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Asymmetric impacts of energy, finance, and urbanization on CO_2 emissions: Evidence from Algeria and Egypt

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ABSTRACT

This study examines the dynamic relationship between carbon dioxide (CO_2) emissions and key determinants, including economic growth, renewable and non-renewable energy consumption, financial development, institutional quality, and urbanization, in Algeria and Egypt over 2000–2024. The purpose is to provide new insights into how these factors shape environmental sustainability in two North African economies. To achieve this, the analysis employs both Autoregressive Distributed Lag (ARDL) and Non-linear ARDL (NARDL) approaches, capturing short- and long-run effects and potential asymmetries in response to positive and negative shocks. The findings confirm the Environmental Kuznets Curve (EKC) hypothesis, indicating that economic growth initially increases emissions but eventually reduces them beyond a certain threshold. Moreover, significant asymmetric effects are observed, particularly regarding energy shocks and urbanization changes, highlighting the importance of directionality in influencing CO_2 emissions. These results provide practical implications for policymakers, emphasizing the need to promote renewable energy adoption, strengthen institutional frameworks, and manage urban expansion sustainably to achieve long-term environmental improvements. By integrating a comprehensive set of determinants and applying both symmetric and asymmetric econometric frameworks, this study offers a novel perspective on environmental dynamics in Algeria and Egypt.

Contribution/ Originality: This study contributes to the existing literature by analyzing CO_2 emissions in Algeria and Egypt using a comprehensive set of determinants. It employs ARDL and NARDL methods to capture asymmetric effects and is among the few studies investigating the combined impact of energy, financial, institutional, and urbanization factors.

1. INTRODUCTION

Since the Industrial Revolution, global carbon dioxide (CO_2) emissions have increased steadily, primarily due to a rising dependence on fossil fuels to drive economic development. Total CO_2 emissions have surpassed 36 billion tonnes, approximately 1.6 times higher than in 1990, contributing to a significant rise in global average temperature and adversely affecting human health and ecosystems (Karl et al., 2015). These environmental challenges have intensified the need to investigate the determinants of CO_2 emissions and their interactions with economic, energy, financial, institutional, and urbanization factors. Global energy consumption has reached 13.7 billion tons of oil equivalent, with fossil fuels accounting for over 80% of the total (International Energy Agency (IEA), 2022). Despite recent environmental reforms, renewable energy remains less than 20% of energy consumption in many developing countries, emphasizing its critical role in mitigating environmental degradation (Beolük & Mert, 2014; Talbi, Hachicha, & Ben Rebah, 2020; U.S. Energy Information Administration (EIA), 2019).

The Environmental Kuznets Curve (EKC) hypothesis provides a theoretical framework for analyzing the relationship between economic growth and environmental quality. According to the EKC, environmental degradation initially increases with economic growth (scale effect) but eventually decreases after reaching a certain income threshold due to structural transformation and technological progress (Dinda, 2004; Grossman & Krueger, 1991; Grossman & Krueger, 1995; Panayotou, 1993). Scale effects reflect higher emissions from industrial expansion, structural effects arise from a shift toward less-polluting sectors, and technical effects capture emissions reductions through technological innovation and energy efficiency (Beolük & Mert, 2014). Empirical studies report mixed outcomes: renewable energy generally reduces CO_2 emissions, whereas dependence on fossil fuels, insufficient financial development, weak institutional quality, and rapid urbanization can exacerbate environmental degradation (Asghar, Amjad, & Rehman, 2023; Dong, Li, & Zhang, 2022; Ozturk & Acaravci, 2013; Shahbaz & Acaravci, 2015; Zhang & Li, 2024).

Energy structure is a key determinant of environmental outcomes. Renewable energy consumption (REC) typically reduces CO_2 emissions, while non-renewable energy consumption (NREC) tends to increase emissions (Talbi et al., 2020; Zhang & Li, 2024). Studies in North Africa highlight that introducing renewable energy significantly mitigates emissions in economies transitioning from fossil fuel dependence (Bouzid & Ben Youssef, 2019). NARDL-based analyses reveal that positive and negative shocks in REC and NREC can differently affect CO_2 emissions, underscoring the importance of capturing asymmetric effects (Asghar, Amjad, & Rehman, 2023).

Financial development (FD) and institutional quality (IQ) influence the effectiveness of environmental and energy policies. Efficient financial systems enable investments in green technologies, while strong institutions improve policy implementation and compliance with environmental regulations (Hossain, Islam, & Rahman, 2022; Shahbaz, Lean, & Farooq, 2023). Poor governance or weak financial markets can reduce the environmental effectiveness of economic growth, particularly in fossil-fuel-dependent economies (Dong et al., 2022; Shahbaz & Acaravci, 2015). Urbanization (URB) affects CO_2 emissions through energy demand, transportation, and infrastructure pressures. Rapid, unplanned urban growth increases emissions, whereas sustainable urban planning, energy-efficient infrastructure, and public transport can mitigate environmental impacts (Asghar et al., 2023; Dong et al., 2022). Country-specific analyses are necessary to tailor urban and environmental policies effectively.

Algeria and Egypt are selected due to their contrasting economic structures, energy profiles, and policy environments. Algeria, heavily reliant on fossil fuel production, experiences fluctuations in energy consumption and industrial activity that strongly influence CO_2 emissions (Bouzid & Ben Youssef, 2019; Talbi et al., 2020). Egypt, with a more diversified economy and a growing renewable energy sector, provides a contrasting context to examine the interplay between GDP growth, energy consumption, and environmental outcomes (Hassan & El-Monier, 2022). Comparing these two countries allows us to capture heterogeneity in North African environmental-economic dynamics and provides tailored policy insights.

The study incorporates seven key variables: GDP and GDP^2 (to test the EKC hypothesis), renewable energy consumption (REC), non-renewable energy consumption (NREC), financial development (FD), institutional quality (IQ), and urbanization (URB). These variables are chosen based on prior literature emphasizing their critical influence on CO_2 emissions and environmental outcomes. Renewable and non-renewable energy capture the impact of energy structure; GDP and GDP^2 allow testing of the EKC; FD and IQ reflect the role of financial markets and governance; and URB accounts for population concentration and urban expansion effects on emissions (Dong et al., 2022; Shahbaz et al., 2023).

Methodologically, we employ both Autoregressive Distributed Lag (ARDL) and Non-linear ARDL (NARDL) approaches. ARDL captures long-run and short-run relationships, accommodating variables integrated at different orders (Narayan, 2005; Pesaran, Shin, & Smith, 2001). NARDL extends this framework by examining asymmetric effects, distinguishing between positive and negative shocks in energy, financial, and urbanization variables on CO_2

emissions (Asghar et al., 2023; Shahbaz et al., 2023; Zhang & Li, 2024). Accounting for asymmetries is essential to avoid underestimating the environmental consequences of policy or structural changes.

This study contributes by integrating symmetric and asymmetric models, employing a comprehensive set of economic, energy, financial, institutional, and urbanization variables, and comparing Algeria and Egypt over the period 2000–2024. This approach allows for a nuanced understanding of CO_2 emissions dynamics, highlighting country-specific policy priorities and extending the literature beyond single-country or panel studies in North Africa. The remainder of this paper is organized as follows: Section 2 outlines the empirical model and econometric strategy, including ARDL and NARDL methodologies. Section 3 reports the empirical findings, while Section 4 concludes with policy implications and recommendations for Algeria and Egypt.

2. DATA AND METHODOLOGY

This research seeks to explore the Environmental Kuznets Curve (EKC) hypothesis by assessing how renewable and non-renewable energy consumption, financial development, institutional quality, and urbanization affect carbon emissions in Algeria and Egypt. To achieve this, the study employs the following log-linear specification.

$$lnCO_{2t} + \theta_0 + \theta_1 lnGDT_t + \theta_2 lnGDP^2{}_t + \theta_3 lnREC_t + \theta_4 lnNREC_t + \theta_5 lnFD_t + \theta_6 lnIQ_t + \theta_7 lnURB_t + \varepsilon_t \quad (1)$$

In this specification, ln CO2 serves as an indicator of environmental degradation, while ln GDP captures economic growth. The squared term $(\ln GDP)^2$ is incorporated to test the potential non-linear relationship between growth and environmental quality, as suggested by the Environmental Kuznets Curve (Grossman & Krueger, 1995; Stern, 2004). ln REC stands for renewable energy consumption, whereas ln NREC denotes non-renewable energy use. Financial development is represented by ln FD, institutional quality by ln IQ, and urbanization by ln URB, with ε representing the error term. The acceleration of economic activity has placed increasing pressure on energy demand and infrastructure expansion, thereby aggravating carbon emissions (Apergis & Payne, 2010). The quadratic term $(\ln GDP)^2$ enables the model to account for the inverted-U-shaped EKC dynamics. Furthermore, the inclusion of renewable and non-renewable energy, financial development, institutional quality, and urbanization reflects their critical roles in shaping ecological sustainability and the energy–environment nexus (Ahmed, Kousar, Shabbir, & Pervaiz, 2020; Al-Mulali, Saboori, & Ozturk, 2015; International Energy Agency (IEA), 2022; Omri, 2013).

To capture possible asymmetric relationships, renewable energy, non-renewable energy, financial development, institutional quality, and urbanization are each decomposed into positive and negative partial sums of changes. Specifically, $\ln REC^+$ and $\ln REC^-$ represent increases and decreases in renewable energy, $\ln NREC^+$ and $\ln NREC^-$ capture the corresponding changes in non-renewable energy, $\ln FD^+$ and $\ln FD^-$ denote positive and negative variations in financial development, $\ln IQ^+$ and $\ln IQ^-$ reflect improvements and deteriorations in institutional quality, while $\ln URB^+$ and $\ln URB^-$ account for expansions and contractions in urbanization.

This decomposition enables the model to distinguish between the potentially different effects of positive and negative shocks, which may not be adequately captured in a standard linear framework. For instance, an increase in renewable energy could reduce carbon emissions, while a decrease might have a weaker or even opposite impact. Similarly, improvements in institutional quality may strengthen environmental regulations, whereas declines could exacerbate environmental degradation. Such an approach follows the nonlinear ARDL framework proposed by Shin, Yu, and Greenwood-Nimmo (2014) and later applied in various environmental and energy economics studies (e.g., (Greenwood-Nimmo, Shin, & Copeland, 2013; Salisu & Isah, 2017)).

The asymmetric model can therefore be specified as:

$$lnCO_{2t} = \theta_0 + \theta_1 lnGDP_t + \theta_2 lnGPD^2{}_t + \theta_3 lnREC_t^+ + \theta_4 lnREC_t^- + \theta_5 lnNREC_t^+ + \theta_6 lnNREC_t^- + \theta_7 lnFD_t^+ + \theta_8 lnFD_t^- + \theta_9 lnIQ_t^+ + \theta_{10} lnIQ_t^- + \theta_{11} lnURB_t^+ + \theta_{12} lnURB_t^- + \varepsilon_t \quad (2)$$

In this asymmetric framework, economic growth remains the central factor driving carbon emissions. The analysis relies on annual data spanning 2000–2024 for Algeria and Egypt. All variables have been transformed into natural logarithms to stabilize variance, normalize distributions, and produce more robust and consistent estimates (Nathaniel, Shahbaz, & Balsalobre-Lorente, 2020). Carbon dioxide emissions are obtained from the World Bank's World Development Indicators (WDI), while data on economic growth, energy consumption, financial development, institutional quality, and urbanization are gathered from WDI, the International Energy Agency (IEA), and the Worldwide Governance Indicators (WGI).

The definitions and sources of the variables used in this study are presented in Table 1.

Table 1. Description of variables.

Variables	Abbreviation	Unit of measure	Data Source
Carbon dioxide emissions	CO_2	MMtonnes CO_2	U.S. Energy Information Administration (EIA)
Renewable energy consumption	REC	Quad Btu	International Energy Agency (IEA)
Non-renewable energy consumption	NREC	Quad Btu	International Energy Agency (IEA)
Financial development	FD	Composite index	World Bank (Global Financial Development Database)
Institutional quality	IQ	Composite index	World Bank (Worldwide Governance Indicators)
Urbanization rate	URB	Percentage of Total Population	World Bank (World Development Indicators)
Gross domestic product	GDP	Constant 2015 US$	World Bank (World Development Indicators)
GDP squared	GDP^2	Constant 2015 US$ (squared)	Calculated from GDP data

The econometric analysis of this study begins with a comprehensive examination of the stationarity properties of all variables, which is a prerequisite for cointegration and causality testing. Unit root tests are first applied to determine the integration order of each series, guiding the use of ARDL and NARDL methodologies. Once the integration orders are confirmed (variables stationary at level or first difference), linear and non-linear cointegration analyses are conducted.

For the empirical investigation, both symmetric (linear) ARDL and asymmetric (non-linear) NARDL models are employed. These techniques are suitable because they accommodate variables integrated at different orders (I(0) or I(1)) and are robust for small sample sizes. ARDL handles potential endogeneity and allows optimal lag length selection, reducing multicollinearity in the NARDL framework (Bahmani-Oskooee & Bekiros, 2015). This framework provides both short-term and long-term estimates, with the lagged ECT term indicating adjustment towards long-term equilibrium.

The ARDL model can be represented as:

$$\Delta lnCO_{2t} = \sigma_0 + \sum \beta_{ak}\,\Delta lnCO_{2t-k} + \sum \beta_{bk}\Delta lnGDP_{t-k} + \sum \beta_{ck}\,\Delta lnGDP^2{}_{t-k} + \sum \beta_{dk}\Delta lnREC_{t-k} + \sum \beta_{ek}\Delta lnNREC_{t-k} + \sum \beta_{fk}\Delta lnFD_{t-k} + \sum \beta_{gk}\Delta lnIQ_{t-k} + \sum \beta_{hk}\Delta lnURB_{t-k} + \beta_1 lnCO_{2t-1} + \beta_2 lnGDP_{t-1} + \beta_3 lnGDP^2{}_{t-1} + \beta_4 lnREC_{t-1} + \beta_5 lnNREC_{t-1} + \beta_6 lnFD_{t-1} + \beta_7 lnIQ_{t-1} + \beta_8 lnURB_{t-1} + \mu_t \quad (3)$$

To capture asymmetric effects, positive and negative partial sums of changes in key variables are computed. For example, for renewable energy: $REC_t^+ = \sum \max(\Delta REC_i, 0)$ and $REC_t^- = \sum \min(\Delta REC_i, 0)$. This decomposition is similarly applied to non-renewable energy, financial development, institutional quality, and urbanization. It allows the model to detect differing effects of positive versus negative changes (Al-Mulali et al., 2015; Umar, Kenourgios, & Papathanasiou, 2020).

The asymmetric NARDL model is formulated as:

$$\Delta CO_{2t} = \sigma_0 + \sum \beta_{ak}\Delta lnCO_{2t-k} + \sum \beta_{bk}\Delta lnGDP_{t-k} + \sum \beta_{ck}\,\Delta lnGDP^2{}_{t-k} + \sum \beta_{dk}\,\Delta lnREC_{t-k}^+ + \sum \beta_{ek}\Delta lnREC_{t-k}^- + \sum \beta_{fk}\Delta lnNREC_{t-k}^+ + \sum \beta_{gk}\,\Delta lnNREC_{t-k}^- + \sum \beta_{hk}\,\Delta lnFD_{t-k}^+ + \sum \beta_{IK}\Delta lnFD_{t-k}^- +$$

$$\sum \beta_{JK} \Delta lnIQ^{+}_{t-k} + \sum \beta_{kk} \Delta lnIQ^{-}_{t-k} + \sum \beta_{lk} \Delta lnURB^{+}_{t-k} + \sum \beta_{mk} \Delta lnURB^{-}_{t-k} + \beta_1 lnCO_{2t-1} + \beta_2 lnGDP_{t-1} + \beta_3 lnGDP^2{}_{t-1} + \beta_4 lnREC^{+}_{t-1} + \beta_5 lnREC^{-}_{t-1} + \beta_6 lnNREC^{+}_{t-1} + \beta_7 lnNREC^{-}_{t-1} + \beta_8 lnFD^{+}_{t-1} + \beta_9 lnFD^{-}_{t-1} + \beta_{10} lnIQ^{+}_{t-1} + \beta_{11} lnIQ^{-}_{t-1} + \beta_{12} lnURB^{+}_{t-1} + \beta_{13} lnURB^{-}_{t-1} + \mu_t \quad (4)$$

We now present the empirical results for Algeria and Egypt (2000–2024), highlighting the key drivers of CO_2 emissions identified by the baseline model.

3. EMPIRICAL RESULTS AND DISCUSSION

We begin the results and discussion section by presenting the outcomes of the unit root tests. The results of the unit root tests (Table 2) indicate that for both Algeria and Egypt, all variables (CO_2, GDP, GDP^2, REC, NREC, FD, IQ, URB) are non-stationary at level, as the ADF and PP statistics are insignificant. However, after first differencing, the series become stationary at the 1% or 5% level of significance. This suggests that the variables are integrated of order one, I(1). These findings are consistent with prior empirical studies and justify moving forward to examine the existence of a long-run cointegration relationship among the variables.

Table 2. Unit root tests.

	Augmented Dickey-Fuller (ADF)		Phillips-Perron (PP)	
	Level T-stat. [Prob.]	Difference T-stat. [Prob.]	Level T-stat. [Prob.]	Difference T-stat. [Prob.]
Algeria				
CO_2	-0.897* [0.784]	-22.302*** [0.000]	-1.010* [0.791]	-20.55*** [0.000]
GDP	-0.959* [0.821]	-7.709*** [0.005]	-0.771* [0.890]	-13.892*** [0.000]
GDP^2	0.989* [0.902]	-8.897*** [0.000]	-0.990* [0.963]	-13.899*** [0.000]
REC	-1.203 *[0.722]	-8.185*** [0.000]	-0.992* [0.897]	-11.202** [0.021]
NREC	-1.004* [0.606]	-4.971*** [0.000]	-1.300* [0.686]	-10.080*** [0.000]
IQ	-0.500* [0.918]	-9.408*** [0.000]	-0.806* [0.801]	-21.621*** [0.010]
FD	-0.690** [0.154]	-4.784*** [0.000]	0.535* [0.909]	-20.311*** [0.000]
URB	0.867 *[0.993]	-7.081*** [0.000]	1.537* [0.966]	7.172*** [0.000]
Egypt				
CO_2	0.315 *[0.899]	-17.563*** [0.000]	0.416* [0.978]	-16.601*** [0.000]
GDP	0.900* [0.983]	-13.0541*** [0.000]	0.505* [0.976]	-12.528*** [0.000]
GDP^2	0.213* [0.970]	-13.085*** [0.000]	0.424** [0.975]	-12.304*** [0.000]
REC	3.102* [0.989]	-18.131*** [0.000]	3.200* [0.999]	-4.991*** [0.000]
NREC	0.719* [0.871]	-17.490*** [0.000]	1.397* [0.953]	-7.879*** [0.000]
IQ	1.211* [0.907]	-17.081*** [0.000]	1.617* [0.966]	-7.212*** [0.000]
FD	1.981*[0.968]	− 6.721*** [0.000]	4.287*[0.987]	− 6.792***[0.000]
URB	2.391*[0.953]	− 4.931***[0.000]	4.510* [0.978]	− 8.796***[0.000]

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

Table 3 reports the results of the bounds testing approach to cointegration. For Algeria, the F-statistics of the linear model (F = 8.6007) exceed the upper critical bound at the 5% level (UCB = 4.40). Similarly, in the non-linear model, the F-statistics (F = 24.4182) are far above the critical values, while the BDM statistic (-10.3152) is also highly significant. These findings confirm the presence of both symmetric and asymmetric long-run cointegration between CO_2 emissions and the explanatory variables in the case of Algeria.

For Egypt, a similar pattern is observed. The linear model's F-statistic (F = 6.6261) surpasses the 5% upper bound, supporting the existence of a long-run relationship. In the non-linear model, the BDM statistic (-9.0304) is also significant, thereby validating asymmetric cointegration among the variables.

Table 3. Bound tests for linear and non-linear cointegration.

Algeria				
Model	**F-statistics**	**BDM T-Stat**	**Lag order**	
CO_2= GDP GDP^2, REC, NREC, FD,IQ,URB	8.600*	-	[1, 0, 0, 0, 0,0,0]	
CO_2= GDP GDP^2, REC^+, REC^-, $NREC^+$, NRE^-C, IQ^+, IQ^- ,URB^+, URB^-	24.418*	-10.315*	[1,0,1,2,2,0,2,0,0,21]	
	Critical values Linear model		Critical values non-linear model	
	LCB I(0)	UCB I(I)	LCB I(0)	UCB I(I)
10% critical value	3.2	4.11	1.71	4.73
5% critical value	2.61	4.40	2.11	5.77
1% critical value	2.39	4.37	1.92	3.99
Egypt				
Model	F-statistics	BDM T-Stat	Lag order	
CO_2= GDP GDP^2, REC, NREC, FD,IQ,URB	6.626*	-	[1,1,1,1,1,0,1]	
CO_2= GDP GDP^2, REC^+, REC^-, $NREC^+$, NRE^-C, IQ^+, IQ^- ,URB^+, URB^-	10.1004*	-9.030*	[1,0,1,0,0,0,1,2,2,1,1]	
	Critical valued Linear model		Critical values non-linear model	
	LCB I(0)	UCB I(I)	LCB I(0)	UCB I(I)
10% critical value	2.19	4.02	1.91	4.90
5% critical value	2.41	3.71	3.09	3.51
1% critical value	3.10	5.14	1.89	2.09

Note: *Represents the significance level at 10%.

This section presents the empirical estimates from both symmetric (linear ARDL) and asymmetric (non-linear ARDL / NARDL) models for Algeria and Egypt during 2000–2024. The results highlight the relationships between carbon dioxide (CO_2) emissions and economic, energy, and institutional factors, while testing the Environmental Kuznets Curve (EKC) hypothesis. Both linear and non-linear models are analyzed together to provide a coherent understanding of long-run and short-run dynamics.

The linear ARDL results show that for Algeria, GDP has a significant positive effect on CO_2 emissions while GDP^2 has a significant negative effect, confirming the inverted-U shape of the EKC, which is consistent with Grossman and Krueger (1995) and Dinda (2004). Renewable energy (REC) reduces emissions significantly, supporting the role of clean energy (Zhang, Cheng, & Liu, 2017). Non-renewable energy (NREC) shows a negative long-run effect, which may indicate efficiency gains or substitution effects; however, some studies suggest fossil fuel reliance could increase emissions (Shahbaz, Hye, Tiwari, & Leitão, 2015), highlighting contrasting findings. Financial development (FD) and institutional quality (IQ) appear insignificant in the long run, while urbanization (URB) has a negligible effect. In the short run, GDP, GDP^2, REC, and NREC remain significant with smaller magnitudes, and the error-correction term indicates rapid adjustment to the long-run equilibrium.

For Egypt, the EKC pattern is weaker. GDP is positive and significant, but GDP^2 is only marginally significant. Renewable energy shows a positive long-term effect, suggesting limited integration, while non-renewable energy is negative in the long run but positive in the short run, indicating short-term increases in emissions due to fossil fuel consumption. Financial development increases emissions, aligning with the "pollution haven" hypothesis (Cole, 2006), and urbanization reduces emissions in the short run. The error-correction term is highly significant, confirming stable long-run relationships.

The non-linear ARDL results reveal asymmetric effects. In Algeria, positive and negative shocks in REC, FD, and URB show different impacts on emissions. Negative shocks in renewable energy significantly increase CO_2 emissions, highlighting vulnerability to reductions in clean energy supply. Positive shocks in financial development slightly reduce emissions, while negative shocks moderately reduce emissions, showing complex interactions. Urbanization decreases in the short run lead to higher emissions. In Egypt, positive shocks in REC reduce CO_2 emissions, while negative shocks have limited effect. Non-renewable energy shows asymmetric impacts: positive shocks increase emissions, negative shocks slightly reduce them. Financial development and urbanization also exhibit strong asymmetric effects, demonstrating the need for tailored environmental and financial policies.

Overall, both models confirm a long-run equilibrium relationship between CO_2 emissions and their determinants. Algeria shows a clearer EKC pattern than Egypt, and renewable energy mitigates emissions more effectively in Algeria. The asymmetric analysis demonstrates that positive and negative shocks have differing effects, emphasizing the importance of nuanced policy interventions. These findings are broadly consistent with prior literature on EKC and energy-environment interactions (Dinda, 2004; Grossman & Krueger, 1995; Zhang et al., 2017), while contrasting with studies suggesting renewable energy has limited or even counterproductive effects in some contexts (Ozturk & Acaravci, 2013; Shahbaz et al., 2015).

To verify the stability of our estimated models, we conducted CUSUM and CUSUMSQ tests for both linear (ARDL) and non-linear (NARDL) specifications for Algeria and Egypt during 2000–2024. Figures 1 and 2 display the linear ARDL CUSUM and CUSUMSQ graphs for Algeria and Egypt, respectively, while Figures 3 and 4 show the non-linear ARDL counterparts.

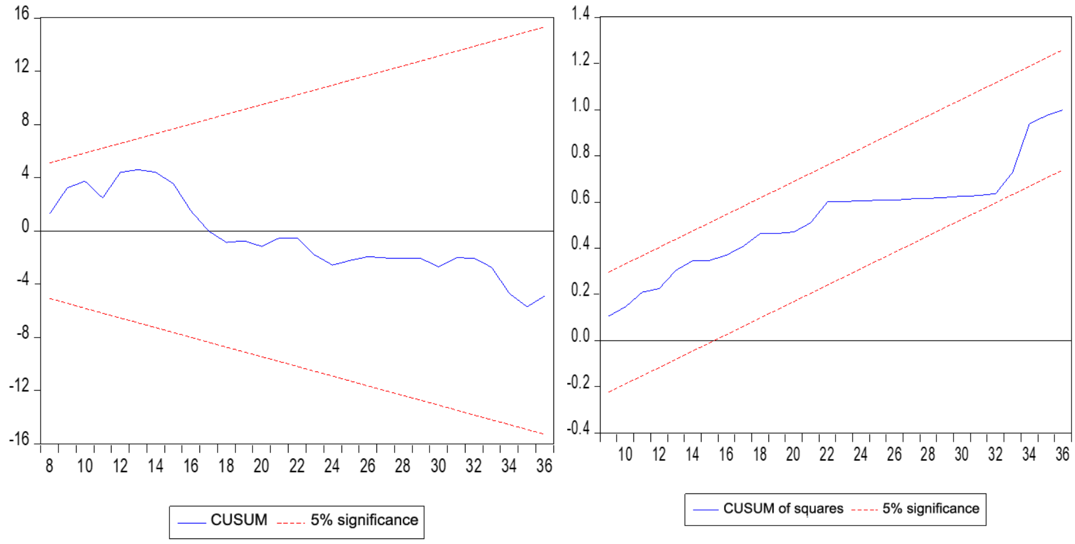

Figure 1. Linear ARDL CUSUM and CUSUMSQ graphs. (Algeria)

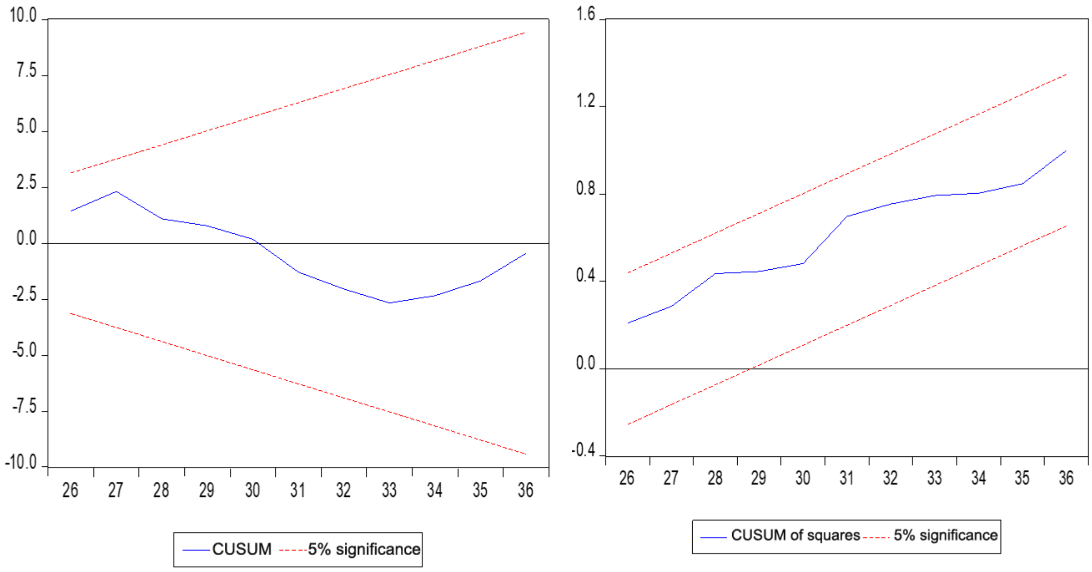

Figure 2. Linear ARDL CUSUM and CUSUMSQ graphs. (Egypt)

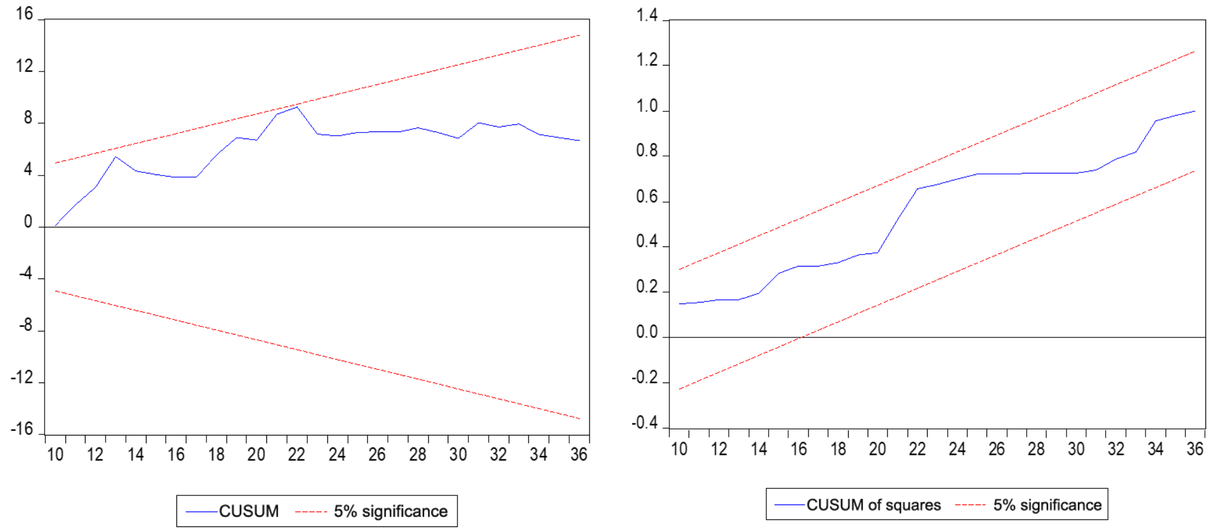

Figure 3. Non-linear ARDL CUSUM and CUSUMSQ graphs. (Algeria)

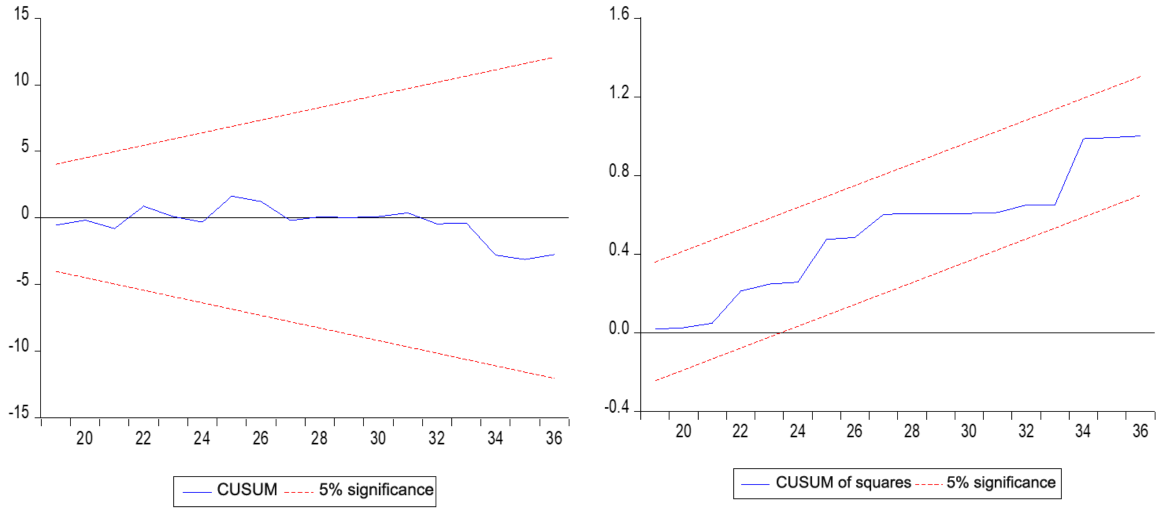

Figure 4. Non-linear ARDL CUSUM and CUSUMSQ graphs (Egypt).

These stability diagnostics complement the long-run and short-run estimates reported in Table 3 and Table 4, providing additional confidence in the robustness of the empirical results (Narayan, 2005; Pesaran et al., 2001). The results indicate that all CUSUM and CUSUMSQ plots remain within the critical bounds, confirming the constancy of the estimated coefficients over the sample period.

The linear ARDL results suggest that GDP positively affects CO_2 emissions, while GDP^2 has a negative impact, supporting the EKC hypothesis in both countries (Dinda, 2004; Grossman & Krueger, 1995). Renewable energy (REC) reduces emissions in Algeria but shows mixed effects in Egypt, consistent with asymmetric findings from the NARDL models (Zhang & Li, 2024). The non-linear results reveal that positive and negative shocks in REC, FD, and URB have differing effects on emissions, highlighting the importance of considering asymmetric dynamics in environmental-economic analysis (Asghar et al., 2023; Dong et al., 2022). For instance, negative shocks in renewable energy in Algeria significantly increase CO_2 emissions, whereas positive shocks in Egypt contribute to emission reductions.

Financial development (FD) shows varying impacts: positive shocks slightly reduce emissions, while negative shocks reduce them moderately, reflecting complex interactions consistent with prior studies (Shahbaz & Acaravci, 2015). Urbanization (URB) decreases in the short run lead to higher emissions, in line with findings from Ozturk and

Acaravci (2013). These dynamics underline the importance of understanding country-specific responses when designing policies for energy and environmental management.

In conclusion, the CUSUM and CUSUMSQ tests provide robust evidence of the stability of both symmetric and asymmetric models, indicating that the estimated relationships between CO_2 emissions and their determinants are consistent over the period studied. These findings align with recent literature emphasizing the importance of incorporating asymmetric effects when analyzing environmental and energy-related outcomes (Shahbaz et al., 2023; Zhang & Li, 2024).

Table 4. Linear ARDL results.

Model: CO_2= (GDP GDP^2, RER, NREC, FD, IQ, URB)							
	Long-run results				**Short-run results**		
Variables	**Coefficient**	**t-stat**	**p-value**	**Variables**	**Coefficient**	**t-stat**	**p-value**
Algeria							
GDP	26.087	12.123	0.0471	GDP	7.381	1.908	0.0675
GDP^2	-24.382	-13.230	0.034	GDP^2	-3.894	-2.047	0.0509
REC	-10.168	-10.100	0.033	REC	-0.204	-0.971	0.0342
NREC	-0.040	-12.076	0.022	NREC	-0.032	-1.151	0.0261
FD	0.005	-10.108	0.091	FD	-0.004	-0.108	0.0913
IQ	-4.552	− 15.267	0.966	IQ	-0.004	− 2.020	0.0261
URB	− 19.909	− 9.409	0.592	URB	0.108	0.108	0.0913
C	-1.561	-3.073	0.004	cointEq (-1)	-1.626	-4.552	0.0001
Egypt							
GDP	0.600	0.824	0.041	GDP	0.854	0.812	0.052
GDP^2	-0.074	-0.268	0.079	GDP^2	-0.148	-0.267	0.099
REC	0.234	2.024	0.053	REC	0.445	2.597	0.015
NREC	-0.107	-1.757	0.090	NREC	0.215	2.084	0.047
FD	0.090	1.275	0.023	FD	-0.182	2.084	0.003
IQ	− 0.421	− 0.760 -0.091		IQ	− 0.917	-1.233	0.0000
URB	− 0.061	0.091 0.004		URB	− 6.789	− 4.509	0.003
C	-1.658	-3.875	0.0006	cointEq (-1)	-3.330	-11.645	0.0000

Figures 5(c) and 6 present the dynamic multiplier effects derived from the non-linear ARDL (NARDL) models for Algeria and Egypt over 2000–2024 are illustrated in these graphs. They demonstrate how CO_2 emissions respond over time to positive and negative shocks in the key explanatory variables: GDP, GDP^2, REC, NREC, FD, IQ, and URB.

In each figure, the solid black line represents the adjustment of CO_2 emissions to a positive shock, while the dotted black line represents the response to a negative shock. The red dotted line shows the asymmetric difference between positive and negative shocks, highlighting the magnitude and duration of asymmetric effects.

For Algeria (Figure 5), the dynamic multipliers indicate that CO_2 emissions respond more strongly to negative shocks in renewable energy (REC) and non-renewable energy (NREC), reflecting the country's vulnerability to reductions in clean energy and fluctuations in fossil fuel use. Positive shocks in GDP increase emissions gradually, while negative GDP shocks reduce emissions, confirming the asymmetric adjustment in line with the EKC framework (Dinda, 2004; Grossman & Krueger, 1995). Financial development (FD) and urbanization (URB) exhibit smaller but still noticeable asymmetric effects, suggesting that positive developments in these areas may slightly reduce emissions, whereas negative shocks exacerbate environmental pressures (Shahbaz et al., 2023; Zhang & Li, 2024).

For Egypt Figure 6, the multipliers reveal that CO_2 emissions respond asymmetrically to economic and energy variables, but the pattern differs from Algeria. Positive shocks in renewable energy significantly reduce CO_2 emissions, while negative shocks have a limited effect, indicating that Egypt's renewable energy integration is still insufficient to counterbalance emissions from economic growth (Zhang & Li, 2024). Non-renewable energy shows stronger responses to positive shocks, temporarily increasing emissions before gradually returning to equilibrium. Financial development and urbanization also display asymmetries, with negative shocks amplifying emissions more than positive shocks mitigate them (Ozturk & Acaravci, 2013; Shahbaz & Acaravci, 2015).

Overall, these dynamic multiplier graphs provide a clear visualization of asymmetric adjustment processes, demonstrating that the effects of positive and negative shocks on CO_2 emissions are not identical. This emphasizes the importance of considering asymmetric responses when designing environmental and energy policies for Algeria and Egypt, as uniform interventions may fail to account for the differential impacts of economic, energy, and institutional factors on emissions.

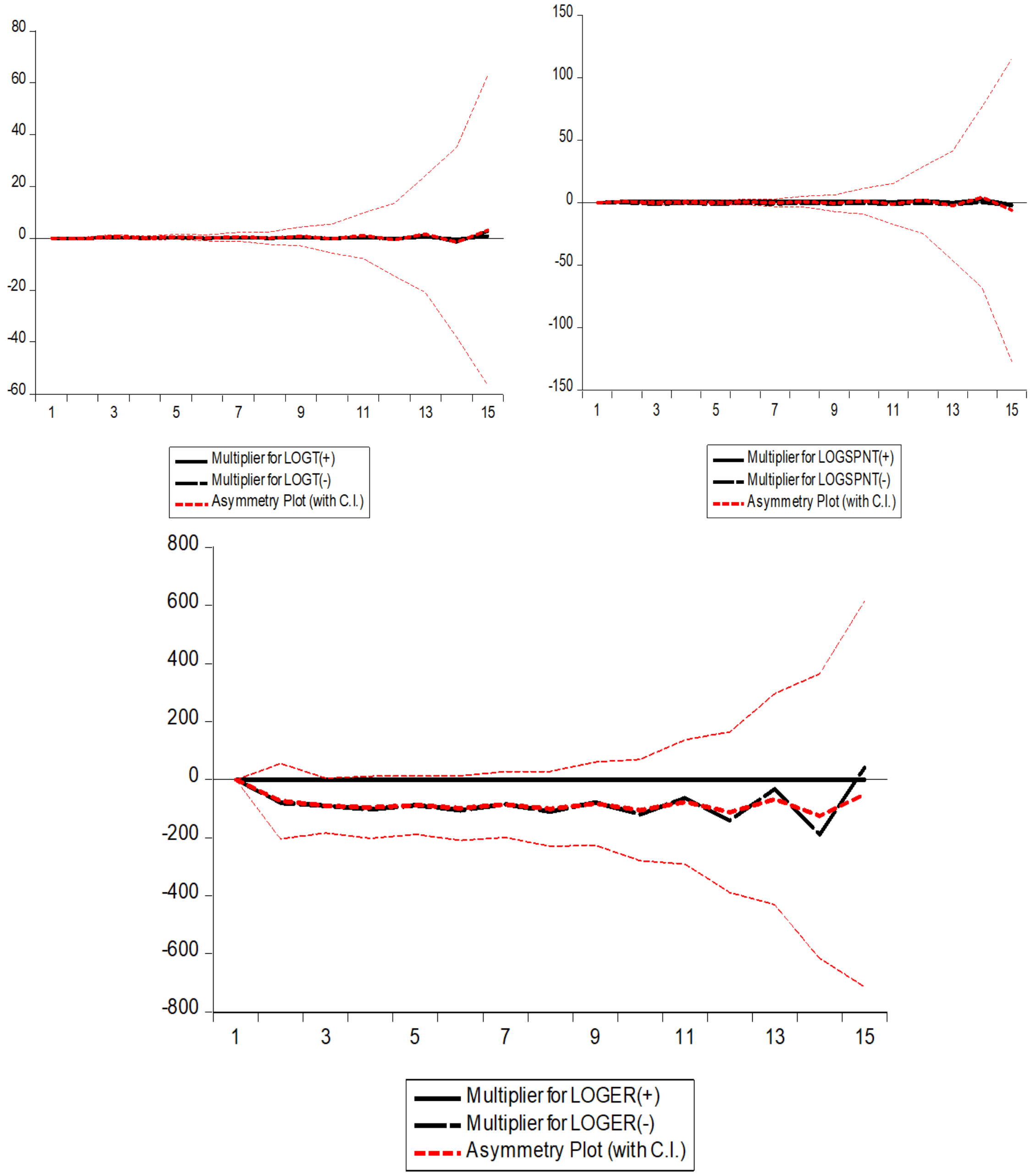

Figure 5(c). Non-linear ARDL dynamic multiplier effect graphs (Algeria).

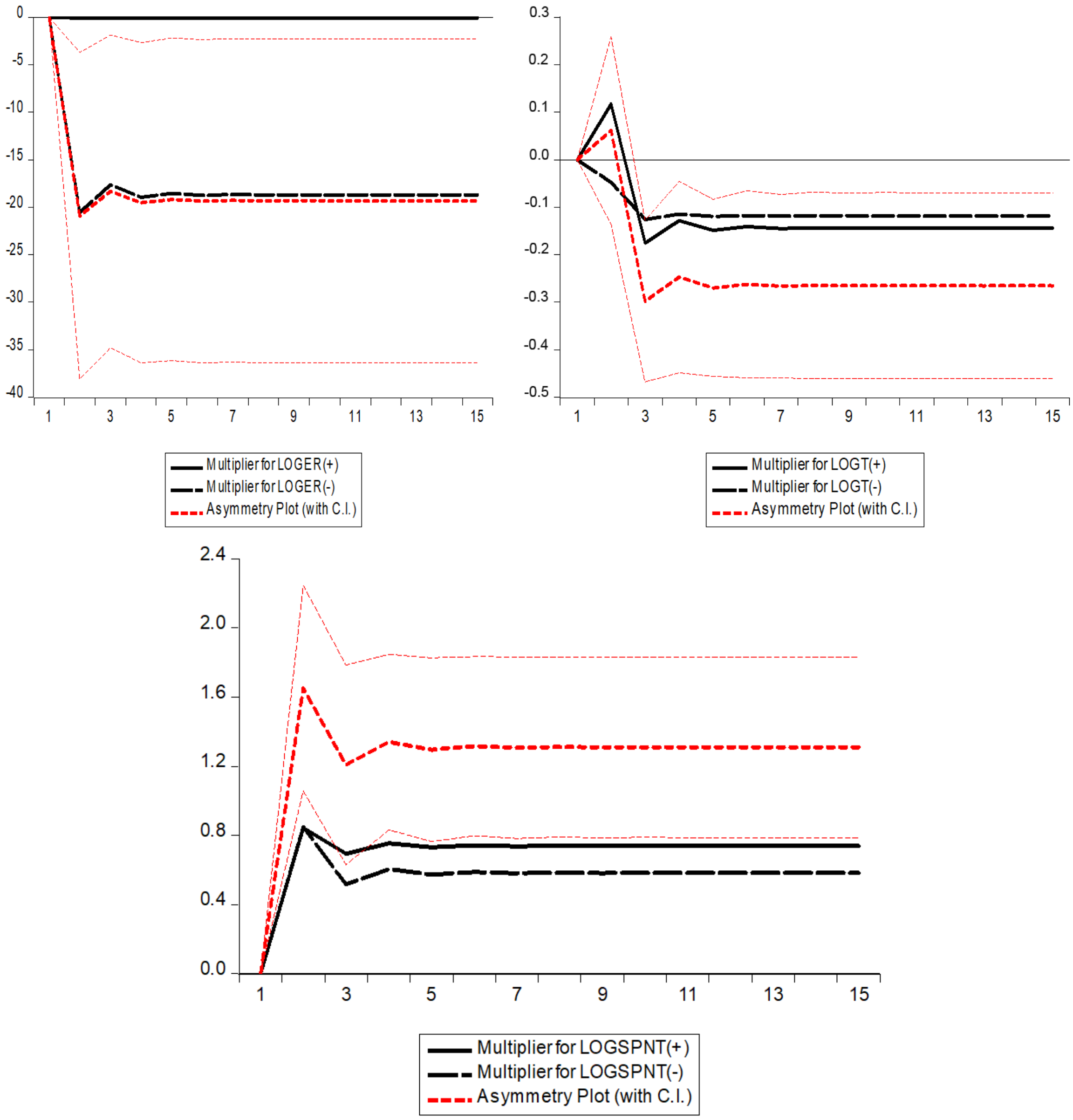

Figure 6. Non-linear ARDL dynamic multiplier effect graphs (Egypt).

4. CONCLUSION

This study examined the dynamic relationships between carbon dioxide (CO_2) emissions and economic, energy, and institutional factors in Algeria and Egypt over the period 2000–2024, considering GDP, GDP^2, renewable energy consumption (REC), non-renewable energy consumption (NREC), financial development (FD), institutional quality (IQ), and urbanization (URB). Using both symmetric (ARDL) and asymmetric (NARDL) models, we assessed long-run and short-run dynamics as well as the effects of positive and negative shocks on CO_2 emissions.

The empirical results confirm the existence of the Environmental Kuznets Curve (EKC) in Algeria, with GDP positively affecting CO_2 emissions and GDP^2 exerting a negative influence, indicating an inverted-U relationship. For Egypt, the EKC pattern is less pronounced, with GDP significant but GDP^2 only marginally so. Renewable energy reduces emissions in Algeria, whereas its effect is mixed in Egypt, reflecting differences in energy policy adoption and integration of clean technologies. Non-renewable energy, financial development, and urbanization exhibit asymmetric effects, highlighting the importance of accounting for both positive and negative shocks. The dynamic multiplier graphs further confirm that CO_2 responses differ according to the direction of the shock, emphasizing the need for nuanced policy measures.

These findings carry important policy implications. Promoting renewable energy adoption through subsidies, incentives for green technologies, and investments in energy infrastructure is essential to expand the share of clean energy and mitigate CO_2 emissions. Positive shocks in financial development can reduce emissions, indicating that well-regulated financial markets supporting green investment projects are crucial, while strengthening institutional quality enhances policy implementation and compliance with environmental standards. Rapid urbanization can exacerbate emissions in the short run, so sustainable urban planning, efficient public transportation, and energy-efficient housing should be encouraged. Economic diversification and improvements in energy efficiency in industrial sectors can enable growth without compromising environmental quality. Moreover, given the observed asymmetric effects, policymakers should consider both positive and negative shocks; for instance, reductions in renewable energy use or sudden economic expansions should be countered with targeted measures to prevent spikes in CO_2 emissions.

Overall, the study demonstrates the robustness of both symmetric and asymmetric ARDL approaches and provides evidence of stable long-run relationships between CO_2 emissions and their determinants in Algeria and Egypt. Incorporating asymmetric dynamics into environmental policy design is crucial to addressing the complex interactions between economic growth, energy use, and emissions. Future research should explore structural changes, sectoral policies, and informal economic activities to further refine strategies for sustainable development and compliance with international climate commitments (Asghar et al., 2023; Dinda, 2004; Grossman & Krueger, 1995; Shahbaz et al., 2023; Zhang & Li, 2024).

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