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Decoupling Economic Expansion from Environmental Degradation: A Panel ARDL Analysis of Renewable Energy's Role in Arab MENA Countries

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ABSTRACT

This paper examines how renewable energy usage and economic expansion contribute to environmental deterioration in six Arab countries — Tunisia, Algeria, Morocco, Egypt, Saudi Arabia, and Jordan — within the MENA region over a three-decade period spanning from 1990 to 2020. To reach this objective, we investigate the long-run nexus and short-run dynamic interactions among key variables, including carbon dioxide emissions (CO_2) as an environmental indicator, real gross domestic product (RGDP) as an economic indicator, and renewable energy consumption (REC). This investigation is carried out through a robust econometric approach using the Panel Autoregressive Distributed Lag (PANEL-ARDL) model, with a particular focus on Mean Group (MG) and Pooled Mean Group (PMG) estimators. The econometric analysis reveals the existence of a long-term interconnected equilibrium among the examined variables. Our empirical research elucidates that, over the long term, renewable energy usage considerably mitigates CO_2 emissions, while economic growth substantially increases these emissions. However, in the short term, fluctuations in economic expansion and renewable energy usage appear to have no significant impact on CO_2 emissions. According to these findings, policymakers in the selected Arab countries must accelerate the adoption of green energy technologies to harness their enduring environmental benefits. Additionally, it is crucial to formulate and implement comprehensive strategies that attenuate the deleterious environmental impact of economic growth.

1. INTRODUCTION

In light of the increasing challenges facing the global economy due to severe climate change, and with the conclusion of the activities of the United Nations Climate Change Conference (COP 28) in December 2023 in the UAE, attention has turned to the countries of the Middle East and North Africa (MENA). The main concern is how these countries can strengthen their climate actions and develop a strategic approach to ensuring the successful transformation of the region to clean energy. As reported by the United Nations Framework Convention on Climate Change [1], climate projections for the MENA region anticipate a global temperature rise of approximately 3 to 4 degrees Celsius by the end of the 21st Century. It is already the scarcest source of water region in the world, and rising temperatures are expected to lead to more persistent and severe droughts. It has become evident for the MENA region that the traditional growth model, characterized by excessive reliance on traditional energy resources and the proliferation of greenhouse gas-intensive industries, will pose a significant threat to environmental integrity and threaten the long-term sustainability of economic advancement in the long term. Therefore, decoupling energy consumption demand from greenhouse emissions, specifically carbon dioxide (CO_2) discharge, is the cornerstone of efforts to meet the objectives of the Paris Agreement and decarbonize the world's economy. In this context, by expanding the proportion of renewable energy (RE) usage in their portfolio, MENA nations can significantly reduce their carbon footprint while fostering sustainable economic growth (EG). This green energy transition supports global climate goals and promotes the region's energy security and economic resilience. Following these economic and environmental goals, the MENA countries have been showing a growing interest in sustainable development, including through efforts to change energy consumption patterns. This interest is fostered by (1) a continued increase of the fossil fuel energy demand in the MENA Arab countries, which is expected to nearly double by 2040, particularly for electricity needs [2]. Demographic developments will continue to drive up energy consumption demand until [3]. (2) An overall energy mix is over 98% fossil fuels, including gas, oil, and coal, with a significant portion coming from natural gas [4]. (3) Huge RE endowments. The MENA region has one of the most significant solar energy potentials globally and a substantial wind energy potential, especially in Morocco and Saudi Arabia.

Despite the substantial potential of RE and the increasing acknowledgment of its critical role in addressing environmental degradation globally, only limited empirical examinations have emphasized the substantial influence that RE consumption, besides economic expansion, may play in reducing the aggregate greenhouse emissions for the MENA region in the long term [5-9]. In this context, Albaker et al. [5] investigated the effects of RE and green innovation on carbon emission levels in MENA countries, showing the significant potential of RE to reduce discharge despite having restricted geographical coverage of the Arab MENA region. Also, Charfeddine and Kahia [9] investigated the relationship between RE, financial development, and carbon discharge using panel vector autoregression, focusing on the wider MENA region, including Turkey. However, Omri and Saidi [7] concentrated on the impacts of renewable and non-RE sources on CO_2 discharge, emphasizing the dominant role of fossil energy. Collectively, these studies highlight the need for a more integrated analysis that considers RE as the centerpiece and considers its long-term implications for Arab MENA countries.

Most existing studies have often overlooked assessing the dynamic relationship between CO_2 discharge and RE use per se; instead, several have analyzed the repercussion of fossil energy usage from the perspective of the growth–environment linkage in isolation [10-19]. To fill the current research gap, this study investigates the long-term connection and short-term dynamic interactions linking sustainable energy usage, EG, and environmental degradation across six Arab MENA territories (Algeria, Tunisia, Egypt, Morocco, Jordan, and Saudi Arabia) during the period 1990 – 2020. The primary objective is to assess how RE adoption and economic expansion affect environmental quality. This investigation uses a robust econometric analysis using the Panel Autoregressive Distributed Lag (PANEL-ARDL) model, focusing on MG and PMG estimators. Therefore, our study aims to enhance the existing body of empirical studies on the connection between RE consumption, EG, and environmental degradation and seeks to provide significant policy implications, especially since decoupling energy consumption demand from greenhouse emissions is an indispensable condition for Arab MENA countries to attain their long-run sustainable development.

The remaining study sections have the following structure. We begin in Section 2 with a comprehensive exploration of current studies on the substantial consequences of green energy use and economic expansion on environmental quality, explicitly focusing on the MENA territories. Next, Section 3 outlines the estimating process, model, and data. Subsequently, in Section 4, we present a detailed breakdown of our empirical findings. Finally, Section 5 concludes with MENA economic reality-based policy recommendations.

2. LITERATURE REVIEW

A substantial corpus of previous research has studied the interactions tying environmental degradation and EG but has ignored the potential influence of green energy use on these interactions. Therefore, such neglect may cause misleading results for some countries in the MENA region, mainly where a series of economic and environmental reforms can induce some permanent structural changes in their sustainable development in the long run. Before developing our predetermined expectations regarding these variables into a cohesive framework, we scrutinize the bilateral interconnection between environmental pollution, RE use, and economic expansion separately.

2.1 The economic growth-environmental pollution nexus

The research investigations exploring the interaction between pollutant emissions (CO_2) and EG in the MENA area remain a contention between researchers. On the one hand, numerous empirical research studies have suggested that EG often enhances the mitigation of CO_2 emissions, which are key indicators of environmental pollution in the MENA region. Among these studies, Ben Cheikh and Ben Zaied [20] carried out one noteworthy research using a nonlinear panel threshold regression framework to reexamine the dynamic interplay between CO_2 pollutant emissions and per capita income in the MENA region. Their results reveal a threshold effect in carbon dioxide evolution, indicating that the influence of income growth follows a nonlinear pattern and is influenced by various energy-related factors. Similarly, to explore the dynamic interactions between economic expansion, energy transition, and technological level in 21 MENA countries from 1997 to 2021, Alariqi et al. [21] applied a Vector Error Correction model (VEC)for the short-run analysis and the ARDL model for the long-run analysis. The authors indicated that as MENA countries experience EG, they tend to direct resources toward environmentally friendly technologies and sustainable practices, which helps minimize pollutant (CO_2) emissions. Omri et al. [22] explored the main factors influencing the CO_2 output for 16 countries in the MENA region between 1990 and 2018. Their study emphasized the capacity of economic development and energy use to influence the dynamics of CO_2 emissions. For this objective, the authors decomposed the economy into a triad of core components: industry, services, and agriculture. The aggregate traditional energy demand was divided into fossil and green energy sources. The authors applied an econometric tool represented by the Augmented Mena Group (AMG) and the Common Correlated Effect Mean Group (CCE-MG). Their empirical findings suggest that a structural shift towards a RE-based economy, driven by EG, can significantly reduce CO_2 emissions.

However, some empirical investigations have indicated a direct interdependence between economic expansion and CO_2 emissions; environmental quality continues to degrade with rising per capita income. in the MENA area. In this context, we can reference the research conducted by Alshehry and Belloumi [23] for 17 MENA countries to examine the asymmetric and symmetric effects of traditional energy use and economic expansion on aggregate CO_2 emissions from 1990 to 2020. To this end, the authors applied a panel linear and nonlinear ARDL estimation approach. They concluded that expanding economic activities in the MENA nations may result in environmental degradation through increased CO_2 discharge in the long term. Meanwhile, increasing energy demand could increase CO_2 emissions in the short-run and long-run.

Additionally, Omri and Saidi [7] assessed the impacts of fossil fuel and green energy sources on CO_2 flows across 14 MENA countries between 1990 and 2019, using vector error correction and fully modified least-squares techniques. Their analysis revealed that fossil energy usage significantly increases CO_2 discharge, while green energy sources have a mitigating effect. However, the overall effect of EG remained detrimental to environmental quality.

To examine the potential impact of excessive usage of traditional energy, urban growth, and economic development on the increase of CO_2 output in Belt and Road countries from 1985 to 2017, Liu et al. [24] applied some econometric techniques, including a panel cointegration approach, Granger causality tests, and heterogeneity analysis. According to their findings, the main factors that negatively affect CO_2 emissions are the increasing use of traditional energy, the expansion of the economy, and the spread of urbanization. Furthermore, according to the panel causality study, their energy usage, GDP growth, urbanization, and CO_2 emissions are all positively correlated.

In the same context, Fodha and Zaghdoud [25] examined the pollutant emissions of Tunisia's economy from 1961 to 2004 with the EG nexus. Employing Johansen's cointegration analysis, the study is conducted regarding the environmental Kuznets curve theory, with CO_2 emission and GDP serving as the environmental and economic indicators, respectively. The findings demonstrated that, over time, the connection between GDP and CO_2 emissions is monotonically growing. In addition, the causality test findings showed that the link between pollution and income in the Tunisian economy is one-way, with income changing the environment and not the other way around.

Several factors explain the apparent contradictions in the literature. The different econometric estimations (such as panel data, time series analysis, or econometric methods such as ARDL and EKC models) often yield different results. Moreover, sample selection variations greatly influence findings; studies of developed nations often find a decoupling effect between EG and emissions, while studies of developing countries frequently report a positive correlation. Also, temporal differences are essential, with the effects of green technologies and policy reforms more likely to be captured in recent studies than in earlier studies. Understanding how economic development and environmental degradation are related across different settings requires the analysis of these patterns.

2.2 The renewable energy consumption-environmental pollution nexus

The literature reveals a complex and multifaceted interrelation between sustainable energy use and environmental pollution in the MENA area. While some studies indicate that green energy consumption can indeed contribute to diminishing CO_2 output pollution, others suggest that, under specific conditions, its adoption may not always translate into environmental improvement. For this instance, Adun et al. [26] ran a scenario study in Algeria, Morocco, Tunisia, Egypt, and Libya using the Energy-PLAN simulation environment to assess the hourly feasibility of clean energy generation for power and freshwater production through desalination. Their research showed that increasing the RE share to 52% in Morocco by 2030 could lead to a 52.09% reduction in carbon emissions. Their empirical result highlights how RE may greatly enhance environmental quality, especially with technological advances.

Al-Ayouty [27] studied 18 MENA nations plus Turkey to scrutinize the interconnection between economic complexity and pollutant emissions from 1990 to 2020. The author employed panel data econometric techniques based on the Fully Modified Ordinary Least Squares (FMLOS) and Granger causality tests. The estimation findings indicated that green energy adoption demonstrates a substantial inverse relationship with CO_2 output, suggesting a significant amelioration in environmental quality. In addition, the econometric estimations validate the Environmental Kuznets Curve concept across the MENA and Turkey. This study's key policy implication is that Turkey should acknowledge the need to pair EG and industrialization with a shift from traditional to knowledge-based economies. Albaker et al. [5] analyzed the effects of shifting to sustainable energy on EG and the emission of greenhouse gases in the MENA region between 1997 and 2021. Advanced econometric techniques (e.g., Method of Moments Quantile Regression) were used. They concluded that RE use adds significantly to economic expansion and reduces CO_2 emissions, implying more investment in renewable technologies.

Alharthi et al. [28] investigated the main factors of CO_2 evolution in MENA countries that adopted empirical aspects of the EKC structure by employing econometric quantile techniques, using data set from 1990-2015 on real per capita income, CO_2 emissions, fossil and green energy sources, and urbanization. The results of their study demonstrated that carbon discharge decreases drastically with the use of sustainable energy, which is observed to be more effective at higher quantiles. This means, in turn, that an expansion in the size and overall real income of economies makes sustainable energy relatively more effective at reducing environmental harm.

On the other hand, some other research reveals that RE consumption may not always translate into environmental improvement. In this context, we can mention the study by Kahia et al. [10] for 24 countries in the MENA area from 1980 to 2012 to analyze the potential impact of sustainable energy use on CO_2 evolution, EG, and financial development. To do so, the authors used the Panel Vector autoregression technique. Their findings revealed that RE use had little influence, indicating that these nations' energy sectors are immature. The results also showed that the examined countries should strengthen the RE industry by facilitating bank loans for green energy project investments to prevent environmental harm and boost EG.

Similarly, in their study, Bélaïd and Youssef [29] applied the ARDL cointegration technique to analyze the correlation between CO_2 emissions and renewable electricity usage in Algeria from 1980 to 2012. Their econometric findings indicate that renewable electricity usage shows no statistically significant effect on CO_2 emissions in the short or long term. However, their empirical results indicate that the utilization of renewable power has a Granger-causal relationship with long-term CO_2 emissions. Lin and Abudu [30] analyzed energy-saving and substitution policies and plans to lower CO_2 output in the electricity sector in the MENA region. Using data from 2000 to 2015, they found that RE intensity is too low to reduce CO_2 discharge effectively.

Moreover, non-renewable energy intensity remains high, contributing to poor energy efficiency at just 40%.

Consequently, current production methods and policies, like subsidies for non-renewable energy, block significant CO_2 reduction. Thus, the region's EG is tied to non-renewable energy use, meaning that cleaner energy and climate goals need substantial policy and technology changes.

2.3 The economic growth-renewable energy consumption nexus

The EG-RE consumption nexus has secured substantial attention in the literature due to its implications for sustainable development and policy planning. In this context, using panel data techniques, Bhattacharya et al. [31] examined the interconnection between RE usage and EG across 38 countries from 1991 to 2012. The estimation findings demonstrated a positive long-term elasticity between RE investments and EG in more than half of the sample, underscoring the global significance of RE in promoting sustainable development. In the same regard, Kayesh and Siddiqa [32] also examined the dynamic associations between RE consumption, natural gas consumption, and EG in Bangladesh from 1980 to 2018. The authors used a combination of the Autoregressive Distributed Lag (ARDL) model for long-term relationship analysis and the Vector Error Correction Model (VECM) for causal inference. Their results revealed a unidirectional long-run causality from RE usage to EG, indicating the key role in achieving Bangladesh's sustainable development goals. In their work, Yildirim et al. [33] explored the U.S. economy's RE consumption–EG nexus over a six-decade period from 1949 to 2010 using bootstrap-corrected and Toda-Yamamoto causality tests. Their empirical result indicated that while biomass-waste-derived energy positively influences GDP, other renewable sources exhibit weaker economic ties.

Similarly, Ocal and Aslan [34] examined the connection between RE consumption and EG in Turkey from 1990 to 2010, using ARDL bounds testing and Toda-Yamamoto causality. Their econometric results provided evidence from Turkey supporting the conservation hypothesis, which suggests that EG drives RE consumption rather than the reverse. These findings show that EG and RE consumption interact in a complex and context-specific manner and highlight the necessity of local and targeted energy policies.

Our review of the literature on the renewable energy-environmental pollution nexus in the MENA region shows that most studies focus on the growth-environment link in isolation, overlooking the dynamic relationship between renewable energy (RE) adoption and pollution. This gap limits understanding of how RE adoption and economic growth affect carbon emissions, especially in the MENA region, where RE sectors are still developing, and economic structures vary significantly. Addressing this relationship is crucial to identifying feedback mechanisms and guiding policy. By analyzing these dynamics, policymakers can better promote economic growth and environmental sustainability, while future research can provide stronger empirical evidence to improve models and predict the long-term effects of green energy transitions. Our study aims to fill this gap and offer actionable policy recommendations for the MENA region.

3. ESTIMATION TECHNIQUES

3.1 Methodology

Our current study analyses the long-term and short-term repercussions of green energy use and economic expansion on environmental pollution across six Arab MENA territories. The study covers four countries in North Africa: Tunisia, Algeria, Morocco, and Egypt, as well as two countries in the Middle East: Saudi Arabia and Jordan. To reach the main objective of our study, we have a panel-ARDL estimation technique.

The choice of the PANEL-ARDL model in this study is driven by its suitability for analyzing datasets with mixed integration orders, accommodating variables that are integrated of order I(0) and I(1). This feature ensures robustness when estimating both short- and long-term relationships among RE consumption, EG, and CO_2 discharge. The model's dynamic framework is particularly advantageous for capturing the long-run equilibrium alongside short-run fluctuations, which coincides substantially with the study's objective of examining the interconnections between economic and environmental factors. Furthermore, using Mean Group (MG) and Pooled Mean Group (PMG) estimators enhances the model's flexibility by addressing heterogeneity across countries while providing efficient estimates of long-run coefficients. Also, several assumptions of the PANEL-ARDL model are tested to validate our approach's reliability. Cross-sectional independence is assessed using Pesaran's CD test, slope homogeneity is examined via Pesaran and Yamagata's slope homogeneity test, and stationarity and cointegration properties are verified through second-generation unit root and cointegration tests.

As a first step, we utilize the CD test developed by Pesaran [35] to test the hypothesis of cross-section dependence (CSD) in residuals. Also, three other tests are applied to investigate the presence of CDS in both fixed and random effects panel models: the Pesaran scaled LM test, the Breusch-Pagan LM test, and the Bias-corrected scaled LM test, which helps in identifying hidden correlations among the panel units. These tests are essential when the analyzed data are panel data that may exhibit cross-sectional dependencies due to standard economic or environmental policies that may impact the countries. Treating cross-sectional dependence (CSD) is indispensable in establishing panel data reliability. The omission of CSD generates inconsistent parameter estimates and invalid inference procedures, as unaccounted for cross-unit interactions through common factors and spatial spillovers violate the fundamental assumption of cross-sectional independence. By employing appropriate CSD diagnostic tests and robust estimation procedures, we obtain consistent and asymptotically efficient parameters reflecting true cross-country economic relationships while controlling for spatial dependencies. Furthermore, to address heterogeneity across the individual units, our model includes fixed and random effects to obtain more accurate findings that reflect the specific characteristics of each country. The following econometric model describes this approach:

$$lnCO_{2it} = B_{1i}lnRGDP_{it} + B_{2i}lnREC_{it} + \mu_{it} \tag{1}$$

$$\begin{gathered} \mu_{it} = \alpha_i + \lambda_i f_t + \varepsilon_{it} \\ i = 1, 2, \ldots, 6 \; and \; t = 1, 2, \ldots, 30 \end{gathered} \tag{2}$$

where, $lnCO_2$ represents the logarithm of CO_2 emissions, lnRGDP denotes the logarithm of the real gross domestic product, and lnREC represents the logarithm of RE consumption. The term μ_{it} Encompasses three components:

α_i, representing time-invariant heterogeneity across the countries; $\lambda_i f_t$, an unobserved com factor yet exhibits heterogeneous loadings, thus addressing time-variant heterogeneity and facilitating the representation of Cross-Section Dependence (CSD); and ε_{it} is the stochastic error term. The letters (*i*) and (*t*) represent the respective countries and year intervals.

The CSD is the primary concern in the context of panel data. Therefore, to address this problem, we utilize the CD test statistic formulated by Pesaran [35], which is given as:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \tag{3}$$

The bias-adjusted of error cross-section independence LM test is:

$$LM^* = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right)\frac{(T-K)\hat{\rho}_{ij}{}^2 - E\left[(T-K)\hat{\rho}_{ij}{}^2\right]}{VAR\left[(T-K)\hat{\rho}_{ij}{}^2\right]} \tag{4}$$

where, $\hat{\rho}_{ij}$ symbolizes the sample-derived estimate of the pairwise residual correlations, determined through Ordinary Least Squares estimation. In the second step, we use the slope homogeneity test introduced by Pesaran and Yamagata [36]. Finally, in the third step, we analyze the stationarity of panel model variables to identify the variables' order of integration by applying two kinds of panel unit root tests: the Cross-Sectional, Pesaran, and Shin (CIPS) test and the Cross-Sectional Augmented Dickey-Fuller (CADF) test [37].

3.2 Model representation

The panel-based ARDL framework is a dynamic analysis regression tool that provides some estimated equations between endogenous and exogenous variables in the short and long run. This model effectively addresses the endogeneity problem by incorporating the autoregressive lags of the endogenous variables in the analysis of short-run fluctuations. Furthermore, the panel ARDL model accommodates homogeneity and heterogeneity in slope coefficients across different panel units, enhancing its versatility in empirical analysis. Furthermore, the panel ARDL framework can be integrated with a Vector Error Correction Model (VCEM) to illustrate and distinguish short-run dynamics from long-run equilibrium adjustments [38].

As outlined in the methodology section, we presented the baseline model employed in this study, which assesses the effect of RE consumption (lnREC) and EG (lnRGDP) on environmental pollution emissions ($\ln CO_2$). This model is given by Eq. (1).

According to Pesaran et al. [39], the ARDL framework can be formulated by the following equation:

$$Y_{it} = \sum_{j=1}^{p}\lambda_{ij}Y_{i,t-j} + \sum_{j=0}^{q}\sigma_{ij}X_{i,t-j} + \mu_i + u_{ij} \tag{5}$$

where, Y_{it} stands for the endogenous variable ($\ln CO_2$) for country i at time t; $\sigma_{ij}X_{i,t-j}$ denotes the vector of all exogenous variables (lnREC and lnRGDP). μ_i accounts for the fixed effects, capturing the unobserved characteristics of individual cross-sectional units. The parameters (p) and (q) refer to the respective number lags for the endogenous and exogenous variables.

The model outlined in Eq. (5) can be reformulated into the VEC system, allowing for the estimation of both long-term equilibrium connections and short-term adjustments, as shown below:

$$\Delta Y_{it} = \emptyset_i\left(Y_{i,t-j} - \beta_i X_{it}\right) + \sum_{j=1}^{p-1}\lambda_{ij}^{*}\Delta Y_{i,t-j} + \sum_{j=0}^{q-1}\sigma_{ij}^{*}\Delta X_{i,t-j} + \mu_i + u_{ij} \tag{6}$$

where,

$$\Delta Y_{it} = (Y_{it} - Y_{i,t-1})$$

$$\emptyset_i = -(1 - \sum_{j=1}^{p}\lambda_{ij}\Delta Y_{i,t-j})$$

$$\beta_i = \sum_{j=0}^{q}\sigma_{ij}$$

$$\lambda_{ij}^{*} = \sum_{m=j+1}^{p}\lambda_{im} \; and \; \sigma_{ij}^{*} = \sum_{m=j+1}^{q}\sigma_{im}$$

3.3 Data

This research covered six Arab countries from North Africa and the Middle East: Tunisia, Algeria, Morocco, Egypt, Saudi Arabia, and Jordan. The chosen variables of the model are illustrated in Table 1.

Table 1. Description and sources of variables

Variables	Description	Units	Sources
CO_2	Carbon dioxide emissions	Kilotons	WDI
REC	Renewable energy consumption	Percentage of aggregate energy consumption	WDI
RGDP	Real gross domestic product	GDP (2015 Constant US$ Billions)	WDI

We applied logarithmic transformations of variables to linearize relationships and appropriately address nonlinear interaction. This approach allows us to use linear modelling techniques to explore the complex dynamics nexus between variables. The World Bank's World Development Indicators (WDI) dataset was the source of all data. Carbon dioxide emissions (CO_2) are used as an environmental indicator expressed in kilotons (kt), while the gross domestic product (RGDP) is an economic indicator expressed in US$ billions at 2015 constant prices. RE consumption (REC) is measured as a proportion of the aggregate energy consumption. Table 1 presents a concise overview of all variables incorporated in our study.

In our empirical study, we have used annual data covering the period from 1990 to 2020, resulting in a balanced panel with a sample size of $N = 186$. This includes six cross-sectional units (n = 6) and 31 time series observations per unit (t = 31).

Our descriptive statistical analysis, detailed in Table 2, shows that mean carbon dioxide emissions are 117,410.8 kilotons, with high variability (skewness: 1.81) indicating a right-skewed distribution dominated by lower emitters. RE consumption averages 6.59%, peaking at 22.97%, highlighting overall low adoption but notable progress in some countries. A negative skew in the logarithmic transformation of RE consumption suggests that reliance on non-renewable sources persists. A strong negative correlation (-0.98) between EG and carbon emissions suggests improved energy efficiency with growth. However, a moderate positive correlation (0.51) between RE usage and emissions may reflect the energy demands of building renewable infrastructure.

The normality results given by the Jarque-Bera test show that all our variables are significant at 1%, indicating that they are not normal distributions.

4. EMPIRICAL RESULTS

Our econometric analysis aims to explore how EG and RE use influence environmental pollution across a selection of Arab nations. In line with this objective, the initial step involved testing the hypothesis that all variables exhibit cross-section dependence. Then, in the second step, we examined the time series stationarity and determined the integration order of each variable in our study. The third step involves investigating a long-run cointegrated connection among the selected variables. In the fourth and final step, we applied two estimators: the MG estimator, formulated by Pesaran and Smith [40], and the PMG estimator, introduced by Pesaran [41].

4.1 Testing cross-sectional dependencies and slope homogeneity

The study employed several tests for cross-sectional dependence to detect possible dependencies among cross-sections. These include the formulae formulated by Pesaran [35], the Bias-corrected scaled LM test, the Breusch-Pagan LM test and the Pesaran scaled LM test. The null hypothesis of all these tests assumes cross-sectional independence. Table 3 summarizes the test results. We can notice that at a 1% significance level, the findings indicate that all variables in the Panel significantly rejected the null hypothesis. The test results substantiate the cross-sectional dependence among all variables, suggesting that the data exhibit interdependencies across various panel units.

Table 4 provides the Pesaran [41] proposed cross-sectional dependence test findings. It indicates that the null hypothesis of cross-sectional independence is statistically rejected at the 5% level and 1% significance levels for the fixed and random effect models, respectively. Furthermore, the adjusted LM test for cross-sectional dependence is significant at the 1% level for both the fixed effect (FE) and ransom effect (RE) models.

Table 2. Descriptive statistics overview

Variables	CO_2	REC	RGDP	$lnCO_2$	lnREC	lnRGDP
Mean	117410.8	6.59	161.31	11.10	0.45	4.53
Median	66574.00	5.27	94.52	11.10	1.66	4.54
Maximum	565190.1	22.97	709.60	13.24	3.13	6.56
Minimum	9781.200	0.01	11.60	9.19	-4.60	2.45
Std. Dev.	131962.5	6.30	171.29	1.09	2.55	1.08
Skewness	1.811829	0.48	1.55	0.21	-0.93	0.08
Kurtosis	5.852705	1.84	4.70	1.88	2.45	1.98
Jarque-Bera	164.83***	17.49***	97.07***	11.16***	29.45***	8.16**
CO_2 correlation	1.00	0.51***	-0.98***	/	/	/
Sum	21838402	1226.20	30003.81	2064.59	83.34	843.64
Observations	186	186	186	186	186	186

Note: The symbols (***), (**) and (*) indicate the statistical thresholds of 0.01, 0.05, and 0.1 in succession

Table 3. Cross-sectional dependence tests

Test	Df	$lnCO_2$	lnREC	lnRGDP
Pesaran scaled LM		77.19***	26.25***	79.15***
Breusch-Pagan LM	15	437.80***	158.79***	448.52***
Bias-corrected scaled LM		77.09***	26.15***	79.05***
Pesaran CD		20.92***	3.80***	21.17***

Note: The symbols (***), (**), and (*) indicate hypothesis H_0: Cross-sectional independence is not accepted at statistical thresholds of 0.01, 0.05, and 0.1 in succession

Table 4. Model comparisons for cross-sectional dependence

Model	Pesaran CD test		Adjusted LM CD test	
	Z-stat	P-value	Chisq-stat	P-value
FE model	-2.44**	0.014	80.04***	0.000
RE model	-2.60***	0.009	90.41***	0.000

Note: The symbols (***), (**), and (*) indicate hypothesis H_0: Cross-sectional independence is not accepted at statistical thresholds of 0.01, 0.05, and 0.1 in succession

Table 5. Slope homogeneity test

	Statistic	P-value
$\tilde{\Delta}$	**16.67*** **	**0.000**
$\tilde{\Delta}_{adj}$	**17.86*** **	**0.000**

Note: The symbols (***), (**), and (*) indicate hypothesis H_0: slope homogeneity is not accepted at statistical thresholds of 0.01, 0.05, and 0.1 in succession

In addition, we applied the slope homogeneity test introduced by Pesaran and Yamagata [36].

The results outlined in Table 5 show that the null hypothesis of slope homogeneity is rejected with a significance level of 1% for the statistics. $\tilde{\Delta}$ and $\tilde{\Delta}_{adj}$. Therefore, it is imperative to consider slope heterogeneity and cross-sectional dependence to prevent estimate bias.

4.2 Panel stationarity tests

Given that our empirical findings revealed interdependencies among cross-sections and heterogeneous slopes across the examined variables, we employed an advanced second-generation methodology to assess stationarity. Specifically, we applied the Cross-Sectional Im, Pesaran, and Shin (CIPS) and the Cross-Sectional Augmented Dickey-Fuller (CADF) tests. The results, presented in Table 6, show that the CIPS and CADF tests confirm the presence of a unit root in all panels, indicating that the variables are not stationary at level, except for lnRGDP, which is stationary, as the P-values for both tests are less than 0.01. However, the first-generation unit root test, such as Maddala and Wu's Fisher test [42], reveals that all variables are initially non-stationary but become stationary after first-order differencing. We prioritized the findings of the CIPS test due to the model's cross-sectional dependence. Based on this approach, we conclude that the variables $lnCO_2$ and lnREC are integrated of the first order, I(1), while lnRGDP is I(0).

Table 6. Panel unite root tests

	Level			1st Difference		
	CIPS test	CADF test	Wu ficher test	CIPS test	CADF test	Wu ficher test
$lnCO_2$	-2.43	-2.25	16.72	-5.36***	-3.34***	38.68***
lnREC	-1.91	-1.40	6.28	-5.19***	-3.34***	58.11***
lnRGDP	-3.31***	-3.09***	11.81	-5.07***	-3.39***	28.02***

Note: The symbols (***), (**), and (*) indicate H_0 = all panels contain unit roots is not accepted at statistical thresholds of 0.01, 0.05, and 0.1 in succession

4.3 Cointegration tests

After we identified that the variables display mixed integration orders, ranging from I(0) to I(1), we explored the presence of cointegrated relationships among them. To this end, we employed three cointegration tests: the Pedroni test [43], the Kao test [44], and the Westerlund test [45]. We specifically included the Westerlund test alongside the widely used Pedroni and Kao tests due to its ability to accommodate cross-sectional dependencies, which is crucial for accurate inference in our panel data where such interdependencies are present. The null hypothesis of all these tests posits no long-run cointegrated connection among the variables.

Table 7. Cointegration tests

	Cointegration Test	Statistic	p-value
Pedroni test	Panel ADF-Statistic	-2.65***	0.00
	Group rho-Statistic	-1.65**	0.04
	Group PP-Statistic	-3.70***	0.00
	Panel v-Statistic	2.36***	0.00
	Panel rho-Statistic	-1.96**	0.02
	Panel PP-Statistic	-2.84***	0.00
	Panel v-Statistic	2.36***	0.00
Kao test	ADF	-1.54*	0.06
Westerlund test	Variance ratio	-1.91**	0.02

Note: The symbols (***), (**), and (*) indicate H_0: No cointegrated relationship is rejected at statistical thresholds of 0.01, 0.05, and 0.1 in succession

The cointegration test results are shown in Table 7. The empirical results illustrate the rejection of the null hypothesis at a 1% significance level, approximately for the most applied tests. Exceptions include the ADF statistic of the Kao test, where the null hypothesis is rejected at a 10% level, the variance ratio statistic of the Westerlund test, and the Panel rho-statistic and Group rho-statistic of the Pedroni test, which are significant at the 5% level. The empirical outcomes support the presence of a long-run cointegrated nexus among the variables, indicating a long-term equilibrium and causal connection between RE usage, economic expansion, and CO_2 discharge. The discovery of these enduring connections helps us achieve the goal of this study. It enables us to assess how green energy utilization and economic expansion affect the evolution of CO_2 emissions in the long and short run across this group of six MENA countries.

4.4 Model estimations

After assessing the stationarity results of the panel data series, we found that the variables demonstrate zero-order integration I(0), and first-order integration I(1). Given the different integration orders, we applied the Panel Autoregressive Distributed Lag (ARDL) method, which is suitable for such mixed-order series, to explore the dynamic interaction among the variables. To explore and estimate the effects of RE usage and economic expansion on CO_2 trend emissions, we applied the ARDL model with the configuration ARDL (1,3,3). This model used the Akaike Information Criterion (AIC) and the Schwarz Bayesian Criterion (SBC) as guiding factors. We also included robust estimation methods such as the MG estimator, formulated by Pesaran and Smith [40], and the PMG estimator, introduced by Pesaran [41]. This methodology provides an extensive framework for studying the dynamic interactions between green energy usage, economic expansion, and CO_2 discharge across different groups within the panel data context. The MG estimator in panel data models adapts to heterogeneity across units by allowing for individual-specific effects while assuming homogeneous time-specific effects across all cross-sections. This method involves estimating models for each unit individually and then averaging these estimates to drive the mean group estimating.

However, the PMG estimator is utilized to assess the long-run relationships between the variables. In general, the PMG estimator outperforms the MG estimator in terms of efficiency, provided that the constraints on the long-term coefficient remain valid. It involves averaging and pooling the coefficients whereby homogeneity is imposed on the long-run coefficients across the cross-sections while allowing heterogeneity in the error variance intercepts and short-run coefficients [46].

To determine whether the MG or PMG estimator was more suitable for our panel data model, we based our analysis on the Hausman test. The null hypothesis considers that the PMG estimator, which assumes long-term coefficient homogeneity, is preferable to the MG estimator. In other words, the null hypothesis evaluates the validity of long-term homogeneity restrictions among the countries in our sample. The findings presented in Table 8 show that the null hypothesis could not be upheld, indicating that the MG estimator, which accounts for heterogeneity in both short-run and long-run coefficients, provides a more efficient fit for our data.

Table 8. Panel long and short run coefficients: Mean Group Estimator (MG)

Dependant Variable D ($lnCO_2$)	Coefficients	Std. Error	t-Statistic	P-value
Long-Run Estimated Coefficients				
lnREC	-0.13***	0.02	-3.85	0.00
lnGDP	0.84***	0.10	6.18	0.00
Short-Run Estimated Coefficients				
ECT	-0.40***	0.16	-3.54	0.00
D(lnREC)	-0.13	0.08	-1.53	0.12
D(lnREC (-1))	0.002	0.04	-0.47	0.96
D(lnREC (-2))	-0.09	0.05	-1.66	0.09
D(lnRGDP)	0.17	0.13	1.31	0.19
D(lnRGDP (-1))	0.10	0.20	0.49	0.62
D(lnRGDP (-2))	-0.30	0.21	-1.44	0.15
Constant	3.01***	0.58	5.16	0.00
@TREND	0.00***	0.00	-1.01	0.31
Hausman test-statistics	Statistic 13.80***	P-value 0.00		

Note: The symbols (***), (**) and (*) indicate the statistical thresholds of 0.01, 0.05, and 0.1 in succession

The choice of MG and PMG estimators provides critical insights into the dynamic interactions among RE consumption, EG, and CO_2 emissions. While the PMG estimator assumes homogeneity of long-run coefficients across countries, the MG estimator allows for heterogeneity in both short- and long-run coefficients, which proves more suitable for this study's panel data, which includes countries with diverse economic structures and RE adoption rates. The Mean Group (MG) estimator accommodates parameter heterogeneity across countries, yielding consistent country-specific coefficients that capture individual slope parameters. This estimation approach reveals significant cross-country parameter heterogeneity in the relationships between EG, RE consumption, and environmental indicators. The robust performance of the MG estimator in this context demonstrates its relevance for studies involving heterogeneous panels.

Consequently, the MG estimator is appropriate for analyzing the short-term and long-term interactions between CO_2 emissions, RE usage, and economic expansion in the six Arab countries studied. Table 8 displays the short-run and long-run MG estimator outcomes for the model coefficients. Furthermore, it estimates the error correction term (ECT), which measures the speed at which the variables converge towards their long-term equilibrium. The ECT shows a negative value and reaches statistical significance at 1%, suggesting a fast return to the long-term equilibrium for the variables. This indicates a robust long-run connection between the variables studied. The estimated value of the error correction coefficient is -0.4, suggesting that approximately 40% of any deviation from the long-term equilibrium is corrected in each period. Hence, this significant adjustment speed verifies a stable long-run connection tying CO_2 emissions, RE use, and economic expansion.

We can notice from Table 8 that the long-term coefficients' *P-values* of lnREC and lnRGDP are less than 0.01, which means that these coefficients are statistically acceptable at 1%. The empirical evidence supports a negative long-term link between RE use and pollutant (CO_2) emissions within this group of Arab countries. A 1% rise in RE consumption corresponds to a 0.13% decrease in CO_2 emissions. Additionally, the results demonstrate a robust and significant positive long-term nexus tying CO_2 emissions and EG, where a 1% expansion in EG causes a 0.84% augmentation in CO_2 emissions. However, in the short term, the coefficients of RE consumption and EG lack statistical significance, indicating that short-term fluctuations in these variables do not affect environmental pollution in the examined Arab countries.

5. CONCLUSIONS

The present research examines the repercussions of RE adoption and economic expansion on greenhouse CO_2 emissions in six Arab MENA countries from 1990–2020. By applying the panel ARDL model with MG and PMG estimators, we contextualize the dynamic nexus between RE use, EG, and environmental quality, offering insights to guide policy interventions for achieving carbon-neutral economies.

The key outcomes of our research are as follow:

•A significant negative long-run connection exists between CO_2 emission flows and RE, with a 1% increase in green energy use resulting in approximately a 0.13% reduction in CO_2 emissions. This empirical result confirms the environmental benefits of adopting sustainable energy sources in the Arab MENA.

•Conversely, we observe a positive long-run connection between EG and CO2 emissions, as a 1% rise in GDP results in a 0.84% increase in CO2 emissions. This finding reflects the carbon intensity of economic activity in the sample countries.

•The short-run coefficients for RE consumption and economic expansion in the CO2 emissions equation lack statistical significance at conventional levels, contrasting with the significant long-run parameters, suggesting that long-run dynamics primarily characterize the estimated relationships.

These empirical outcomes align with prior studies and support earlier research conclusions, such as Bhattacharya et al. [31] and Alharthi et al. [28], who also disclosed that green energy has positive environmental implications in the MENA region. Nevertheless, our results differ from those of Jia et al. [8], who stated a less severe effect, which may be attributed to the methodological variation between the two studies. In the same way, the negative effects of economic expansion on environmental pollution highlighted in our research findings correlate with the results highlighted by Alshehry and Belloumi [23] and Zaghdoud [11] to emphasize the environmental problems of economic expansion in some countries within the MENA region.

Our study findings suggest strengthening policies supporting RE projects through incentives and ensuring that environmental goals are incorporated into economic policies through green fiscal and regulatory measures [47, 48]. Furthermore, raising people's consciousness regarding the significance of RE and sustainable measures may also enhance the same policies. Adopting such an approach offers the six Arab countries a tremendous opportunity for profound changes in their development strategies. Thus, through improving the environmental quality and promoting new sources of income and employment, these countries can pursue sustainable economic development and meet the significant ecological challenges.

Our research provides important insights into how green energy consumption and economic expansion influence environmental quality in six Arab nations in the MENA region. Nevertheless, it does have certain limitations. The scope of our research is limited to six countries only, which may not represent the overall MENA region's economic, cultural, and environmental conditions. For example, Morocco and Saudi Arabia have developed RE sectors, whereas other MENA countries are heavily reliant on traditional energy and do not have comprehensive RE policies. This difference highlights the need to design country-specific policy interventions. Policymakers should look at how each country's economy and energy use differ to ensure that plans to use RE and protect the environment work well and fairly for everyone in the area.

The consistency of our estimates may be compromised by measurement error in the underlying data and potential endogeneity due to omitted variable bias, particularly from an unobserved institutional quality and environmental regulatory factors that could violate the zero-conditional-mean assumption of the error terms. Despite formal testing procedures, the cross-sectional independence assumption may not adequately address nuanced spatial dependencies in the panel, potentially affecting both the consistency of estimates and the validity of asymptotic inference.

Although our parameter estimates for six Arab MENA economies provide robust signal of the dynamic associations amongst RE consumption, EG, and environmental indicators, generalizing these empirical findings to the broader MENA region necessitates additional diagnostic testing and parameter stability analysis. Heterogeneity in economic structures and RE implementation frameworks, particularly the advanced industrial composition in Morocco and Saudi Arabia, may limit parameter stability when extending findings to other MENA economies. The estimation framework and derived parameter estimates about RE adoption and policy measures maintain their statistical properties, subject to appropriate controls for country-specific fixed effects. Extending this framework to more MENA countries would enable a deeper understanding of regional dynamics.

Further empirical research could focus on the role of green energy sources with other variables, such as technological innovations and green taxes, to evaluate their long-run effects on pollutant Ms in the MENA region. Such studies would, therefore, shed new light on the complex relationships linking EG, innovative practices, and environmental quality across the MENA territories.

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