum_{i=1}^{p-1} \psi_i \Delta \ln \mathrm{CO2}_{t-i} + \sum_{j=0}^{qRE-1} \delta_j^{RE} \Delta \mathrm{lnRE}_{t-j} + \sum_{k=0}^{qGDP-1} \delta_k^{GDP} \Delta \mathrm{lnGDP}_{t-k} + \sum_{l=0}^{qGDPsq-1} \delta_l^{GDPsq} \Delta \mathrm{lnGDP\_SQ}_{t-l}$$

The bounds test examines $H_0: \lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = 0$ against the alternative of a levels relationship. We adopt an intercept (no trend) deterministic specification with $k = 3$ long-run regressors (ln RE, ln GDP, $[\ln(GDP)]^2$), and compare the F-statistic to the critical values of Pesaran et al. [37].

With: Δ denotes the first-difference operator and, $\mathrm{lnGDP\_SQ}_t = [\ln(GDP_t)]^2$.

These findings support the use of the ARDL bounds testing approach, as each variable is I(0) or I(1) and thus suitable for cointegration analysis. We therefore employ the ARDL bounds test to assess the existence of a long-run relationship among the variables. The calculated F-statistic is 6.04 (see Table 4). Using $k = 3$ long-run regressors and an intercept (no trend) specification [37], 5% critical value bounds are I(0) = 2.79 and I(1) = 3.67, and the 10% bounds are I(0) = 2.37 and I(1) = 3.20. The F-statistic lies above the 10% I(1) upper bound, providing evidence of cointegration and rejecting the null of no long-run levels relationship at the 10% significance level. This indicates that $CO_2$ emissions, renewable energy consumption, and economic growth (including the quadratic income term $[\ln(GDP)]^2$ are cointegrated over 1980–2019 in Morocco. In practical terms, a stable long-run linkage exists among these variables despite short-run fluctuations, which justifies reporting the long-run coefficients and the short-run ECM in the next subsections.

**Table 4.** Autoregressive distributed lag (ARDL) bound-test

| F-Bounds Test | | Null Hypothesis: No Level Relationship | | |
|---|---|---|---|---|
| Test statistic | Value | Critical threshold | Lower terminal I(0) | Top terminal I(1) |
| F-statistic | 6.042403 | 10% | 2.370 | 3.200 |
| K | 3 | 5% | 2.790 | 3.670 |
| | | 1% | 3.650 | 4.660 |

### 5.3 Long-run effects: Environmental Kuznets Curve and energy dynamics

Following the confirmation of cointegration through the ARDL bounds test, the long-run coefficients from the selected ARDL(2, 4, 4, 4) model are examined (see Table 5). These results provide strong empirical support for the EKC hypothesis in the Moroccan context.

**Table 5.** Long-term estimation

| Variable | Coefficient | Std. Error | T-Stat | Prob |
|---|---|---|---|---|
| ln(RE)_t | 0.48089 | 0.13224 | 3.636 | 0.002 |
| ln(GDP)_t | 1.1876 | 0.4484 | 2.648 | 0.017 |
| [ln(GDP)]²_t | -0.0758 | 0.0296 | -2.558 | 0.020 |
| C | -3.1903 | 1.5184 | -2.101 | 0.051 |
| R-squared | 0.696 | Adjust R-squared | | 0.392 |
| F-statistic | 2.292 | Durbin Watson stat | | 2.210 |
| Dependent variable: ln($CO_2$) per capita | | | | |

Notes: lnRE is constructed from the aggregate WDI "renewable energy" indicator, which includes traditional biomass; interpret long-run elasticities with this composition in mind.

5.3.1 Environmental Kuznets Curve validation

The results provide clear empirical support for the EKC hypothesis in Morocco. The coefficient on GDP per capita is positive and statistically significant (1.188, p = 0.017), while the squared GDP term is negative and significant (–0.076, p = 0.020). These signs confirm the existence of an inverted-U-shaped relationship between economic growth and $CO_2$ emissions. Specifically, a 1% increase in real GDP per capita leads to an estimated 1.19% increase in emissions, but the impact diminishes as income rises, eventually reversing direction.

Using the standard formula for the turning point of an inverted-U:

$\ln CO2 = \alpha + \beta_1 \ln GDP + \beta_2 (\ln GDP)^2$ ,

the turning point income is $\ln GDP^* = -\beta_1/(2\beta_2)$ .

with $\beta_1 = 1.1876$ and $\beta_2 = -0.0758$, we obtain $\ln GDP^* = 7.834$ and $GDP^* = \exp(7.834) \approx 2{,}524$ USD.

This turning point implies that $CO_2$ emissions in Morocco are expected to begin declining once real GDP per capita exceeds approximately USD 2,524; all turning-point and income comparison values are expressed in constant 2015 US dollars. According to World Bank data, Morocco's GDP per capita in 2019 was approximately USD 3,200, suggesting the country may have recently crossed this critical threshold. This finding reinforces the empirical relevance of the EKC framework in the Moroccan context and implies that, under suitable policy conditions, further economic growth could coincide with environmental improvements.

5.3.2 Renewable energy and composition effects

Contrary to theoretical expectations, the estimated long-run coefficient for per capita renewable energy consumption is positive and highly significant (0.481, p = 0.002). This result may appear counter-intuitive but is consistent with the structure of Morocco's energy system and with the measurement of the WDI renewable indicator. Several key explanations are likely:

- Traditional biomass dominance: A significant portion of Morocco's renewable energy mix, especially in earlier decades, has consisted of fuelwood, charcoal, and agricultural waste. According to the IEA (2015), traditional biomass accounted for a large share of renewable energy consumption in Morocco in the early 2000s. Although a full time-series breakdown of biomass's share across the entire 1980–2019 study period is not available for Morocco at a granular level, the aggregate WDI renewable energy indicator used in this study inherently conflates traditional biomass with modern renewables throughout the sample. The dominance of biomass in earlier decades — when modern renewable deployment (solar, wind, hydro) was minimal — means that a significant fraction of the aggregate renewable signal in the data captures biomass combustion rather than clean energy generation. As Morocco's renewable capacity has expanded in later years under the Noor solar programme and wind projects, the biomass share has likely declined; this temporal shift in composition reinforces the interpretation that the positive long-run RE–$CO_2$ coefficient reflects a legacy biomass effect rather than a structural property of modern renewables. While renewable by classification, traditional biomass sources emit substantial amounts of $CO_2$ and other pollutants when combusted inefficiently, distorting the aggregate emissions profile.
- Complementarity, not substitution: The growth in renewables has often occurred alongside increased overall energy demand, meaning that new renewable capacity added to, rather than displaced, fossil fuels, especially coal and oil.
- Construction-phase emissions: Emissions associated with the construction and deployment of renewable energy infrastructure (e.g., cement use, material transport) may temporarily inflate $CO_2$ emissions, especially in the absence of cleaner production chains.
- Grid inefficiencies and fossil-based backup: In the absence of flexible and modernised grid systems, renewable electricity supply in Morocco is frequently backed up by fossil-fuel power, especially during peak loads or intermittent supply conditions.

These contextual elements help explain why the long-run impact of renewable energy on emissions may remain positive at this stage of Morocco's energy transition. This positive long-run lnRE–$CO_2$ elasticity is not unique to Morocco. Zoundi [11] documented it for several African countries with high biomass shares; Salahuddin and Gow [10] found analogous patterns in Qatar, and Bouyghrissi et al. [9] report the same result for Morocco over 1990–2015. The finding underscores the importance of disaggregating the renewable indicator into modern and traditional components.

### 5.4 Short-run dynamics and error correction mechanism

Table 6 indicates the output of the short-run dynamic model based on the ARDL specification and the ECT, which describes how fast the system moves towards the long-run equilibrium.

5.4.1 Model convergence and error correction term

The estimated error-correction coefficient is ECT=−0.1901 with a t-statistic of –6.11 and a p-value of 0.000, indicating that it is highly statistically significant. The negative sign is theoretically expected and confirms that the system is directionally stable. The coefficient magnitude indicates that approximately 19 percent of any short-run deviation from the long-run equilibrium is corrected within one year, implying a gradual rather than abrupt adjustment toward equilibrium. This relatively slow speed of adjustment is consistent with the structural inertia typical of energy systems in developing economies, where institutional and infrastructure constraints limit the pace of change. Taken together with the bounds test result, this highly significant ECT provides robust evidence of a stable, self-correcting long-run relationship among $CO_2$ emissions, income, and renewable energy consumption in Morocco.

**Table 6.** Short-term estimation

| Variable | Coefficient | Std. Error | T-Statistic | Prob |
|---|---|---|---|---|
| ECT | -0.1901 | 0.03112 | -6.109 | 0.000 |
| Δln(CO2)_t | -0.2329 | 0.14661 | -1.588 | 0.127 |
| Δln(RE)_t | 0.26795 | 0.04301 | 6.230 | 0.000 |
| Δln(RE)_t-1 | -0.13366 | 0.04303 | -3.106 | 0.005 |
| Δln(RE)_t-2 | -0.19808 | 0.04311 | -4.595 | 0.000 |
| Δln(RE)_t-3 | -0.18345 | 0.04435 | -4.136 | 0.001 |
| Δln(GDP)_t | 2.35729 | 0.70285 | 3.354 | 0.003 |
| Δln(GDP)_t-1 | 2.03752 | 0.72892 | 2.795 | 0.011 |
| Δln(GDP)_t-2 | 2.78829 | 0.69268 | 4.025 | 0.001 |
| Δln(GDP)_t-3 | 2.65247 | 0.80853 | 3.281 | 0.004 |
| Δ[ln(GDP)]²_t | -0.16618 | 0.04915 | -3.381 | 0.003 |
| Δ[ln(GDP)]²_t-1 | -0.15832 | 0.05221 | -3.032 | 0.006 |
| Δ[ln(GDP)]²_t-2 | -0.21298 | 0.04965 | -4.290 | 0.000 |
| Δ[ln(GDP)]²_t-3 | -0.18616 | 0.05806 | -3.206 | 0.004 |
| R-squared | 0.696 | F-statistic | | 3.704 |
| Adjusted R-squared | 0.508 | Prob(F-statistic) | | 0.004 |

The bounds test, as proposed by Pesaran et al. [37], established the existence of a long-run cointegrating relationship between the variables through the F-bounds test. The highly significant ECT further corroborates this finding by confirming that the system converges toward its long-run equilibrium following any short-run shock, lending additional robustness to the cointegration result.

5.4.2 Short-run impact of consumption of renewable energy

The short-run coefficients associated with renewable energy consumption exhibit a rich, time-dependent pattern. The modern change in the consumption of renewable energy has a positive and statistically significant coefficient (coefficient = 0.268, $p < 0.01$). This finding indicates that an increase in the consumption of renewable energy by one percent corresponds with an increment of 0.27 percent in $CO_2$ emissions the same year, which can be counterintuitive. This outcome can be explained by a number of reasons. First, the initial integration can also involve the need for a backup fossil generation during times when the renewable energy capacity is still new and therefore the grid is not as flexible as it will be in the future. Second, the environmental costs of the renewable infrastructure construction (emissions during manufacturing, transportation, and installation) can be measured in the increment of short-term emissions. Third, the summative WDI indicator of renewable energy incorporates traditional biomass, which, despite being considered renewable, is also a great contributor to $CO_2$ emissions. Notably, this short-term impact seems to be transitional. The initial lag of the renewable energy consumption is negative (–0.134) and insignificant ($p = 0.067$). The second (-0.198) and the third lag (-0.183) are both significant at the 5 percent level. These results imply that $CO_2$ emissions decrease in the following years after a short-term increase in the amount of renewable energy. This must be indicative of the eventual integration of renewables into its operations and the ultimate replacement of the generation through fossil fuels.

This is indicated by a rebound-correction effect, whereby early rises in emissions are compensated in the long term by the structural decarbonisation of the energy system.

5.4.3 Short-run effects of economic growth

The immediate effects of the economic growth on emissions are high and short-lived. There is a statistically significant (5 percent) positive correlation between a 1 percent growth in GDP per capita and a 2.36 percent growth in $CO_2$ emissions in the same year. This high elasticity indicates Morocco's continued reliance on fossil fuels and energy-sector-intensive industries at high economic growth rates. Moreover, the impact of GDP has a lasting effect. The coefficients of the first, second, and third lags of the GDP growth are also large and significant with approximate values of +2.04, +2.79, and +2.65, respectively. This trend affirms the fact that the emissions that are induced by GDP do last several years, which highlights the significance of the carbon intensity of the growth channels in the short run. Interestingly, the coefficients of the changes in the squared GDP term are negative and significantly important throughout the same period. As an illustration, the contemporaneous coefficient is -0.166, and there are additional significant negative coefficients on the first three lags. This dampening effect means that the higher the income, the smaller the marginal effect of further growth on emissions, which is in line with the EKC hypothesis. Even in the short term, these findings indicate that the additional growth incomes will be less costly to the environment, and thus the EKC logic can be applied in a dynamic context.

The findings underscore the importance of long-term planning and phased investment in renewable energy infrastructure. Policymakers should anticipate that initial expansions in renewable energy may not immediately reduce emissions, particularly in developing economies with fossil-intensive grids and infrastructure constraints. However, the delayed emission reductions support sustained and multi-year investment strategies in clean energy. Similarly, economic growth continues to pose significant short-term environmental challenges, although these diminish at higher income levels.

**5.5 Model diagnostic and stability tests**

To evaluate the parameter stability of the estimated ARDL model over time, we applied the Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) tests, following the methodology of Brown et al. [38]. These tests are widely used to detect structural instability in time-series models by analyzing whether the residuals remain within their expected bounds under the null hypothesis of parameter constancy.

- CUSUM test examines the stability of the model's coefficients by tracking the cumulative sum of recursive residuals.
- CUSUMSQ test is more sensitive to sudden changes in variance and helps detect heteroskedasticity or structural shocks.

The results of both tests are graphically presented in Figures 1 and 2.

In Figure 1, the blue line represents the CUSUM of recursive residuals, while the dashed orange lines represent the 5% significance bounds.

- The CUSUM line remains entirely within the critical bounds from 1996 through 2018.
- This indicates that the coefficients of the ARDL model are stable over the full sample period.
- There is no evidence of significant structural breaks, suggesting that macroeconomic events, such as

policy reforms or global shocks, did not materially alter the relationship between $CO_2$ emissions, GDP, and renewable energy consumption.

This result validates the reliability of the long-run parameters, which reflect consistent economic dynamics across time. The model's structural integrity is therefore not dependent on a specific sub-period, enhancing confidence in the robustness of the findings.

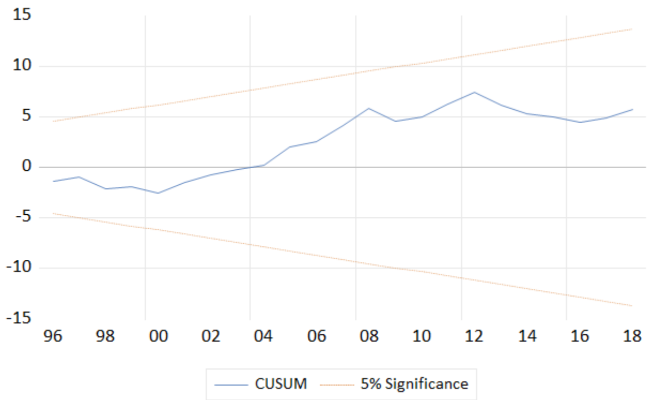


**Figure 1.** CUSUM stability test

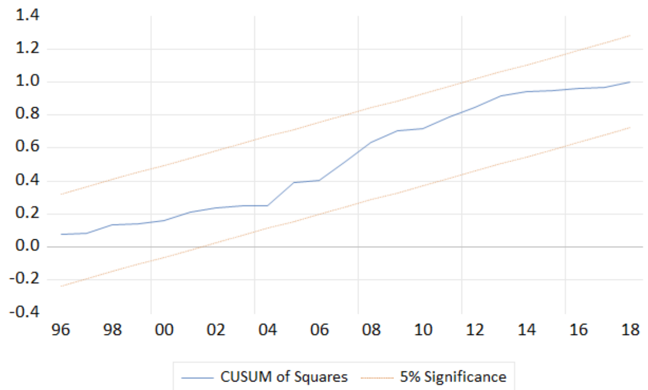


**Figure 2.** CUSUMQ stability test

Figure 2 presents the CUSUMSQ test, which provides a complementary assessment by examining the variance stability of the regression residuals.

- The CUSUMSQ statistic also remains within the 5% significance bounds over the entire sample period.
- This result further confirms that no episodes of heteroskedasticity, variance shifts, or omitted variable biases are affecting the residuals.
- Even during periods of substantial economic transformation in Morocco (e.g., scaling up renewable energy, economic liberalization), the model variance remained stable.

This outcome indicates that the parameters of the ARDL model are stable across the sample period. Specifically, the fact that the CUSUM and CUSUMSQ curves do not cross the critical bounds implies that there were no significant structural breaks that would undermine the validity of the estimated relationships. In other words, the model's parameters remained consistent despite economic reforms, policy shifts, or external shocks that Morocco may have experienced during these decades. This reinforces confidence in the robustness of the long-run elasticities obtained for GDP, $GDP^2$, and renewable energy consumption.

In conclusion, the diagnostic and stability tests confirm the statistical soundness of the ARDL model. The residuals show desirable properties, the parameter estimates are stable over time, and the model successfully captures both long-term structural relationships and short-term adjustments. These findings lend credibility to the empirical results discussed in earlier sections.

## 6. CONCLUSION AND POLICY IMPLICATIONS

This paper has analysed the relationship between renewable energy consumption, economic growth, and $CO_2$ emissions in Morocco over the period 1980–2019 using an ARDL bounds testing framework. By combining annual data on per capita emissions, real income, and aggregate renewable energy use, we tested the EKC hypothesis and examined the role of renewables in the country's decarbonisation path. The results from unit root tests and the bounds procedure indicate a stable long-run cointegrating relationship among the variables, which justifies modelling their joint dynamics within a single system. The long-run estimates support the existence of an inverted U-shaped EKC for Morocco. At low and middle income levels, higher GDP per capita is associated with rising $CO_2$ emissions, but the marginal impact of further growth diminishes and eventually becomes negative beyond a certain income threshold. The calculated turning point lies in the upper middle-income range, and Morocco's income level by 2019 is already above this threshold. This suggests that, under the right policy and technological conditions, future growth can be compatible with stabilising or even reducing emissions rather than mechanically worsening environmental pressures. By contrast, the long-run coefficient on renewable energy consumption is positive, indicating that, over the sample period, higher aggregate renewable use has coincided with higher $CO_2$ emissions. While this finding may appear counterintuitive, it is consistent with the structure of Morocco's energy system and with the way renewables are measured in aggregate statistics. The renewable portfolio still includes a large share of traditional biomass, which can be highly emission-intensive when used in inefficient combustion technologies. In addition, much of the new modern renewable capacity has so far complemented, rather than fully replaced, fossil-based generation, and its deployment has required carbon-intensive investment in infrastructure.

The contemporaneous effect of renewable energy changes is positive and significant, while the lagged coefficients are negative and significant, suggesting a transitional dynamic. In the initial stage of renewable deployment, the expansion of renewables is accompanied by higher emissions, due to the embodied carbon in the infrastructure, the joint operation of fossil and renewable generation capacity, and also the adjustment cost of an electricity system that is not yet fully flexible. As renewable projects are completed and as they displace fossil capacity, the net effect becomes emission-reducing. The error-correction term is negative and highly significant, confirming that any departure from the long-run relationship between emissions, income, and renewables is gradually adjusted, and the system converges towards the stable long-run emissions income renewables relationship.

These results lead to a number of policy conclusions. First, since Morocco's per capita income has surpassed the estimated EKC turning point, it is well positioned to decouple further income growth from rising emissions. Realising this potential requires deliberate policy action, not passive reliance on the EKC mechanism. Concretely, this means accelerating energy efficiency standards across industry and transport, favouring less carbon-intensive growth sectors such as services and light manufacturing, and phasing out subsidies to the most polluting technologies, consistent with Morocco's Nationally Determined Contribution targets under the Paris Agreement. Second, the long-run positive association between aggregate renewable consumption and $CO_2$ emissions underscores the urgency of restructuring the renewable energy portfolio. Reducing dependence on traditional biomass combustion—which accounts for a disproportionate share of aggregate renewable energy in Morocco—and redirecting investment toward utility-scale solar (such as the Noor Ouarzazate and Noor Midelt complexes), onshore wind (such as the Tarfaya and Akhfennir parks), and run-of-river hydro projects will be essential for realising measurable emission reductions. Morocco's comparative advantage in solar and wind resources, combined with its ambition to export clean electricity to European markets via planned interconnectors, further strengthens the rationale for prioritising these technologies. Third, the short-run dynamics highlight the importance of system-level reforms to accompany generation investments. Investment in renewable capacity must be complemented by upgrades to transmission and distribution infrastructure, deployment of battery and pumped-hydro storage, demand-side management programmes, and strengthened grid interconnections with Algeria, Spain, and Portugal. These measures are specifically relevant to Morocco given its current reliance on gas and coal backup capacity during renewable intermittency. Without them, new generation capacity is likely to complement rather than replace fossil-based power, prolonging the transition period during which renewable expansion does not translate into net emission reductions.

This research has certain limitations, which also indicate directions for future studies. The analysis focuses on a small set of determinants and considers aggregate annual data for 2019. Researchers may also capture the effect of the COVID-19 shock and the subsequent energy price crisis by further extending the dataset. One might be able to disentangle the different channels through which growth and energy use influence emissions using additionally other explanatory variables (such as trade openness, industrial composition, type of fossil fuel utilization, financial development, or institutional quality). Finally, in future work, the non-linear and asymmetric responses could be investigated more explicitly, for instance, by separating modern from traditional renewables or by employing non-linear ARDL models, and Morocco could be situated in a wider regional context via panel analyses of the North African or MENA countries.

Overall, the case of Morocco highlights the possibilities for as well as the limits to fossil-dependent economies seeking to scale up renewable energy while maintaining growth. The findings of this paper imply that ambitious renewable targets and increasing income levels are necessary but not sufficient conditions for decarbonisation, that what really counts is the energy mix composition, the pace of structural change, and the capacity of the energy system to convert new capacity into actual emission reductions.

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## APPENDIX

A summary of the variables, units, and data sources is provided in Table A1.

**Table A1.** Variables, units, and data sources

| Variable | Unit | Source | Database / Link |
|---|---|---|---|
| Total Energy Consumption | Million Tonnes (Mt) | Energy Institute (formerly BP) | Statistical Review of World Energy |
| Renewable Energy Consumption | Million Tonnes (Mt) | World Bank (WDI) & Energy Institute | WDI Database (EG.FEC.RNEW.ZS) |
| Real GDP per capita | Constant 2015 USD | World Bank (via Knoema) | WDI Database (NY.GDP.PCAP.KD) |
| $CO_2$ Emissions | Million Tonnes (Mt) | Energy Institute (formerly BP) | Statistical Review - Main Indicators |
| $CO_2$ per capita | Tonnes per capita | International Energy Agency (IEA) | IEA Morocco Statistics |
| Total Population | Inhabitants | World Bank (via Knoema) | WDI Population Statistics |