MEST Journal

ORIGINAL RESEARCH ARTICLE
MEST Journal

BEYOND THE POLLUTION HAVEN: TRADE OPENNESS, RENEWABLE ENERGY, AND ARAB ECONOMIES

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ARTICLE INFO

CC BY

Open access

JEL Category:
C23, F18, O13, Q53, Q48

Keywords:

pollution
emerging economies
energy policies
panel data models
trade flows.

ABSTRACT

This study investigates the dynamic relationship between trade openness, renewable energy share, and carbon dioxide CO2 emissions as a proxy for environmental degradation, focusing on a sample of seven Arab economies (Algeria, Egypt, Saudi Arabia, UAE, Qatar, Kuwait, and Oman) over the period 2013–2023. To address econometric challenges concerning cross-sectional dependence and slope heterogeneity, the study employs second-generation panel unit root and cointegration tests, alongside the Panel Autoregressive Distributed Lag (Panel - ARDL) model using the Pooled Mean Group (PMG) estimator. The empirical results reveal a robust self-correcting mechanism, with approximately 73.79% of short-run disequilibrium shocks corrected annually. In the long run, the estimates identify a positive and statistically significant impact of trade openness on CO2 emissions, providing strong empirical support for the "Pollution Haven Hypothesis" within the sampled countries, largely driven by the localization of energy-intensive industries. Conversely, the impact of renewable energy consumption remains marginal and statistically insignificant, suggesting that current green infrastructure investments have yet to reach the critical threshold required to mitigate environmental degradation. The study concludes that achieving sustainability in these rentier-based Arab economies necessitates not only intensified clean energy deployment but also rigorous institutional governance to internalize the negative externalities of trade, coupled with enhanced cross-border regional coordination to overcome structural barriers to green development.

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Received: 16.07.2026
Revised: 21.07.2026
Accepted: 23.07.2026
Available online: 23.07.2026

1 INTRODUCTION

In recent decades, the world has witnessed a growing concern over ecological issues, climate change, and global warming, which are now classified among the most prominent challenges of the twenty-first century. These phenomena are mainly attributed to the continuous rise in greenhouse gas emissions, most notably carbon dioxide CO_2. This increase is a direct result of the historical accumulation of intensive industrial activities and the excessive reliance on traditional energy sources (fossil fuels) to drive economic growth and meet the ever-increasing global consumption demand (Stern, 2008). This issue carries paramount and twofold importance for Arab countries, specifically the sample of this study: Algeria, Egypt, Saudi Arabia, the United Arab Emirates, Qatar, Kuwait, and the Sultanate of Oman. On one hand, the economic structures of these countries have historically relied on rentier revenues derived from the extraction and export of hydrocarbons, making their carbon footprint relatively high. On the other hand, this geographical region is considered one of the most vulnerable and exposed areas to the negative repercussions of climate change. Therefore, these countries find themselves today facing a strategic challenge to balance the preservation of their developmental achievements, the requirements of transitioning toward diversified economies, and the fulfillment of their international environmental commitments.

In the context of global economic dynamics, trade openness has played a pivotal role in strengthening interconnectedness among economies and integrating them into international supply chains. However, this openness has sparked a wide and complex debate in environmental economics literature, especially when applied to hydrocarbon-exporting countries; its impact can be deconstructed into three main mechanisms reflecting the reality of the sample countries. This is manifested first in the scale effect, as the integration of these countries into the global economy has expanded their economic activity, particularly through the massive expansion in the production and export of fossil fuels and their derivatives. This production expansion explains why some of the sample countries record some of the highest global per capita carbon dioxide CO_2 emission rates, with this indicator exceeding the threshold of 15 metric tons annually per capita in some Gulf countries like Qatar, Kuwait, Saudi Arabia, and the UAE, due to the rapid pace of exports and intensive consumption of extracted energy (World Bank, 2024). This effect also appears through the composition effect, where the "pollution haven hypothesis" warns that developing countries may turn into recipients of pollution-intensive industries (Copeland & Taylor, 2004). In their serious attempts to diversify their economies away from crude oil exports, many of the sample countries have focused on localizing heavy and energy-intensive industries such as petrochemicals, aluminum smelting, cement, and steel, which structurally increased the domestic carbon footprint of these nations. In contrast, the technique effect emerged as a positive aspect confirming that trade liberalization facilitates technological transfer (Grossman & Krueger, 1991). Trade openness has enabled the sample countries to import clean production technologies and localize green tech. Countries like the UAE, Saudi Arabia, and Egypt have become major importers and developers of solar panel and wind turbine technologies in the Middle East and North Africa region, gradually contributing to improving energy efficiency.

To confront these complex challenges, the transition toward renewable energy consumption has emerged as an inevitable option in modern developmental policies. Studies collectively agree that integrating clean energy sources into the energy mix is a cornerstone for mitigating environmental degradation and decoupling economic expansion from carbon emissions (Apergis & Payne, 2010). These trends are no longer merely theoretical propositions in the sampled countries; rather, they have been translated into national strategies and large-scale implementation projects. Saudi Arabia launched the Saudi Green Initiative, aiming for renewable energy to account for approximately 50% of electricity generation by 2030 while pursuing net-zero emissions by 2060 (Saudi Green Initiative, 2024; Ministry of Energy, Saudi Arabia, 2024). Meanwhile, the UAE Energy Strategy 2050 seeks to expand the contribution of clean energy while supporting flagship projects such as the Mohammed bin Rashid Al Maktoum Solar Park. In

North Africa, Egypt's Integrated Sustainable Energy Strategy promotes a substantial increase in renewable energy generation through projects such as the Benban Solar Park. Algeria likewise plans to expand renewable electricity generation to 15,000 MW by 2035, primarily exploiting its considerable solar potential. Qatar has commissioned the Al Kharsaah Solar Power Plant as part of its national energy transition strategy, while Oman has adopted a national pathway toward net-zero emissions by 2050 and Kuwait continues developing the Shagaya Renewable Energy Complex.

Despite this academic momentum, a clear research gap stands out in the scarcity of studies evaluating the dual and simultaneous impact of trade openness and the transition toward renewable energy specifically within the context of this selected combination of Arab countries. Most of the literature focuses either on advanced industrial economies or examines the two variables in isolation from each other. Consequently, this research seeks to bridge this knowledge gap and provide a comprehensive insight that studies this shared economic specificity.

2 LITERATURE REVIEW

Contemporary economic and environmental literature exhibits a broad consensus regarding the transition toward renewable energy sources, positioning it as the foundational cornerstone for achieving the multi-dimensional facets of sustainable development, namely, environmental, economic, and social dimensions. Empirical evidence put forward by Algarni et al. (2023), Agbakwuru et al. (2024), and Ullah et al. (2024) strongly demonstrates that clean energy deployment plays a critical role in fostering green economic growth, mitigating carbon emissions, alleviating poverty, and driving rural electrification in alignment with the United Nations Sustainable Development Goals (SDGs). However, this transition is not without structural bottlenecks; as Owusu and Asumadu-Sarkodie (2016) point out, high initial capital requirements, technological constraints, market failures, and inadequate carbon pricing mechanisms remain significant challenges that hinder the full-scale, sustainable deployment of renewable technologies.

Concurrently, the literature reveals a stark division and empirical ambiguity concerning the exact impact of trade openness and economic liberalization on sustainable outcomes. On one hand, Ullah et al. (2024) identify a positive and statistically significant long-run impact of trade openness on the sustainable development of G20 nations, arguing that open markets facilitate the cross-border spillover of clean technologies and optimize resource allocation (Ullah et al., 2024). On the other hand, (Sheikh et al., 2020) counter this conventional economic optimism through their empirical analysis of India. They demonstrate a negative correlation between trade openness and Green GDP growth, warning that unbridled trade integration often triggers severe resource depletion and environmental degradation, thereby compromising the ecological rights of future generations.

To reconcile these conflicting empirical narratives, recent econometric inquiries have shifted focus toward unpacking the conditional and moderating roles of governance, institutional quality, and regional frameworks. Employing a dynamic Bayesian perspective, Nga and Huy (2025) uncover a critical nuance: while trade openness and growth-oriented government efficiency may independently exert negative impacts on sustainability, their joint interaction produces a robust positive effect. This implies that state capacity and stringent environmental governance are vital to internalizing the negative externalities of trade. This institutional prerequisite aligns with the findings of Balogun et al. (2024) in the ECOWAS region, who observe that trade openness can positively moderate the poverty-sustainability nexus in the long run, provided it is complemented by heavy investments in human capital development. Similarly, Arif et al. (2022) underscore that integrating trade globalization with robust financial development acts as a catalyst for sustainable eco-economic growth in South Asian economies.

Adding a final layer of complexity to this interactive framework, Ullah et al. (2024) offer a vital spatial dimension by examining countries along the Belt and Road Initiative (BRI). Their study reveals that multi-dimensional regional integration acts as an asymmetric moderator; while regional integration successfully amplifies the positive effects of the renewable energy transition on sustainable development in Asia and Europe, it exerts a negative moderating effect in Middle East-African economies. This disparity underscores that the success of trade-led and energy-driven sustainability pathways is highly contingent upon regional macroeconomic stability and institutional maturity, making a one-size-fits-all policy approach inherently flawed.

Based on this regional disparity and empirical ambiguity observed in the literature, the research gap highlighted by this study is further reinforced. This gap underscores the imperative of investigating the simultaneous and interactive impact of trade openness and renewable energy, while accounting for the unique structural characteristics of the seven selected Arab countries under study.

3 MODEL SPECIFICATION

This stage aims to construct the econometric model and specify its variables across both cross-sectional and temporal dimensions, drawing upon contemporary environmental economics literature that investigates the determinants of environmental degradation. The model is formulated as a functional relationship linking carbon dioxide CO2 emissions as the dependent variable to the share of renewable energy and trade openness as the explanatory independent variables.

3.1 Mathematical Specification of the Model

The static baseline panel data model is specified in its log-linear form as follows:

$$LnCO2_{it}=\beta_0+\beta_1 LnRE_{it}+\beta_2 LnTR_{it}+\varepsilon_{it}$$

Where the symbols denote the following:

I – Represents the cross-sectional dimension (the sampled countries), where i = 1, 2, … 7.

t – Represents the temporal dimension (the time period), where t = 2013, 2014, …, 2023.

$lnCO2_{it}$ – The natural logarithm of total carbon dioxide emissions (measured in metric tons per capita), serving as the dependent variable reflecting environmental degradation.

$LnRE_{it}$ – The natural logarithm of the renewable energy consumption share out of total final energy consumption, with an expected negative sign ($\beta_1 < 0$).

$LnTR_{it}$ – The natural logarithm of the trade openness index (the ratio of total merchandise trade to GDP), whose coefficient sign (β_2) depends on the empirical validation of the Pollution Haven Hypothesis.

β_0 – The constant term (intercept) of the model.

β_1, β_2 –The long-run parameters to be estimated.

ε_{it} – Error term.

3.2 Data Sources

The study sample consists of a structural synthesis comprising seven Arab countries that represent a mix of diverse oil-exporting and developing economies, namely: Algeria, Egypt, the Kingdom of Saudi Arabia, the United Arab Emirates, Qatar, Kuwait, and Oman.

The study covers an annual time series spanning from 2013 to 2023, yielding a total balanced panel of N ×T = 7 ×11 = 77 observations. To ensure the robustness and quality of the empirical analysis, data collection for the variables was compiled from highly reliable official international databases, as detailed in Table 1.

Table 1. *Research Variables*

Variable	Measures	Source
CO_2	Carbon dioxide emissions	World Bank
RE	Renewable energy share	Our world in data
TR	Trade openness	World Bank

Source: author's own work based on data from World Bank and Our World in Data

3.3 Descriptive and Exploratory Data Analysis

3.3.1 Descriptive Statistical Analysis of the Study Variables

Table 2 presents the descriptive statistics for the study variables in their logarithmic form, based on 77 observations. The results indicate a notable convergence between the mean and median values across all variables, particularly for the variable (ltr), which exhibits a mean of 1.8870 and a median of 1.9510. This proximity suggests the absence of severe dispersion or extreme outliers, indicating that the data distribution is approximately normal. Furthermore, the variable (lco2) demonstrates moderate variation within the sample, ranging from a minimum of 0.3432 to a maximum of 1.7267. Conversely, the variable (lre) recorded negative values for its mean (-0.9766) and minimum (-3.9840). This is mathematically justified, as the original values prior to the logarithmic transformation were likely percentages or fractions below one. Overall, these findings reflect an acceptable level of statistical homogeneity, establishing a robust foundation for proceeding with unit root testing and subsequent panel data econometric analysis.

Table 2. *Descriptive Statistics of Key Variables*

Variable	Mean	Median	Min	Max	Observations
lco2	1.1314	1.2872	0.3432	1.7267	77
lre	-0.9766	-1.0664	-3.9840	0.7758	77
ltr	1.8870	1.9510	1.4750	2.2990	77

Source: author's own work based on data from World Bank and Our World in Data

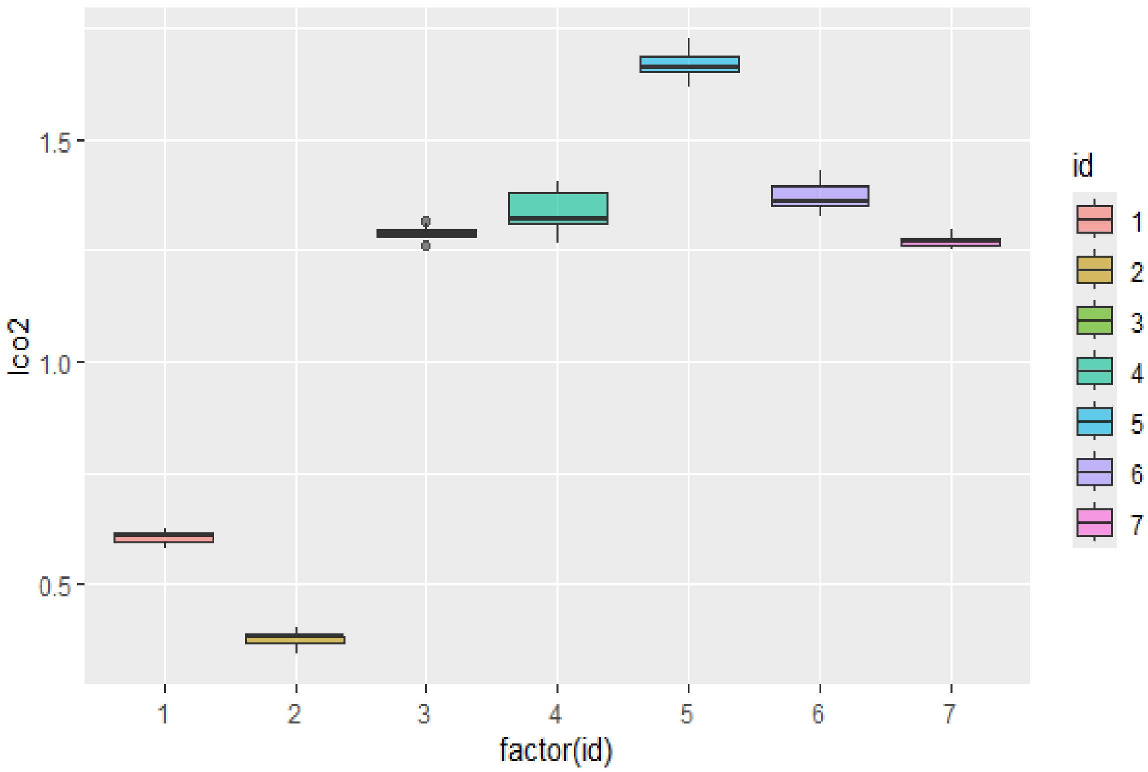

Figure 1. *Heterogeneity and Distribution of lco2 Emissions Across MENA Countries*
Source: (Own elaboration based on R 4.6.0 software output)

3.3.2 Cross-Sectional Heterogeneity Analysis

Figure 1 illustrates a pronounced structural divergence and fundamental cross-sectional heterogeneity in the logarithmic levels of carbon dioxide emissions (lco2) across the seven Arab countries constituting the sample. Certain economies (particularly those heavily reliant on fossil fuels) dominate the upper bound of the cross-sectional spectrum with elevated emission rates, whereas other Arab nations in the sample occupy lower, relatively stable positions within the statistical box. This distinct cross-unit structural variation methodologically justifies the application of panel data models that account for country-specific effects and unobserved heterogeneity, thereby preventing estimation bias in subsequent empirical steps.

Furthermore, these findings emphasize the underlying economic structural differences, where high-income oil- exporting states display distinct baseline emission trends compared to more diversified regional economies. Consequently, explicitly incorporating these cross-sectional dynamics ensures that subsequent panel estimations remain unbiased, highly robust, and statistically consistent.

3.3.3 Historical Trajectories and Temporal Trends of the Variables

Shifting from the comparative structural dimension to the temporal dynamics, Figure 2 displays the cumulative pooled historical path of emissions from 2013 to 2023. This is further enriched by Figure 3, which decomposes this evolution into individual historical trajectories for each Arab country separately. A pattern of relative stability or highly moderated fluctuations is discernible in the time-series behavior of most of these countries over the last decade. This behavior reflects a certain rigidity in the pace of emission reduction within the countries themselves, especially when contrasted against the substantial scale of variance observed between the different nations within the Arab group.

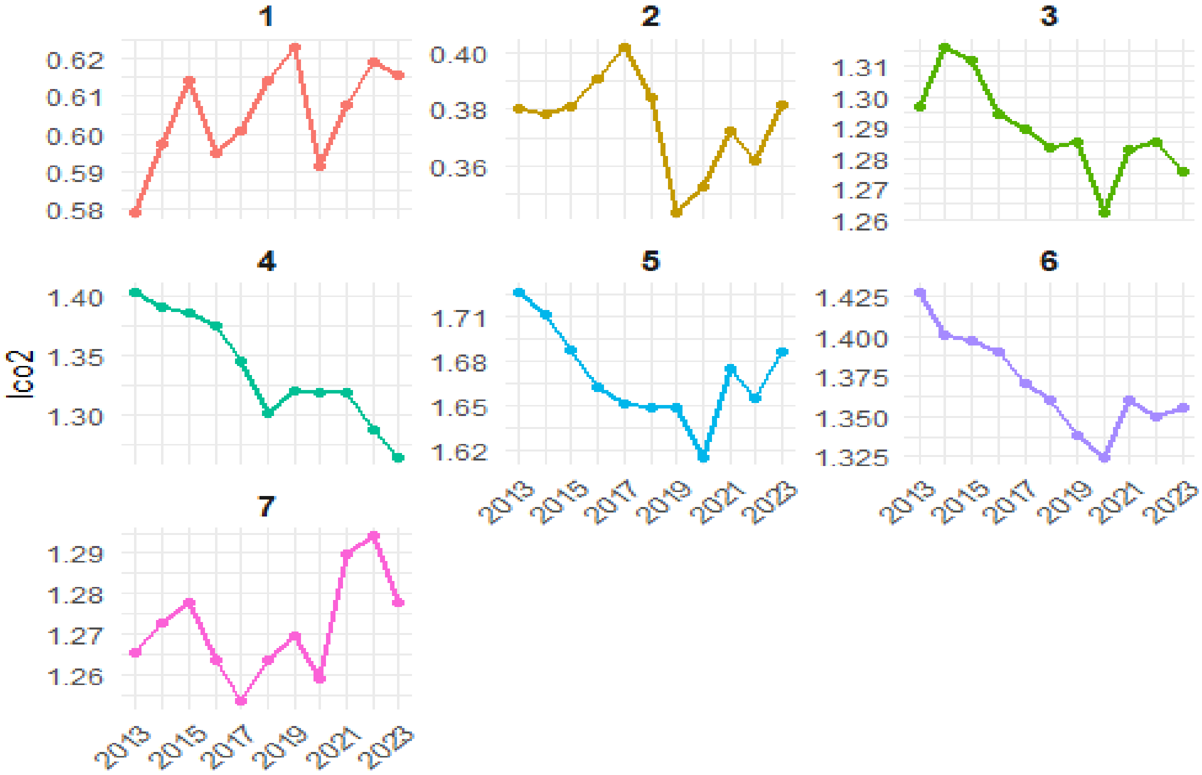

Figure 2. *Time Series Trends of lco2 Emissions 2013-2023*
Source: (Own elaboration based on R 4.6.0 software outputs)

3.3.4 Bivariate Association and Multivariate Synthesis

As a prelude to constructing the econometric model, the scatter plot in Figure 3 clarifies the baseline bivariate association between the log of carbon emissions and the renewable energy share (lre). The downward slopes of the trend lines for the majority of the seven Arab countries indicate an initial inverse relationship, confirming that an increased adoption of alternative energy sources is dynamically accompanied by dropping environmental pollution indicators within these economies.

Concluding this analytical sequence, the correlation matrix heatmap presented in Figure 4 synthesizes the comprehensive framework of statistical associations among all variables within the pooled sample. It numerically and visually demonstrates a significant negative correlation between renewable energy and emissions, reaching (-0.55). Conversely, a robust and pronounced positive correlation is found between trade openness (ltr) and emissions at (0.76). These descriptive and behavioral indicators are highly consistent, effectively establishing the logical groundwork to proceed with panel unit root tests as a prerequisite for estimating the dynamic Panel-ARDL model tailored to these heterogeneous Arab economies.

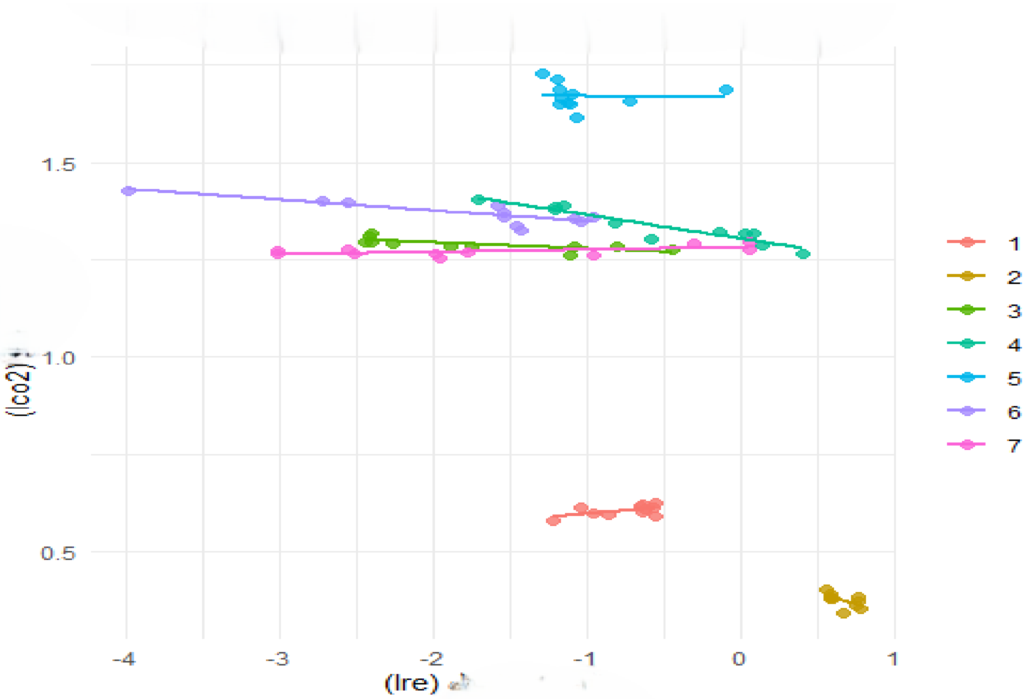

Figure 3. *Cross-Sectional Association Between lco2 and lre*
Source: (Own elaboration based on R 4.6.0 software outputs)

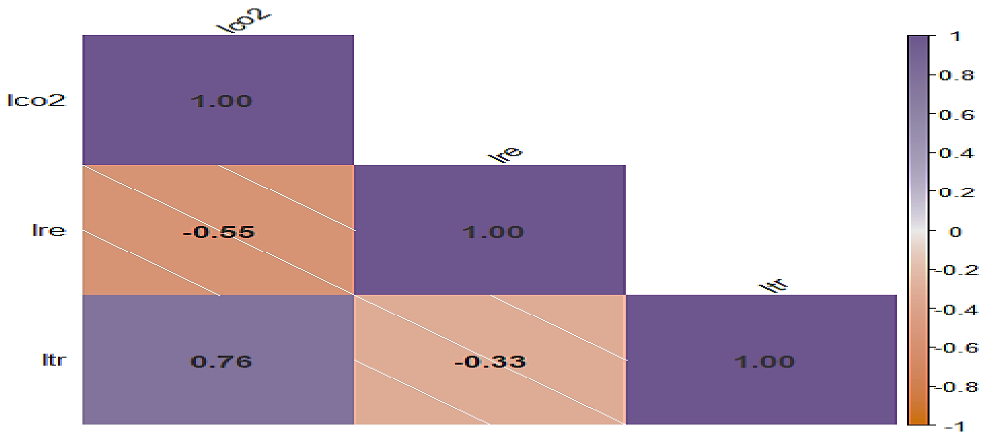

Figure 4*. Correlation Matrix Heatmap*
Source: Own elaboration based on R 4.6.0 software outputs

4 METHODOLOGY: THE PANEL-ARDL MODEL

To investigate the empirical relationships among the variables, this study employs the Panel Autoregressive Distributed Lag (Panel-ARDL) approach. This framework is uniquely suited for analyzing macro-panel data characterized by mixed orders of integration, as it accommodates variables that are either integrated of order I(0) or I(1), or a combination of both. Consequently, the Panel-ARDL approach ensures robust and consistent estimates of both short-run dynamics and long-run equilibrium relationships among the following variables:

CO2 – Carbon Dioxide Emissions.

RE – Renewable energy share.

TR – Trade openness.

To capture cross-country heterogeneity while maintaining efficiency in estimating long-run coefficients, we utilize both the Mean Group (MG) and Pooled Mean Group (PMG) estimators. To ensure the empirical validity and reliability of the Panel-ARDL estimation, the dataset is subjected to a battery of rigorous diagnostic tests, focusing on three core econometric assumptions:

- Cross-Sectional Dependence (CSD): Evaluated via Pesaran's (2004) CD test.
- Slope Homogeneity: Examined using the Pesaran and Yamagata (2008) test.
- Stationarity and Cointegration: Verified through second-generation panel unit root and cointegration tests, which explicitly account for cross-sectional interdependencies.
- Diagnostic Checking for Cross-Sectional Dependence (CSD)

Given the highly interconnected nature of global economies, panel datasets often exhibit cross-sectional dependence due to unobserved common shocks, spatial spillovers, or socio-economic linkages. Ignoring CSD can severely compromise the estimation process, leading to biased, inconsistent parameters and invalid statistical inferences. Therefore, as a preliminary diagnostic step, this study implements the pioneering Cross-Sectional Dependence (CD) test proposed by Pesaran (2004) on the residual series (H. Pesaran et al., 2004).

To ensure comprehensive robustness across different model specifications, three additional Lagrange Multiplier (LM) type tests are deployed to detect CSD within both fixed-effects and random-effects frameworks:

- The Pesaran Scaled LM test.
- The Breusch-Pagan LM test.
- The Bias-Corrected Scaled LM test.

Accounting for CSD is an indispensable prerequisite for establishing data reliability. Unaccounted-for cross-sectional interactions - arising from common factors or spatial dependencies - violate the fundamental assumption of independently distributed errors. By employing these advanced diagnostic tests alongside robust estimation procedures, this study yields consistent and asymptotically efficient parameters that accurately reflect the true economic relationships while controlling for spatial and unobserved co-movements.

5 EMPIRICAL RESULTS

In our econometric analysis, we aim to explore the impact of renewable energy share RE and trade openness on carbon dioxide (CO2) emissions. To achieve this objective, we follow a four-step empirical procedure:

- Cross-Sectional Dependence Testing. We begin by testing the hypothesis that all variables exhibit cross-sectional dependence (CSD) to ensure the validity of subsequent tests.
- Unit Root Testing. We examine the stationarity of the series and determine the order of integration for each variable included in the study.
- Cointegration Analysis. We investigate whether a long-term cointegrating relationship exists among the variables.

Model Estimation. Finally, we estimate the model using the Mean Group (MG) estimator proposed by Pesaran and Smith (M. H. Pesaran et al., 1997) and the Pooled Mean Group (PMG) estimator developed by Pesaran et al. (1999).

5.1 Testing Cross–Sectional Dependencies and Slope Homogeneity

By applying cross-sectional dependence tests, the study yielded two primary empirical findings:

At the Variable Level: The results in Table 3 indicate a strict rejection of the null hypothesis of cross-sectional independence for all study variables (LCO2, LRE, and LTR) at the 1% significance level across all employed tests (Breusch-Pagan LM, Pesaran scaled LM, Bias-corrected scaled LM, and Pesaran – CD). This confirms that the sampled countries are susceptible to unobserved common shocks, and by applying cross-sectional dependence tests, the study yielded two primary empirical findings.

At the Model Level (Residuals): The diagnostic results in Table 4 confirm the presence of cross-sectional dependence within the residuals of both the Fixed Effects (FE) and Random Effects (RE) models. Specifically, the LM - type tests exhibit high statistical significance with p -values = 0.000, thereby reinforcing the rejection of the cross-sectional independence hypothesis in the residuals, despite the Pesaran - CD test being statistically insignificant for the FE model alone.

Table 3. *Cross–Sectional Dependence Tests*

Test	df	LCO2	LRE	LTR
Breusch-Pagan LM	21	60.8584***	134.1820***	63.0401***
Pesaran Scaled LM		6.1502***	17.4643***	6.4869***
Bias- Corrected Scaled LM		5.8002***	17.1143***	6.1369***
Pesaran CD		3.1194***	11.3071***	3.7841***

Note: ***, **, and * denote rejection of H_0 at the 1%, 5%, and 10% levels, respectively.

Source: (Own elaboration based on STATA 17 software outputs)

Table 4. *Model Comparisons for Cross-Sectional Dependence*

Model	Pesaran CD test		Adjusted LM CD test		Pesaran Scaled LM		Breusch-Pagan LM	
	Z- stat	P-value	Chisq-stat	P-value	Chisq-stat	P-value	Z- stat	P-value
FE model	1.2801	0.200	4.8536***	0.000	5.2036***	0.000	54.7236***	0.000
RE model	1.0709	0.284			5.6105***	0.000	57.3602***	0.000

Note**:** Significance symbols are as defined in Table 3.

Source: (Own elaboration based on STATA 17 software outputs)

5.2 Stationarity Test

Based on these robust empirical indicators, relying on traditional "First-Generation" panel unit root tests would yield biased and misleading inferences. Consequently, it is imperative to shift toward Second-Generation panel unit root tests (such as CIPS and CADF) and adopt advanced dynamic estimators that explicitly account for cross-sectional dependence (e.g., CS - ARDL) to guarantee the accuracy and reliability of long-run estimates.

Based on the empirical outputs presented in Table 5, the stationarity of the panel series was examined using Pesaran's second-generation Cross-Sectionally Augmented IPS (CIPS) test (Pesaran, 2007), which is robust to cross-sectional dependence across units.

The findings reveal the following:

- For the dependent variable, carbon dioxide emissions (Lco2), the empirical results indicate that it achieves statistical stationarity in its level form without the need for differencing, yielding a test statistic of -3.668. This value is highly significant and exceeds Pesaran's critical values at the standard conventional thresholds, thereby rejecting the null hypothesis and confirming that the variable is stationary at level, i.e., integrated of order zero I(0).
- Conversely, the level test statistics for the independent variables—namely, trade openness (LTR) and renewable energy consumption (LRE) indicate statistical insignificance, with values standing at -1.261 and -1.257, respectively. These values are higher than Pesaran's critical values, leading to the non-rejection of the null hypothesis and implying that these series are non-stationary and contain a unit root at their levels.
- However, upon shifting to the first differences and by relying on the truncated CIPS statistics, which are statistically more robust, it is observed that the trade openness variable (DLTR) becomes entirely stationary at a value of -4.130, which is highly significant at the 1% level. Similarly, the renewable energy consumption variable (DLRE) achieves statistical stationarity at the first difference with a value of -3.349, significant at the 5% level.

Based on these econometric indicators, it is evident that the study's independent variables are stationary in their first differences and are integrated of order one, I(1). This divergence in the orders of integration [between I(0) and I(1)], in the presence of cross-sectional dependence and slope heterogeneity, provides a solid methodological justification to proceed to the next stage: conducting a second-generation panel cointegration test (e.g., Westerlund, 2007) to verify the existence of a long-run equilibrium relationship among these macroeconomic environmental and economic variables.

Table 5: *Panel Unit Root Test*

	Level	1st Difference	
	CIPS Test	CIPS Test	Truncated CIPS
Lco2	-3.668		
LTR	-1.261	-1.609	-4.130***
IRE	-1.257	-1.720	-3.349**

Note**:** Significance notation is the same as in Table 3.

Source: (Own elaboration based on STATA 17 software outputs)

5.3 Cointegration Tests

Following the unit root analysis, Pedroni's residual panel cointegration test was implemented to examine the existence of a long-run equilibrium relationship among the variables (Pedroni, 2004). The null hypothesis posits no cointegration against the alternative hypothesis of a cointegrating relationship. The empirical results strongly reject the null hypothesis across the majority of the computed test statistics (Table 6):

Within-dimension statistics reveal that both the Panel PP-Statistic and Panel ADF-Statistic are statistically significant, with p-values of 0.023 and 0.004, respectively, thereby exceeding the critical thresholds at the 5% and 1% levels. This is further validated by the weighted statistics, where both the weighted PP and ADF statistics exhibit high significance (p-values of 0.008 and 0.001, respectively).

Between-dimension (Group) statistics corroborate these findings, as the Group ADF-Statistic is highly significant at the 1% level (p-value = 0.000) and the Group PP-Statistic is significant at the 5% level (p-value = 0.012).

Table 6. *Results of Pedroni Residual Cointegration Test*

Tests	Statistics	Probabilities
Panel v-Staistic	-0.523	0.699
Panel rho-Statistic	-0.277	0.390
Panel PP-Statistic	-1.996**	0.023
Panel ADF-Statistic	-2.587***	0.004
Group rho- Statistic	1.011	0.844
Group PP- Statistic	-2.234**	0.012
Group ADF- Statistic	-3.269***	0.000

Note: Significance notation is the same as in Table 3

Source: (Own elaboration based on STATA 17 software outputs)

Conclusively, since the most robust measures, specifically the ADF and PP-based panel and group statistics, consistently reject the null hypothesis, we confirm the presence of a stable, long-run cointegrating equilibrium among carbon dioxide emissions, renewable energy consumption, and trade openness across the sampled economies.

5.4 Model estimation

Table 7. *PMG Regression*

Depedent varaiables LCO2	Coeff.	Std-Error	T-Statistic	Prob.
Long run equation				
LRE	0.002	0.001	1.502	0.137
LTR	0.203	0.020	9.814	0.000
C	0.502	0.164	3.056	0.003
Short run equation				
COINTEQ	- 0.737	0.152	-4.830	0.000

Source: Own elaboration based on STATA 17 software outputs

To verify the validity of the long-run homogeneity restrictions and to select the most appropriate econometric technique, the PMG Hausman Specification Test was executed, comparing the Pooled Mean Group (PMG) estimator against both the Mean Group (MG) and Dynamic Fixed Effects (DFE) estimators. The empirical test results presented in Table 8 reveal the following insights:

- PMG vs. MG Comparison (Table 8): The joint Hausman test statistic records a p-value of 0.9806. Since this probability value is substantially above the conventional 5% statistical threshold ($p > 0.05$), we fail to reject the null hypothesis (H0). This indicates that the long-run homogeneity constraint is valid, confirming that the PMG estimator is both consistent and asymptotically efficient relative to the MG alternative.
- PMG vs. DFE Comparison: The corresponding p-value yields 0.1350, which is also statistically insignificant at the 5% level, further reaffirming the robust superiority and

statistical preference of the PMG approach over the DFE specification. Consequently, the empirical outputs generated by the PMG (1,1,1) estimator are formally adopted as the definitive model to explain the long-run equilibrium elasticities and short-run error correction dynamics.

Table 8. *Hausman Test*

Hausman Test

PMG Hausman Specification Test
Null hypothesis: Estimator is statistically similar to the PMG estimator

Estimator	Stat.	DOF	p-Value
Mean Group	0.039256	2	0.9806
Dynamic Fixed Effects	4.004496	2	0.1350

Differences: Mean Group

Coefficient Difference Overview: Mean Group

Variable	MG	PMG	Var(Diff.)	p-Value
LRE	0.007572	0.002631	0.000907	0.8697
LTR	0.279091	0.203253	0.146807	0.8431

Differences: Dynamic Fixed Effects

Coefficient Difference Overview: Dynamic Fixed Effects

Variable	DFE	PMG	Var(Diff.)	p-Value
LRE	-0.012258	0.002631	0.000089	0.1149
LTR	0.004384	0.203253	0.019966	0.1593

Source: Own elaboration based on EVIEWS 13 software outputs

The estimation results of the PMG model reveal the following (Table 7):

- The Error Correction Term (COINTEQ): This parameter represents the most pivotal structural advancement in this empirical specification. Aligning with macroeconomic theory, the adjustment coefficient is negative (-0.7379) and exhibits absolute statistical significance (p-value = 0.0000). This confirms the existence of a robust and rapid self-correcting mechanism, implying that approximately 73.79 % of short-run deviations and systemic shocks are equilibrated annually back toward the steady-state long-run equilibrium path.
- Long-run Pooled Elasticities: Trade Openness (LTR): Trade openness exerts a positive and highly significant long-run impact on carbon emissions at the 1% level, yielding an elasticity coefficient of 0.2032 (p-value = 0.0000, t-stat = 9.81). This robust outcome strongly reinforces the empirical validity of the Pollution Haven Hypothesis across the investigated panel, indicating that trade liberalization tends to attract carbon-intensive activities to the sampled economies.
- Renewable Energy Consumption (LRE): Conversely, renewable energy consumption registers a negligible positive coefficient of 0.0026, remaining statistically insignificant (p-value = 0.1377). This suggests that during the analyzed period, renewable energy infrastructure had not yet scaled sufficiently to induce a meaningful mitigating effect on environmental degradation.

6 CONCLUSION

This study represents a scientific contribution aimed at disentangling the structural dichotomy between economic growth requirements and environmental commitments within a distinct rentier context. The econometric approach originated from an attempt to explore the combined and specific impact of both trade openness and renewable energy consumption on carbon dioxide (CO_2) emission rates, as a dependent variable reflecting the magnitude of environmental degradation. The study sample consisted of a structural synthesis comprising seven Arab countries that blend oil-exporting and developing economies (Algeria, Egypt, Saudi Arabia, the UAE, Qatar, Kuwait, and Oman), covering a time series extending from 2013 to 2023, yielding a balanced panel of 77 observations. To overcome the limitations of traditional econometric tools in accommodating cross-sectional dependence and slope heterogeneity among the studied units, the study relied on second-generation testing methodologies and the Panel Autoregressive Distributed Lag (Panel-ARDL) model, employing the Pooled Mean Group (PMG) estimator.

The empirical applications of the model yielded highly significant outputs on both theoretical and practical levels. The econometric coefficients of the error correction model revealed a negative and highly significant structural adjustment mechanism of -0.737. This result uncovers a high dynamic resilience of the studied economies in absorbing short-run shocks and disequilibrium distortions, as approximately 73.79% of these deviations are corrected annually, swiftly converging back toward the path of stability and long-run equilibrium. In the long run, the pooled estimation elasticities revealed a fundamental paradox: trade openness recorded a positive and highly statistically significant elasticity coefficient at the 1% level, with a value of 0.2032, reflecting a strong direct correlation between trade liberalization and escalating environmental degradation. In contrast, the model yielded a very marginal, positive, and statistically insignificant coefficient for renewable energy consumption at a value of 0.0026. This econometric finding confirms that clean energy investments in the studied countries, despite their institutional and political momentum, did not reach the critical mass or productive threshold during the study period required to exert a genuine and tangible mitigating effect on the overall carbon footprint structure.

The econometric outputs of this study acquire a distinct academic specificity when placed within the comparative analytical framework of contemporary economic and environmental literature, offering a qualitative interpretation that transcends theoretical generalizations:

Divergence from Clean Energy Optimism Literature: The results of this study delineate a methodological departure from the findings of Algarni et al. (2023), Agbakwuru et al. (2024), and Ullah et al. (2024), which collectively agreed that deploying renewable energy sources represents the immediate cornerstone for fostering green growth, reducing carbon emissions, and achieving sustainable development goals. The model demonstrates the insignificance of the renewable energy variable within the Arab country sample. This discrepancy is attributed to the fact that those previous studies were conducted on advanced economies or mixed international panels that have successfully surpassed the foundational stages of green infrastructure. Meanwhile, the sample countries continue to face structural constraints and bottlenecks related to high initial capital intensity and limited carbon pricing efficiency, which partially aligns with the theoretical warnings raised by Owusu & Asumadu-Sarkodie (2016).

Supporting the Pollution Haven Hypothesis over Globalization Optimism: On the other hand, the highly significant positive result for the trade openness variable (0.2032) serves as an empirical refutation of optimistic propositions, such as the thesis by Ullah et al. (2024) applied to the G20, which claims that market liberalization stimulates clean technological spillovers and enhances sustainability. Instead, this study provides strong and explicit empirical support for the findings of Sheikh et al. (2020) in their study on India, suggesting that unregulated integration into global supply chains drives natural resource depletion and environmental degradation. Contextually, this is explained by the sample countries' attempts to diversify their economies away from crude oil exports, which has directed investment flows toward localizing heavy, energy-intensive industries such as petrochemicals, aluminum, cement, and iron and steel. This has triggered a negative "Scale Effect" and structurally validated the "Pollution Haven Hypothesis."

Emphasizing the Role of Governance and Differentiated Regional Contexts: The econometric results intersect with the dynamic frameworks of Nga & Huy (2025) and Balogun et al. (2024), which stipulate the necessity of institutional efficiency and state capacity to internalize the negative externalities of trade. This study substantiates the strategic concept posited by Ullah et al. (2024) that regional integration acts as a dampener or an asymmetric negative moderator in Middle Eastern and African economies compared to Europe and Asia. It is evident that the absence of joint environmental and legislative coordination among Arab oil-exporting countries in the face of cross-border shocks and cross-sectional dependence undermines the capacity of the "Technique Effect" to transform trade openness into a genuine lever for green localization.

7 RECOMMENDATIONS AND FUTURE PERSPECTIVES

Based on the econometric rigor demonstrated by the PMG estimator results, and given the definitive implications of the trade openness coefficients alongside the insignificance of renewable energy, the following strategic recommendations are formulated with strict practicality and seriousness.

1- Transitioning from Quantitative Trade Liberalization to Environmentally Conditional Qualitative Trade Openness

Given the high level of statistical significance regarding the impact of trade openness on exacerbating environmental degradation, policymakers in the sample countries are advised to immediately abandon foreign direct investment attraction policies that solely rely on facilitating quantitative procedures. "Environmental Screening Instruments" must be rigorously imposed on investment flows directed at industrial processing sectors, alongside a prohibition on hosting industrial activities migrating from developed countries to escape their domestic carbon restrictions. Furthermore, future trade agreements must be legally bound to a "Mandatory Green Tech Transfer" clause to ensure the genuine activation of the technique effect.

2- Surmounting the Econometric Insignificance Threshold via Massive and Concentrated Capital Financing

Since renewable energy consumption has not yet attained a structural weight capable of meaningfully reducing emissions, current strategies demand a qualitative financial leap. Governments in Algeria, Egypt, and the Gulf states must not settle for prolonged timelines; rather, they must aggressively accelerate the injection of direct sovereign investments to operate and expand mega-projects (e.g., green hydrogen plants in Oman, the Shagaya complex in Kuwait, the Benban complex in Egypt, and Algeria's 15,000 MW national program). The objective is to propel the share of clean energy in the national mix rapidly beyond the statistical and practical critical threshold point to trigger actual substitution.

3- Rectifying Market Failure through Mandatory Carbon Pricing and Climate Compensation Funds

To counter the rentier structure that facilitates polluting industrial expansion, binding economic instruments must be formulated to ensure the internalization of external pollution costs. Decision-makers are strongly recommended to adopt strict Carbon Pricing Schemes or impose progressive carbon taxes on emission-intensive industries (such as petrochemicals and steel). The revenues from these taxes and fees should be channeled directly into "independent sovereign funds for environmental protection and green innovation support," thereby helping to rein in the negative scale effect resulting from trade expansion.

4- Establishing a Regional Coordinating Council to Manage Cross-Sectional Dependence and Environmental Shocks

Given that diagnostic tests have confirmed the presence of severe and strict cross-sectional dependence among the seven nations at the level of variables and model residuals, isolated and individual environmental policies for each country will remain inadequate and prone to failure due to rebound effects and shared, cross-border shocks. The study recommends the establishment of a "Unified Arab Council for Climate and Environmental Policies" comprising the sample countries. Its mission would be to harmonize environmental legislation and standards for imports and exports, and to exchange clean energy through integrated regional grid networks, thereby preventing negative spillovers caused by intra-regional economic disparities and confronting climate challenges as a unified negotiating and executive bloc.

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