JOURNAL OF CULTURAL ANALYSIS AND SOCIAL CHANGE

Journal of Cultural Analysis and Social Change,
2025, 10(4), 1273-1283
ISSN: 2589-1316

Assessing the Effectiveness of the Energy Transition in Reducing CO_2 Emissions: A New Indicator for MENA Countries

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Citation: Nadia, F. (2025). Assessing the Effectiveness of the Energy Transition in Reducing CO_2 Emissions: A New Indicator for MENA Countries. *Journal of Cultural Analysis and Social Change*, *10*(4), 1273–1283. https://doi.org/10.64753/jcasc.v10i4.3012

Published: December 08, 2025

ABSTRACT

This study investigates the effectiveness of the energy transition in reducing CO_2 emissions in six MENA countries (Algeria, Egypt, Kuwait, Qatar, Saudi Arabia, and the United Arab Emirates) over the period 1980–2024. To assess the cleanliness and quality of the energy mix, we employ a novel composite indicator, the Green Quality of Energy Mix (GQEM) (Lau et al., 2023). Annual data are converted into quarterly series and analyzed using advanced econometric techniques, including quantile-on-quantile regression (QonQR), quantile regression (QR), and Kernel Regularized Least Squares (KRLS). The results reveal asymmetric, nonlinear, and heterogeneous relationships between energy transition and CO_2 emissions. North African countries display a stronger negative impact of GQEM on emissions, whereas Gulf economies show unstable effects, reflecting their structural dependence on hydrocarbons. These findings highlight the importance of multidimensional indicators and nonlinear methods to accurately assess the energy transition in heterogeneous economies.

Keywords: Energy transition, CO_2 emissions, MENA, GQEM, QonQR, KRLS

INTRODUCTION

The energy transition has become a critical challenge for reducing CO_2 emissions and addressing climate change, particularly in MENA countries, where economies remain heavily dependent on hydrocarbons (Al-Mulali & Ozturk, 2016; Salahuddin & Gow, 2023). Historically, energy policies in these countries have prioritized industrial expansion and oil production, resulting in high levels of emissions (Charfeddine & Kahia, 2019). However, international climate commitments and the volatility of hydrocarbon prices have emphasized the need to diversify the energy mix and adopt more sustainable solutions (Rehman et al., 2020; Destek, 2023).

Previous studies on the effectiveness of energy transition have often relied on partial indicators, such as energy or carbon intensity, which fail to capture the complexity of interactions between economic structure, energy mix, and institutions (Salahuddin et al., 2018; Saidi & Hammami, 2015; Ben Jebli et al., 2021). Recent research highlights the importance of multidimensional and composite indicators, integrating energy mix quality, institutional capacity, technological innovation, and hydrocarbon dependence (Shahbaz et al., 2022; Kahia et al., 2022; Alola et al., 2021; Balsalobre-Lorente et al., 2022). This study utilizes the *Green Quality of Energy Mix* (GQEM) proposed by Lau et al. (2023), a synthetic indicator capturing the actual cleanliness of national energy mixes. To assess its impact on CO_2 emissions, we apply advanced econometric techniques, including quantile-on-quantile regression (QonQR) (Sim & Zhou, 2015), quantile regression (QR) (Koenker & Bassett, 1978), and nonparametric *Kernel Regularized Least Squares* (KRLS) (Hainmueller & Hazlett, 2014). This methodology allows for a robust and nuanced analysis, capturing nonlinear and asymmetric effects that linear models typically overlook. The article is structured as follows: **Section 2** presents the data and methodology, including the calculation of GQEM and the transformation of annual series into quarterly data; **Section 3** reports the empirical results, robustness checks, and sensitivity analyses for each country; **Section 4** discusses policy and institutional implications in the context of national energy structures; and **Section 5** concludes by summarizing the main findings, limitations, and future research directions, including energy digitalization, climate resilience, and economic diversification.

DATA AND METHODOLOGY

To empirically analyze the impact of the energy transition (ENT) which reflects the shift from fossil-fuel-dependent energy sources toward more sustainable and environmentally friendly alternatives on CO_2 (carbon dioxide) emissions in MENA countries, namely Algeria (ALG), Egypt (EGY), Kuwait (KIW), Qatar (QAT), Saudi Arabia (SDA), and the United Arab Emirates (UAE), we rely on the longest available annual time-series data for selected MENA economies, covering the period 1980–2024. To quantitatively assess the stages of the MENA region's energy transition, we use a newly developed metric: the Green Quality of Energy Mix (GQEM), proposed by Lau et al. (2023). The GQEM measures the cleanliness of a country's energy mix. A higher GQEM score reflects a stronger reliance on cleaner energy sources. We computed annual GQEM values for each MENA country using the following formula developed by Lau et al. (2023):

$$GQEM_{i,t} = \frac{1}{1.0121*\frac{CEC_{i,t}}{TPEC_{i,t}}+0.9513*\frac{OEC_{i,t}}{TPEC_{i,t}}+0.4107\frac{NGEC_{i,t}}{TPEC_{i,t}}} \quad (1)$$

- **CEC**: represents coal energy consumption.
- **OEC**: represents oil energy consumption.
- **NGEC**: represents natural gas energy consumption.
- **TPEC**: represents total primary energy consumption.

Where i represents the nations, namely ALG, EGY, KIW, QAT, SDA, UAE, and t denotes the year from 1980 to 2024. Equation (1) indicates that the calculation of the GQEM index relies on the same energy components (coal, oil, natural gas, and total primary energy consumption) for all countries. These elements are relevant to national energy profiles, enabling a coherent and generalizable assessment of the energy transition despite their heterogeneity. From 2000 to 2025, the nations of the MENA region have achieved significant progress in the development of renewable energy, although these advances vary considerably from one country to another. Countries such as Morocco, Egypt, and the United Arab Emirates have launched significant solar and wind energy projects to diversify their energy supplies and reduce their dependence on fossil fuels. These initiatives are part of a regional objective to address climate, economic, and energy challenges while leveraging the region's substantial solar and wind potential. These advancements provide valuable insights for determining the relationship between energy transition and the environment. Annual data for ALG, EGY, KIW, QAT, SDA, UAE, and CO_2 emissions in the MENA region have been obtained Statistical Review of World Energy (https://www.energyinst.org/statistical-review/home). Figure 1 illustrates the annual trends of CO_2 (Panel A) and the ENT data series calculated over the period 1980–2024. Panel A shows the progression of CO_2 emissions (in million tons) in six MENA and Gulf nations: Algeria (ALG), Egypt (EGY), Kuwait (KIW), Qatar (QAT), Saudi Arabia (SDA), and the United Arab Emirates (UAE). The analysis of the data highlights divergent dynamics across the countries. Saudi Arabia stands out with considerably higher emission levels compared to the other nations.

This trend primarily stems from a marked dependence on fossil fuels, driven by an economic expansion based largely on petroleum extraction. It is nevertheless noteworthy that a temporary slowdown appears around 2015, which may be attributable to energy-efficiency initiatives or to cyclical economic fluctuations. The United Arab Emirates (UAE) rank second, exhibiting a substantial rise in emissions—particularly after the year 2000—reflecting rapid industrialization and intensive energy use. Similarly, Algeria and Egypt display a persistent upward trajectory in their emissions. While Egypt maintains a moderate growth path, Algeria shows a pronounced acceleration after 2010, likely associated with rising industrial output and expanding energy production. By contrast, Qatar and Kuwait exhibit lower emission levels in absolute terms, despite their status as hydrocarbon-producing economies. This outcome can be attributed to their relatively small populations and, to a lesser extent, to more targeted energy policies. Overall, these findings reflect the region's persistent dependence on fossil fuels, although some countries display signs of stabilization or deceleration. This evolution underscores the need to intensify efforts toward energy transition and economic diversification in the broader context of global climate-change mitigation. The diagram presented in Panel B: *Energy Transition* illustrates the evolution of the CQEM indicator over the period 1980–2024 for a group of six MENA countries—Algeria (ALG), Egypt (EGY), Kuwait (KIW), Qatar (QAT), Saudi Arabia (SDA), and the United Arab Emirates (UAE). This index, which reflects the quality or composition of the energy mix, provides an assessment of each nation's progress toward an energy transition. The examination of the curves reveals heterogeneous dynamics across countries. The United Arab Emirates, Saudi Arabia, and, to some extent, Algeria display relatively high CQEM levels throughout the study period, suggesting stronger commitments to energy-mix diversification and the adoption of renewable energy sources. These countries appear to have implemented gradual structural reforms, particularly since the 2000s, with a marked intensification between 2015 and 2024. This acceleration coincides with the expansion of global climate ambitions and the development of national sustainable-development strategies. Conversely, Kuwait, Qatar, and Egypt exhibit lower CQEM values, indicating a continued reliance on fossil fuels and slower progress in deploying substitution and low-carbon strategies. Nevertheless, since 2010, all countries in the sample show a slight upward trend, which may reflect a combination of international climate commitments, economic pressures stemming from oil-price volatility, and a growing interest in securing long-term energy stability. Overall, these findings point to a gradual yet uneven trajectory of energy transition across the MENA region. They highlight the leading role played by key Gulf economies—such as the United Arab Emirates and Saudi Arabia—in reshaping the regional energy landscape, even as significant challenges remain in achieving a more harmonized and balanced energy framework among countries. We evaluated the quarterly figures derived from the annual data calculated and collected for GQEM and CO_2 emissions, respectively, by applying the squared-cumulative transformation to obtain a sufficiently large sample for empirical analysis, in line with recent studies (see, for example, Afshan et al., 2023; Chen et al., 2023; Lee et al., 2023; Saqib et al., 2023). The estimated quarterly series is subsequently converted into a differenced logarithmic form (Ln I (1)) to account for non-stationarity (see Appendix Table 1). The quarterly Ln I (1) data are reported in Table 1. The statistical examination of CO_2 emissions (Panel A) and the variables derived from the GQEM model reveals a pronounced deviation from normality across all countries, as evidenced by the consistently significant Jarque–Bera test statistics. However, notable differences emerge between hydrocarbon-exporting and hydrocarbon-importing economies. Exporting countries such as Qatar and the United Arab Emirates exhibit distributions characterized by considerable skewness and extreme kurtosis values, reflecting exceptional volatility driven by their direct exposure to global energy market fluctuations. In contrast, Egypt and, to a lesser extent, Kuwait—although not immune to shocks—display lower means and comparatively less extreme distributional shapes, suggesting a more stable dynamic, albeit still marked by persistent non-normality. Algeria and Saudi Arabia fall into an intermediate position, with strongly skewed and leptokurtic series, indicative of their sensitivity to both external and internal shocks.

Overall, these results highlight the structural instability of CO_2 emissions in the region, amplified by the economic characteristics of the countries under study, where oil and gas rents remain decisive in shaping environmental and economic trajectories. To further validate the evidence from kurtosis and the Jarque–Bera statistics, we plot the quantile–quantile (QQ) diagrams of the quarterly Ln I (1) series (see Figure 2). These plots also demonstrate that the CO_2 emissions and GQEM series follow a non-normal distribution with noticeably heavier tails.

In this study, we assess the potential nonlinearity of the quarterly Ln I (1) series using the BDS test developed by Broock, Dechert, Scheinkman, and LeBaron (1996), in line with recent empirical contributions (Adebayo et al., 2022; Ojonugwa et al., 2023; Ozcan et al., 2023). The BDS test results presented in Table 2 clearly indicate that all data series related to CO_2 emissions and GQEM exhibit nonlinear behavior over the sample period. Indeed, the null hypothesis of linearity is consistently rejected at the 1% and 5% significance levels. The deviation from normality—evidenced by heavy tails and the nonlinear structure of the Ln I (1) series for CO_2 emissions and GQEM—highlights the need for a robust econometric framework capable of capturing the full distributional dynamics rather than focusing solely on mean effects. To address this, we employ the quantile-on-quantile regression (QonQR) technique introduced by Sim and Zhou (2015). This method considers the entire distribution of both the dependent and explanatory variables by modeling the relationships across their respective quantiles. QonQR enables us to examine not only the average effect of GQEM on CO_2 emissions but also the variation in this relationship across different levels of GQEM and CO_2 emissions. In this study, the effect of GQEM quantiles on the quantiles of CO_2 emissions for MENA countries is estimated using the QonQR approach as follows:

$$\varphi_{r,\theta}\left(\frac{CO2_i}{GQEM_i}\right) = \alpha_0(r,\theta) + \alpha_1(r,\theta)GQEM_i \quad (2)$$

Where the constant and slope parameters are respectively denoted by $\alpha_0(r,\theta)$ et $\alpha_1(r,\theta)$, with ϑ- iéme quantile of ENT and τ-iéme quantile of $CO2$ emissions. Equation (2) presents a model that examines the influence of different GQEM levels on various CO_2 concentration ranges for all MENA countries. Following Lau et al. (2023), this study advances the hypothesis that an increase in GQEM may enhance environmental quality in MENA countries by reducing their CO_2 emissions. We assess the robustness of the obtained results using several complementary methods. To validate the coefficients derived from the QonQR analysis, we apply the quantile regression (QR) method introduced by Koenker and Bassett (1978). We then compare these coefficients with the average QonQR estimates reported by Pavel and Polina (2024) and Zhang et al. (2024). The following equation is employed to compute the QR coefficients:

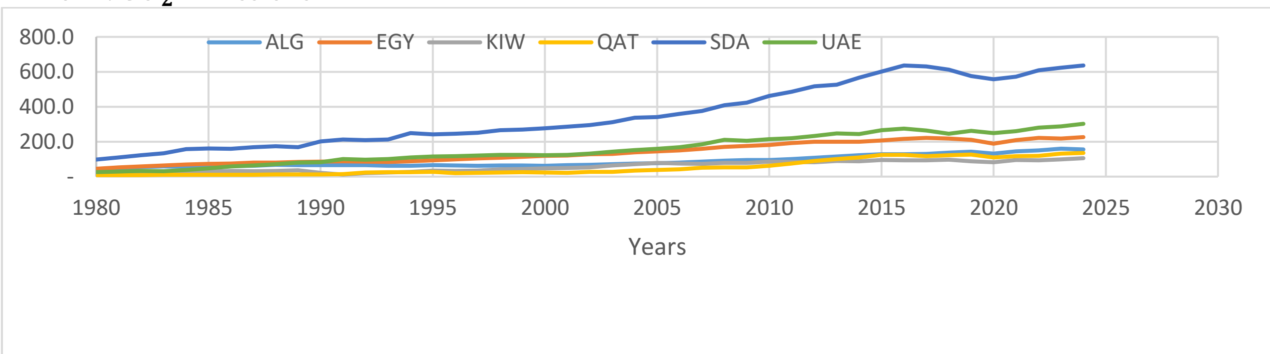
$$Q_r\left(\frac{CO2_i}{GQEM_i}\right) = \alpha_0(r) + \alpha_1(r)GQEM_i \quad (3)$$

It should be specified that when comparing the QR with the QonQR, we are referring to the estimated slope parameter. $\alpha_1(r,\theta)$ Of the QR with the mean of the estimated slope parameter and $\alpha_0(r)$, by examining the quantile trends of these estimates (Fig.5). The Pearson, Kendall, and Spearman correlations among these variables are presented in Table 3. To further investigate the QonQR results, we also employ the Kernel Regularized Least Squares (KRLS) machine learning method developed by Hainmueller and Hazlett (2014) and implemented by Ferwerda et al. (2017), while taking into account recent studies (Alola et al., 2023; Özkan et al., 2023). KRLS is a flexible, non-parametric machine learning approach that uncovers complex and nonlinear relationships between variables, often overlooked by traditional econometric techniques, without requiring strict assumptions about the underlying data. It relies on ridge regression with a kernel, specifically employing a Gaussian kernel. This analytical method allows us, within the scope of this research, to assess the impact of GQEM fluctuations on CO_2 emissions in selected MENA countries. In this study, we evaluate the pointwise marginal effects of GQEM on CO_2 emissions in the BRIC nations using the KRLS technique as follows:

$$\upsilon_V\left(\frac{CO2_i}{GQEM_i}\right) = \alpha(v)GQEM_i \quad (4)$$

$\alpha(v)$ denotes the pointwise marginal effect parameter, representing the marginal effect of GQEM on the v-th value of CO_2 emissions for the i-th MENA country.

Panel A: CO_2 Emissions



Panel B: Energy transition.

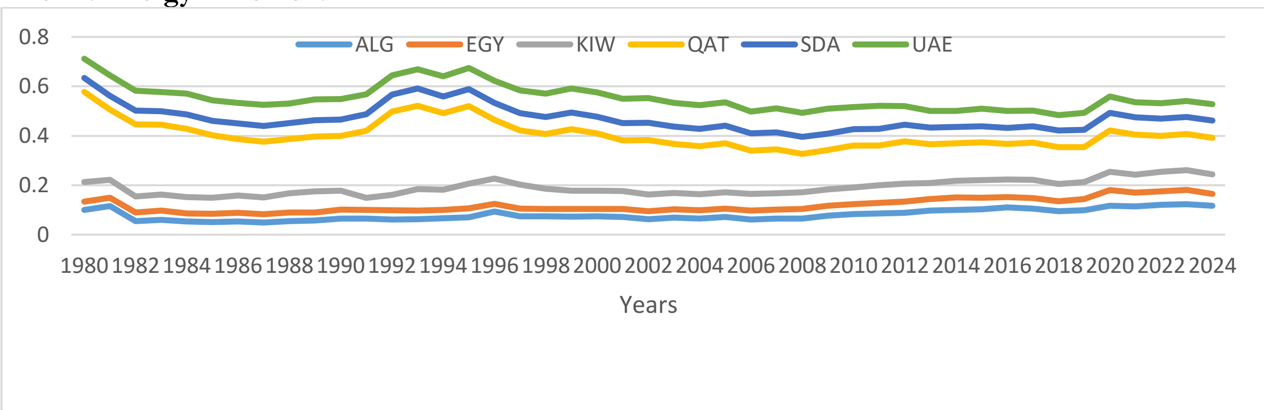


Figure 1. Time Trends of the CO2 Emissions and Energy Transition Data Series from 1980 to 2024.

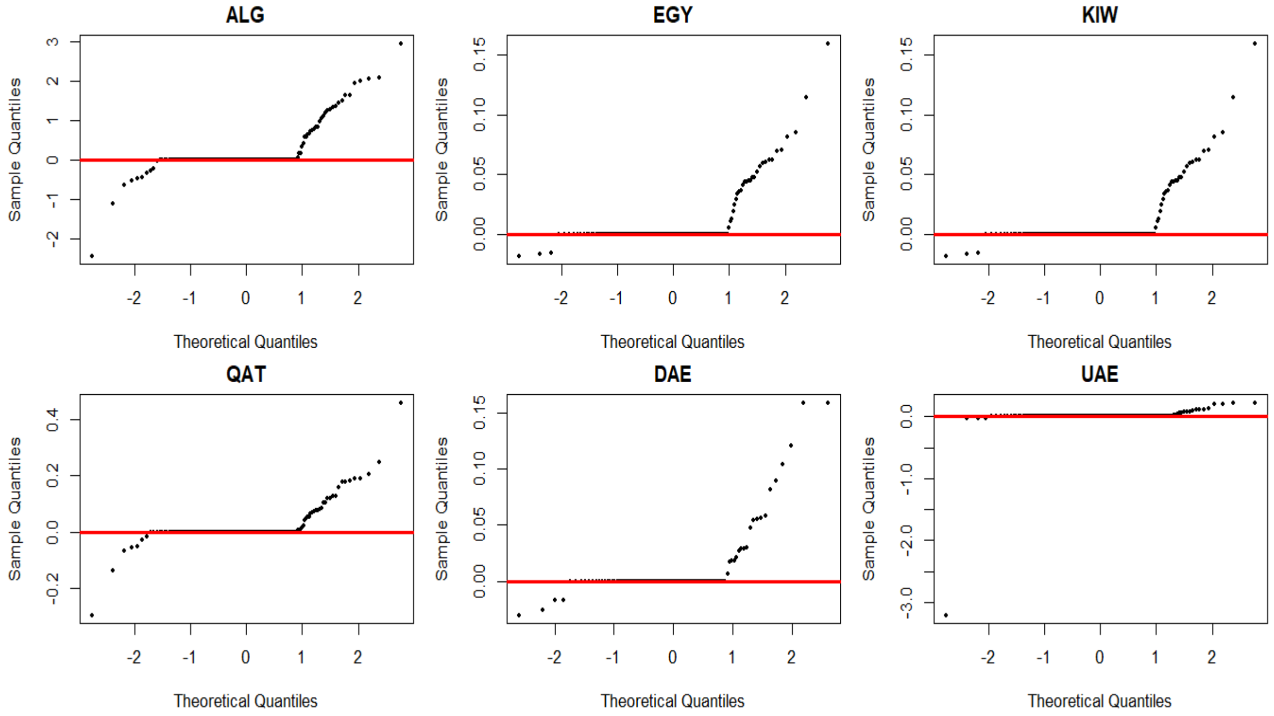
Table 1. Descriptive Statistics of the Quarterly LnI(1) Series

Panel A: CO2 Emissions						
	Mean	**Standard Deviation**	**Skewness**	**Kurtosis**	**Jarque-Bera**	**Probability**
ALG	0.169	0.582	1.657	10.222	471.068	0.000***
EGY	0.009	0.026	1.935	12.191	741.809	0.000***
KIW	0.008	0.026	1.914	11.897	699.760	0.000***
QAT	0.014	0.063	2.143	20.170	2335.93	0.000***
SDA	0.0103	0.031	2.921	13.423	1064.928	0.000***
UAE	-0.004	0.244	-12.688	167.166	2050.2	0.000***
Panel GQEM						
ALG	0.008	0.074	-5.578	62.659	2474.60	0.000***
EGY	-3.949	0.267	0.218	1.819	11.964	0.002***
KIW	-0.009	0.057	-1.101	62.659	6086.378	0.000***
QAT	-0.005	0.048	-1.021	16.783	1448.168	0.000***
SDA	0.001	0.011	3.128	24.639	3784.455	0.000***

UAE	0.002	0.033	-2.657	5.5860	21.904	0.000***

Note: Statistical significance is market with *** at the 1% level.

Panel A : CO2 Emissions



Panel GQEM:

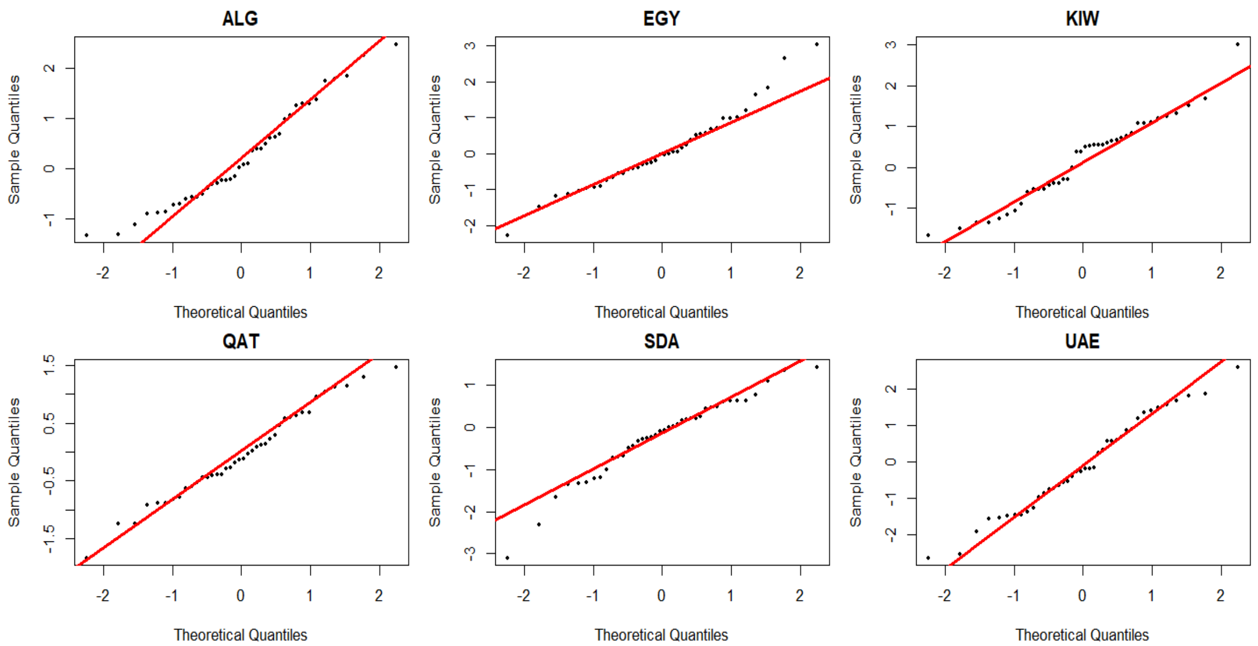


Figure 2. QQ Graphs of the Quarterly LnI(1) Series.

EMPIRICAL RESULTS

Quantile On Quantile Régression Results

This study employs the Quantile-on-Quantile Regression (QonQR), developed by Sim and Zhou (2015), to examine the effect of Green Environmental Quality and Energy Management (GQEM) on CO_2 emissions in six MENA countries. The results reveal asymmetric, nonlinear, and highly heterogeneous relationships between the two variables, confirming the relevance of quantile-based approaches to capture conditional dynamics often overlooked by linear models

Or standard quantile regression (Koenker and Bassett, 1978). The estimates indicate that Algeria experiences a stable and pronounced negative effect of GQEM on emissions, particularly at higher CO_2 quantiles, consistent with the predictions of the inverted U-shaped Environmental Kuznets Curve (Grossman & Krueger, 1995) and reflecting an effective improvement in environmental efficiency. In Egypt, the impact is also negative but asymmetric, becoming significant only when GQEM reaches high levels, supporting the notion that a minimal institutional threshold is required for environmental policies to yield results (Shama, 2011). Kuwait exhibits a weak and nearly linear impact, aligning with studies documenting the low sensitivity of hydrocarbon-dependent economies to environmental policies (Sadorsky, 2010; Al-Mulali, 2012). In Qatar, the relationship is unstable and nonlinear, reflecting rebound effects where technological gains paradoxically increase energy demand, as noted by Greening et al. (2000). In Saudi Arabia, the effect of GQEM appears conditional: substantially negative at high quantiles but neutral or positive at lower quantiles, suggesting that the effectiveness of environmental reforms depends on the level of institutional and energy capacities attained (York, 2012). In the United Arab Emirates, the coexistence of negative and positive effects indicates a high risk of macroeconomic rebound (Sorell, 2009; Saunders, 2013). Overall, the results demonstrate that the impact of GQEM on CO_2 emissions is highly country-specific: significant in North African countries, partially effective in Saudi Arabia, but limited or unstable in Gulf economies. These findings corroborate the literature indicating that the effectiveness of environmental policies depends on the combination of institutional capacity, energy structure, and hydrocarbon dependency (Popp, 2002; Farhani & Shahbaz, 2014), highlighting the need for differentiated approaches tailored to national energy profiles.

Robustness Results

This research employs multiple methods to assess the robustness of the results derived from the QonQR analysis. In this context, the results comparing the quantile-on-quantile regression (AQonQR) coefficients with traditional quantile regression (QR) coefficients are presented in Figure 4. The results shown in Figure 4, comparing the classical quantile regression (QR) (Koenker & Bassett, 1978) and the asymmetric quantile-on-quantile regression (AQonQR) proposed by Sim and Zhou (2015), highlight marked heterogeneity in the effect of Green Economic Quality and Environmental Management (GQEM) on CO_2 emissions in hydrocarbon-rich MENA countries. Overall, AQonQR captures more pronounced structural asymmetries than QR, confirming that the impact of green economic development simultaneously depends on both the emission quantile and the GQEM quantile, which conventional methods fail to capture. In Algeria and Saudi Arabia, increasing coefficients at higher quantiles indicate that environmental policies become truly effective only when emission levels reach a critical threshold, corroborating the empirical argument that the effects of green transitions are amplified in highly polluted environments (Balcilar et al., 2017; Khan et al., 2021). In Egypt, the observed decreasing effect reflects an incomplete energy transition vulnerable to environmental shocks, confirming findings from Shahbaz et al. (2017) on emerging economies. Nonlinear dynamics observed in Kuwait and the United Arab Emirates reveal that the impact of GQEM can become negative or unstable depending on pollution regimes, likely due to heavy reliance on the oil sector and limited energy diversification efforts, a phenomenon also identified by Omri et al. (2019). Finally, the upward profiles of Qatar and Saudi Arabia across quantiles support the notion that Gulf countries tend to achieve environmental gains primarily under high-carbon intensity conditions, confirming the relevance of the quantile-on-quantile approach to analyze nonlinear interactions between green development and pollution (Sim & Zhou, 2015). These results suggest that green transition policies in the MENA region are generally reactive rather than preventive, and their effectiveness increases mainly during high pollution phases, emphasizing the need for structural and anticipatory reinforcement of ecological investments to stabilize impacts across the full distribution of emissions. In the final stage, the effects of the energy transition on environmental degradation are verified using the Kernel Regularized Least Squares (KRLS) method. The results of this analysis, which calculates the pointwise marginal effects of explanatory variables on carbon emissions, are presented in Figure 5. The empirical results highlight an overall negative relationship between the quality of economic governance and CO_2 emissions in several MENA countries, notably Algeria, Egypt, Saudi Arabia, and the United Arab Emirates. This dynamic supports the foundations of institutionalism (North, 1990), according to which robust institutions enhance regulatory capacity, promote organizational innovation, and strengthen the adoption of low-emission technologies. However, in economies historically specialized in hydrocarbon extraction and export, such as Qatar and Kuwait, the observed effects remain unstable. This instability aligns with the path dependence logic (Pierson, 2000), highlighting the structural rigidity of development trajectories based on fossil rents. The observed fluctuations also corroborate the Environmental Kuznets Hypothesis, whereby institutional improvements may initially increase economic activity and thus emissions before generating sustainable environmental gains. These findings gain particular resonance in light of the just transition theory, which emphasizes the need to integrate decarbonization, social inclusion, and economic transformation. In rentier states, where hydrocarbons structure employment, public revenues, and political balances, the energy transition relies as much on institutional reform as on governments' capacity to support equitably the most vulnerable economic sectors and populations affected by forthcoming changes. Thus, while governance improvements constitute a key lever for transitioning to low-carbon models, their effectiveness closely depends on the adoption of compensatory policies, investments in human capital, and progressive economic diversification. In sum, the observed relationship suggests that governance is not merely a technical factor of environmental performance but a structural determinant of the transition to sustainable and socially equitable development in MENA economies

Sensitivity Analysis

As part of the sensitivity analysis, we examine how GQEM fluctuations influence CO2 emissions in MENA countries, using conditional expectation forecasts from the KRLS model.The KRLS results presented in Figure 6 reveal a clearly nonlinear relationship between CO_2 emissions and GQEM across all countries examined. Although the marginal effect of GQEM varies from one country to another, a general pattern emerges: improvements in environmental governance tend overall to reduce CO_2 emissions, albeit with different intensities and thresholds depending on national contexts. In countries such as Algeria, Egypt, Saudi Arabia, and the United Arab Emirates, the curve shows a predominantly negative effect, suggesting that strengthening GQEM contributes significantly to mitigating emissions, even if this impact tends to weaken beyond certain levels. Conversely, in Kuwait and Qatar, the responses exhibit stronger fluctuations, indicating more complex structural interactions between environmental governance, energy dependence, and economic activity. Overall, these results confirm that the effectiveness of GQEM is not linear; its impact depends on country-specific thresholds that reflect how environmental policies are embedded within energy-dominated economies.

Table 2. BDS Test Results of the Quarterly Ln I(1) Series.

Panel A: CO2 Emissions						
		Dim[2]	Dim[3]	Dim[4]	Dim[5]	Dim[6]
ALG	Z-statistic	-3.3451	-4.4947	-4.4773	-2.8411	-2.0204
	Probability	0.0008***	0.0000***	0.0000***	0.0045**	0.0433**
EGY	Z-statistic	-3.3686	-4.6165	-4.4511	-2.5749	-1.5617
	Probability	0.0008***	0.0000***	0.0000***	0.0100**	0.0184**
KIW	Z-statistic	-3.8358	-4.8452	-4.570	-2.693	-1.700
	Probability	0.001***	0.000***	0.000***	0.007***	0.008***
QAT	Z-statistic	-3.104	-4.214	-4.542	-2.852	-2.152
	Probability	0.001***	0.000***	0.000***	0.003***	0.031**
SDA	Z-statistic	-3.781	-4.833	-4.029	-2.198	-1.250
	Probability	0.000***	0.000***	0.000***	0.002***	0.001***
UAE	Z-statistic	-0.530	-0.734	-0.896	0.687	1.472
	Probability	0.005***	0.004***	0.003***	0.004***	0.001***
Panel B: GQEM						
ALG	Z-statistic	-2.610	-3.6335	-4.188	-2.650	-1.973
	Probability	0.009	0.000	0.000	0.008	0.048
EGY	Z-statistic	-2.6267	0.218	-4.0988	-2.5949	-1.7851
	Probability	0.008	0.000	0.000	0.009	0.051
KIW	Z-statistic	-2.2219	-3.1464	-3.8452	-2.4908	-1.785
	Probability	0.026	0.001	0.000	0.012	0.074
QAT	Z-statistic	-2.650	-3.705	-4.356	-3.025	-2.458
	Probability	0.008	0.000	0.000	0.002	0.014
SDA	Z-statistic	-2.843	-3.944	-4.516	-2.952	-2.243
	Probability	0.004	0.000	0.000	0.003	0.024
UAE	Z-statistic	-3.035	-4.172	-4.620	-2.791	-1.896
	Probability	0.002	0.000	0.000	0.005	0.057

Note: Statistical significance is market with *** and ** at the 1% and 5% levels.

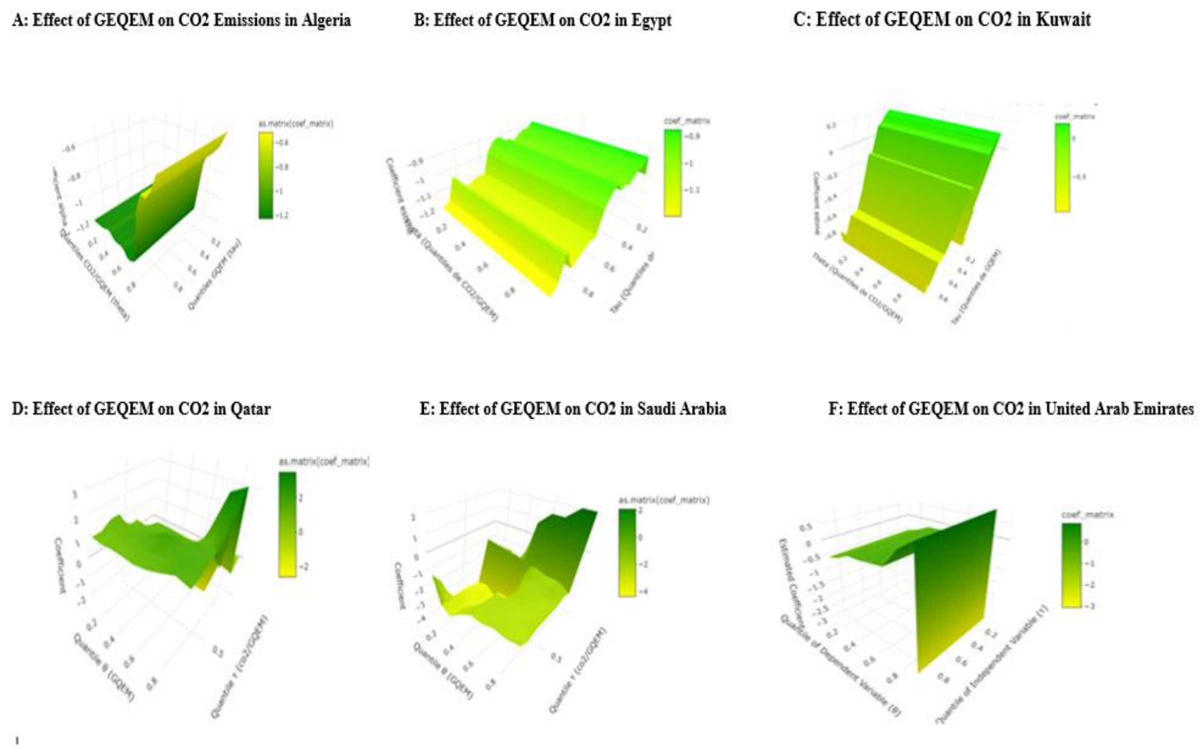


Figure 3. QonQR Results.

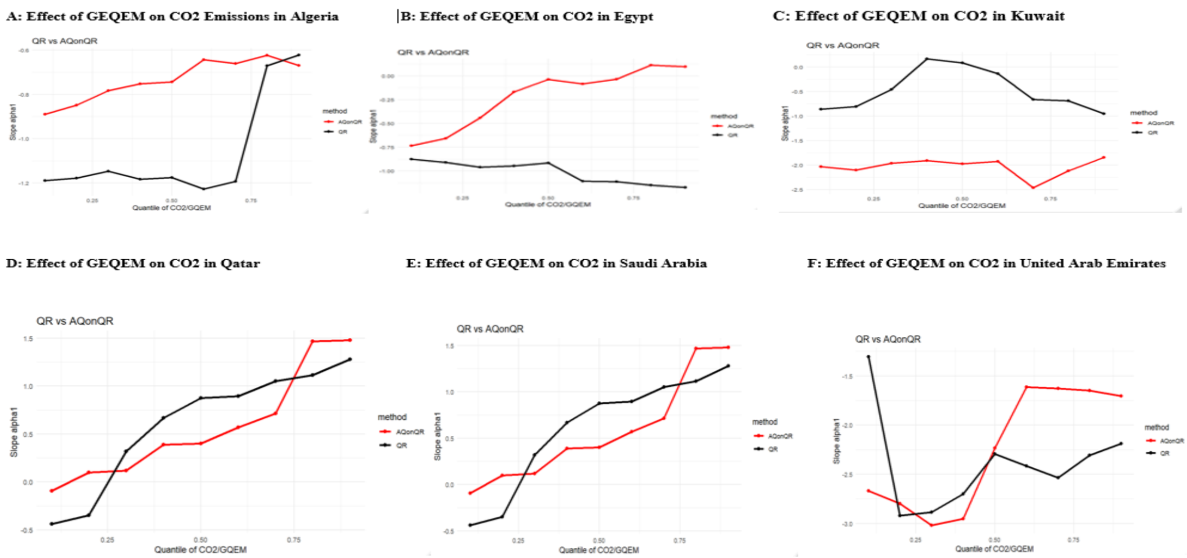


Figure 4. QR and AQonQR Results.

Table 3. Pearson, Kendall, and Spearman Correlations between QR and AQonQR.

	Pearson	**Probability**	**Kendall**	**Probability**	**Spearman**	**Probability**
	Correlation		Correlation		Correlation	
Algeria	-0.922	0.000	-0.824	0.000	-0.938	0.000
Egypt	-0.886	0.000	-0.764	0.000	-0.618	0.000
Kuwait	-0.282	0.06	-0.197	0.193	-0.197	0.056
Qatar	0.207	0.171	0.319	0.032	0.256	0.012
Saudia Arabia	-0.756	0.000	-0.544	0.000	-0.397	0.000
United Arab Emirate	-0.140	0.031	-0.379	0.010	-0.274	0.007

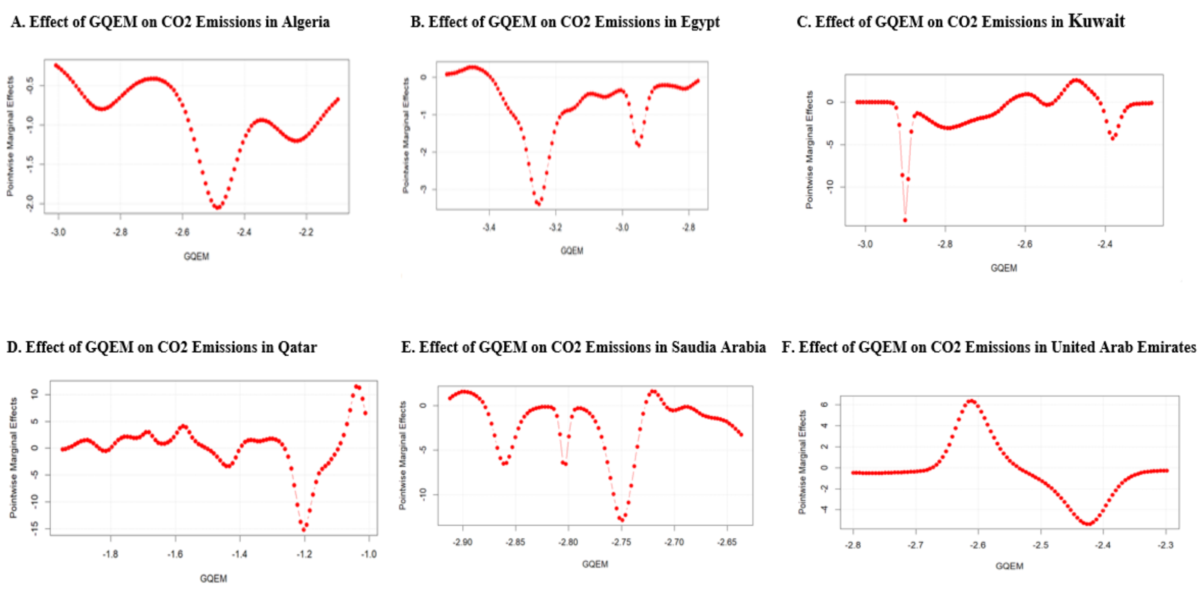


Figure 5. KRLS Pointwise Marginal Effects Results.

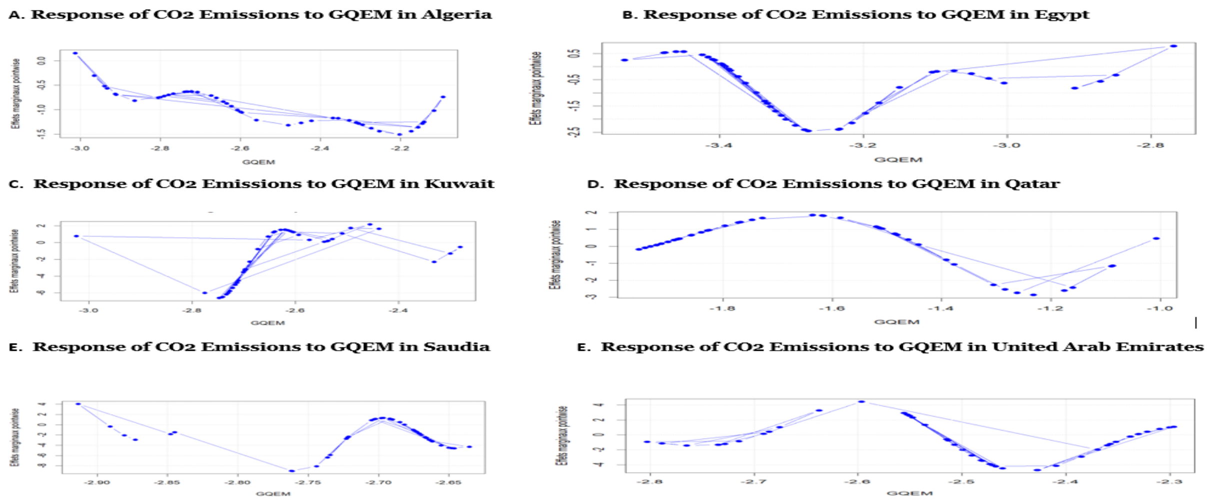


Figure 6. KRLS Conditional Expectation Reculs

CONCLUSION

The energy transition in the MENA region has become a central component of climate mitigation strategies aimed at reducing CO_2 emissions, in line with the theoretical foundations of ecological economics and the Environmental Kuznets Curve, which posit the possibility of decoupling economic growth from environmental degradation (Grossman & Krueger, 1995; Stern, 2004). Recent studies highlight that improvements in energy efficiency, an increasing share of renewable energy, and structural shifts in the energy mix constitute the key drivers of this transition (Charfeddine & Kahia, 2019; Salahuddin et al., 2018; Alola et al., 2021; Shahbaz et al., 2022). However, the existing literature remains fragmented, relying predominantly on partial indicators such as energy intensity or carbon intensity, which fail to capture the systemic and nonlinear dimensions of the transition in economies still heavily dependent on hydrocarbons (Saidi & Hammami, 2015; Ben Jebli et al., 2021; Al-Mulali & Ozturk, 2016). More recent work shows that the effects of the energy transition vary significantly according to economic diversification, institutional quality, and technological innovation capacity, particularly within GCC countries (Rehman et al., 2020; Kahia et al., 2022; Destek, 2023). This context underscores the need for developing a composite indicator of energy transition efficiency that captures the interactions between productive structure, technological progress, the carbon content of energy, and emission dynamics. Nonetheless, this approach faces several limitations, including heterogeneous data availability, structural disparities between energy-exporting and energy-importing countries, econometric specification biases, and challenges in integrating climate feedback mechanisms into modelling frameworks (Balsalobre-Lorente et al., 2022; Salahuddin & Gow, 2023). Future research directions call for the construction of dynamic indicators incorporating energy system digitalization, institutional reforms, green investment flows, climate vulnerability, and resilience policies, while broadening empirical analyses to explore the interactions between the energy transition, green growth, and socio-economic stability across the MENA region.

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Annexe 1 . ADF and PP Unit Root Tests Results.

Panel CO2 Emissions								
	ADF (Dickey & Fuller, 1979)				**PP (Phillips & Perron, 1988)**			
	Level		**First-Difference**		**Level**		**First-Difference**	
	t-Stat	**Prob**	**t-Stat**	**Prob**	**t-Stat**	**Prob**	**t-Stat**	**Prob**
ALG	0.9344	0.9951	-6.3675	0.000*	1.001	0.9959	-6.009	0.000*
EGY	-0.4911	0.8832	-5.6624	0.000*	-0.4952	0.882	-5.6069	0.000*
KIW	-0.2663	0.9216	-6.324	0.000*	-0.2753	0.9203	-6.3250	0.000*
QAT	1.0911	0.9968	-5.2143	0.000*	0.7302	0.9916	-5.2918	0.000*
SDA	-0.1564	0.9362	-4.3073	0.001*	0.0100	0.9541	-4.1655	0.002*
UAE	0.1405	0.9653	-6.7498	0.000*	0.1820	0.9684	-6.7507	0.000*
Panel GQEM								
	Level		**First-Difference**		**Level**		**First-Difference**	
	t-Stat	**Prob**	**t-Stat**	**Prob**	**t-Stat**	**Prob**	**t-Stat**	**Prob**
ALG	-1.6042	0.4720	-8.6790	0.000*	-1.459	0.5447	-8.4555	0.000*
EGY	-0.4911	0.8832	-5.6624	0.000*	-0.4952	0.8824	-5.6069	0.000*
KIW	-2.9042	0.5290	-6.0074	0.000*	-3.0564	0.374	-6.6072	0.000*
QAT	-2.438	0.1374	-6.788	0.000*	-2.4588	0.1323	-6.788	0.000*
SDA	-2.539	0.1135	-5.862	0.000*	-2.191	0.2120	-5.862	0.000*
UAE	-1.077	0.716	-7.4611	0.000*	-1.0770	0.7166	-7.4505	0.000*

Note: Statistical significance is market with * at the 5%.

