Does Innovation Drive Renewable Energy in Arab Countries? Insights from Method of Moments Quantile Regression

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Abstract. This study examines how innovation affects renewable energy adoption across 11 Arab countries from 2007 to 2023, addressing a critical gap in the literature on the so-called innovation paradox in resource-rich economies. Using the Method of Moments Quantile Regression (MMQR), the analysis captures heterogeneous effects across the distribution of renewable energy consumption. The findings reveal a counterintuitive negative association between the Global Innovation Index and renewable energy uptake in the middle and upper quantiles, providing empirical support for the resource curse hypothesis: innovation capacity in hydrocarbon-rich Arab states is often channeled toward fossil fuel sectors rather than clean energy. In contrast, human development emerges as the most robust and consistent driver of renewable energy deployment, while oil rents positively influence renewable energy across all quantiles, suggesting successful rent recycling in some cases. Financial development, measured by domestic credit, shows a persistent negative effect, reflecting sectoral biases in credit allocation. Government effectiveness becomes significant only at higher quantiles, highlighting the threshold role of institutional quality as renewable energy systems mature. These results underscore the need for targeted policy interventions that realign innovation incentives, strengthen human development, and enhance institutional quality to overcome structural lock-ins and accelerate the energy transition in Arab countries.

Keywords: Innovation, Renewable Energy, Arab Countries, Method of Moments Quantile Regression (MMQR).
JEL Classification : O31, O33, Q42, Q43, C23

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1 Introduction

The global energy landscape is undergoing unprecedented transformation as nations worldwide grapple with the imperative to decarbonize their economies while maintaining sustainable economic growth. Innovation has emerged as a critical catalyst in this transition, with technological advancement, human capital development, and resource efficiency serving as endogenous drivers of renewable energy adoption and long-term sustainable development (Vurur et al., 2024). The relationship between innovation and renewable energy deployment has become particularly salient as countries seek to balance economic development objectives with environmental sustainability commitments under frameworks such as the Paris Agreement and the United Nations Sustainable Development Goals (Danish & Isaifan, 2024). Research consistently shows that innovation encompasses not only technological breakthroughs in photovoltaic materials, energy storage systems, and smart grid technologies, but also business model redesigns, financing mechanisms, and policy frameworks that collectively reduce costs, enhance system flexibility, and stimulate renewable energy uptake across diverse geographies (Adebayo et al., 2022; Y. Jiang et al., 2023).

However, the innovation-renewable energy nexus is marked by remarkable complexity and regional heterogeneity, particularly in resource-rich developing economies, where abundant fossil fuel endowments create unique structural dynamics. Recent empirical evidence suggests that the relationship between innovation and renewable energy adoption is not universally positive, with several studies documenting counterintuitive findings in which elevated innovation indices paradoxically correlate with slower renewable energy transitions (Radulescu et al., 2022). This phenomenon appears particularly pronounced in hydrocarbon-dependent economies, where the resource curse hypothesis provides a theoretical basis for understanding how abundant natural resource wealth can systematically divert innovation efforts toward optimizing fossil fuel extraction and processing rather than promoting clean energy technologies (Bigerna et al., 2024; Almutairi & Alhamad, 2025). Such structural lock-in effects, characterized by entrenched fossil-fuel infrastructure that absorbs innovation inputs, create path-dependent processes that reinforce conventional energy systems even as countries achieve higher overall innovation rankings (Al-Ismail et al., 2023).

Arab countries offer a compelling empirical context for examining the complex dynamics between innovation and renewable energy, given their unique combination of substantial hydrocarbon wealth, ambitious renewable energy commitments, and evolving policy landscapes. The region spans economies with varying degrees of oil dependence, from heavily hydrocarbon-reliant Gulf Cooperation Council (GCC) states to more diversified North African economies, providing valuable variation for understanding how resource endowments interact with innovation systems to shape renewable energy outcomes (Rastegar et al., 2024). Recent strategic initiatives, particularly Saudi Arabia's Vision 2030 commitment to generate 50% of energy from renewable sources and deploy 58.7 GW of renewable capacity, alongside similar ambitious targets in the UAE, Qatar, and other Arab states, represent fundamental shifts in regional energy policy that create natural experiments for analyzing innovation's role in facilitating or hindering energy transitions (Mohammed et al., 2024). Despite possessing some of the world's most abundant solar and wind resources, Arab countries have historically adopted renewable energy more slowly than other regions, primarily because of abundant local fossil fuel reserves, historically low energy prices, and established energy infrastructures (Miao et al., 2024).

The empirical literature examining the impact of innovation on renewable energy in Arab countries remains limited and is characterized by significant methodological and substantive gaps. While extensive research documents determinants of renewable energy globally, comprehensive quantile regression analyses specifically focused on Arab economies are notably scarce, with most existing studies employing conditional mean techniques that obscure important distributional heterogeneity (Bigerna et al., 2024). Previous studies have predominantly used ordinary least squares with fixed effects, which offer limited insight into how innovation and other determinants may affect renewable energy adoption differently across countries at various stages of renewable energy development (Ali et al., 2021; Almutairi & Alhamed, 2025). Furthermore, the existing literature pays insufficient attention to the innovation paradox in resource-rich contexts, with few studies providing empirical evidence to support theoretical predictions about how resource curse effects shape the allocation of innovation between traditional and clean energy sectors (Sun et al., 2024). The methodological limitations of previous research are particularly problematic given the substantial heterogeneity within the Arab region, where countries exhibit vastly different economic structures, development levels, and renewable energy penetration rates, likely to yield heterogeneous relationships between innovation and clean energy adoption.

This study addresses these critical research gaps by employing the MMQR approach to examine the heterogeneous impacts of innovation on renewable energy consumption across 11 Arab countries from 2007 to 2023. The MMQR methodology, introduced by Machado and Silva (2019), represents a significant advancement in panel quantile regression, offering superior handling of high-dimensional fixed effects while avoiding the incidental parameters problem that plagues traditional quantile regression. This methodological innovation enables examination of distributional effects rather than merely average relationships, providing nuanced insights into how innovation, human development, government effectiveness, financial development, and other determinants affect renewable energy adoption across different quantiles of the renewable energy distribution (Elmonshid et al., 2024). By analyzing effects across the 10th to 90th quantiles, this study can identify threshold effects and heterogeneous relationships that would be masked by conventional mean regression techniques, offering policy-relevant insights for countries at different stages of renewable energy development.

The remainder of this paper is structured as follows: Section 2 provides a comprehensive literature review of theoretical frameworks and empirical evidence on the relationships between innovation and renewable energy. Section 3 describes our econometric methodology, with particular emphasis on the MMQR approach and its advantages for analyzing distributional effects in panel data contexts. Section 4 presents our empirical results, including diagnostic tests, quantile regression estimates, and robustness checks. Section 5 discusses the policy implications of our findings and their contributions to the broader literature on energy transitions in resource-rich economies. Section

6 concludes with recommendations for future research directions and policy interventions to overcome the innovation paradox identified in Arab countries.

2 Literature Review

The relationship between innovation and renewable energy has emerged as a critical area of research for global climate change mitigation and sustainable development. Innovation is a fundamental driver of renewable energy adoption, technological advancement, and market penetration, while renewable energy deployment creates new opportunities for further innovation (Rastegar et al., 2024).

Endogenous growth theory provides a foundational framework for understanding how innovation drives renewable energy development through technological advancement and knowledge accumulation (Ogunsola & Zwane, 2025). This approach emphasizes that technological innovation, human capital, and resource efficiency are endogenous factors that sustain long-term economic growth and facilitate energy transitions (Ogunsola & Zwane, 2025; Peng et al., 2023). The theory particularly illuminates how renewable energy consumption, technological innovation, and export diversification create positive feedback loops that enhance economic expansion in emerging economies (Alhashim et al., 2024). Research using this framework on energy transitions shows that countries following endogenous growth trajectories can achieve significant reductions in fossil fuel consumption while maintaining economic development (Peng et al., 2023).

The diffusion of innovations theory offers critical insights into how renewable energy technologies spread across adopter categories and social systems (Wanless et al., 2023). This framework explains how renewable energy innovations progress from initial development to widespread adoption, shaped by factors such as relative advantage, compatibility, complexity, trialability, and observability (Bridi & Alhosani, 2021). Studies applying this theory to renewable energy markets show that adoption patterns vary significantly across technologies, with solar energy diffusing faster than wind energy in certain contexts (Wanless et al., 2023). The theory's emphasis on communication channels and social networks is particularly relevant for understanding how renewable energy innovations gain acceptance within communities and organizations (Van Der Waal et al., 2018). Research using diffusion theory shows that government sponsorship and policy incentives play crucial roles in accelerating the adoption of non-drastic renewable energy innovations (Abbruzzese et al., 2025).

The innovation paradox theory offers important clues as to why innovation may not always facilitate the adoption of renewable energy, particularly in resource-rich economies (Wei et al., 2023; Najam, 2023). This framework explains how elevated innovation indices in fossil fuel-dependent countries can hinder renewable energy development due to path dependency and the misallocation of innovative resources across sectors. Research shows that abundant hydrocarbon wealth systematically diverts innovation efforts toward optimizing fossil fuel extraction rather than promoting clean energy technologies (Najam, 2023). The resource curse hypothesis extends this analysis by showing how oil rents and established energy infrastructures create structural lock-in effects that absorb innovation inputs (Wei et al., 2023; Najam, 2023). Studies applying this theoretical lens reveal that countries with high Global Innovation Index scores may paradoxically experience slower renewable energy transitions when innovation is concentrated in traditional energy sectors (Najam, 2023). This framework helps explain why technological advancement does not automatically translate into gains in renewable energy in resource-rich regions (Wei et al., 2023).

Innovation systems theory offers a comprehensive framework for understanding how institutional arrangements, knowledge networks, and policy environments shape outcomes of renewable energy innovation (Dzwigol et al., 2023; Jiang et al., 2025). This approach emphasizes that successful renewable energy development requires well-functioning national and sectoral innovation systems that facilitate the creation, diffusion, and application of knowledge. Research applying this framework shows that renewable energy enterprises benefit from integrated networks that link knowledge subsystems, R&D member networks, and supportive policy environments (H. Sun et al., 2024). The theory's focus on system-level interactions helps explain why performance in renewable energy innovation varies significantly across countries with different institutional configurations. Studies demonstrate that innovation systems with strong environmental regulations and transparent stakeholder engagement mechanisms achieve superior outcomes in renewable energy (Dzwigol et al., 2023). The framework also shows how digital technologies and reconfiguration capabilities within innovation systems can enhance productivity in the renewable energy sector (Jiang et al., 2025).

Schumpeter's theory of creative destruction offers insights into how innovations in renewable energy disrupt existing energy systems and create new market structures. This framework explains how renewable energy technologies displace established fossil fuel industries while creating new economic opportunities and employment patterns (Urban & Heydenrych, 2015; Girón, 2025). Research applying this theory to renewable energy transitions shows that state intervention, institutional finance, and corporate governance drive structural changes in productive systems (Girón, 2025). The creative destruction perspective helps explain why renewable energy adoption requires fundamental transformation rather than incremental change in energy systems. Studies demonstrate that effectuation processes and technology orientation in renewable energy sectors embody the essence of creative destruction through experimentation, flexibility, and strategic alliance formation (Urban & Heydenrych, 2015). The framework also illuminates how China's energy transition represents creative destruction at a global scale, combining technological innovation with institutional transformation (Girón, 2025).

The transition from fossil-based to renewable energy systems has been profoundly shaped by innovations spanning technological breakthroughs, business model redesigns, financing mechanisms, and policy frameworks. At the heart of this transition is the capacity of novel technologies—ranging from advanced photovoltaic materials and high-performance batteries to artificial intelligence-enabled smart grids—to drive down costs, enhance system flexibility, and stimulate uptake across scales and geographies (Khan & Su, 2023; Muñiz et al., 2024). Concurrently, the emergence of innovative business models, such as prosumer-centered platforms and community energy cooperatives, has altered value propositions and revenue streams for both incumbents and new entrants, facilitating more inclusive and decentralized energy markets (Braunholtz-Speight et al., 2020). Financial innovations—including green bonds, crowdfunding, and dynamic feed-in tariffs—have expanded capital flows into renewable installations, reduced dependence on traditional lenders, and mitigated investment risk (Strielkowski, 2024). Moreover, policy interventions, such as R&D subsidies and auction-based procurement, have signaled governmental commitment, mobilized private investment, and guided innovation trajectories toward sustainability objectives (Khan & Su, 2023). Beyond isolated measures, the interplay among spatial spillovers, sector coupling, and circular-economy synergies underscores the systems-level nature of innovation impacts, whereby advances in one region or sector propagate benefits through knowledge diffusion, infrastructure integration, and collaborative governance (Noseleit, 2018).

The intersection of innovation and renewable energy deployment in Arab nations is closely tied to their historical reliance on hydrocarbons, evolving legal frameworks, and emerging environmental imperatives (Alouani & Driouchi, 2014; Nicolini & Porcheri, 2014; Olawuyi, 2022). Recent scholarship emphasizes that, despite vast solar and wind resources, policy inertia and traditional subsidy regimes have impeded technology diffusion until very recently (Nicolini & Porcheri, 2014; Olawuyi, 2022). Moreover, the global energy transition has compelled Gulf states to reorient national visions toward green growth, integrating innovation targets into Vision 2030 plans (Olawuyi, 2022). Significant fossil fuel revenues have provided capital for large-scale pilot projects, but without corresponding advances in local R&D, uptake remains limited (Alouani & Driouchi, 2014; Nicolini & Porcheri, 2014). Therefore, a comprehensive understanding of institutional and economic drivers is essential for steering Arab countries toward an innovation-led renewable energy paradigm.

3 Methodology and Data

This study examines data from 11 Arab countries (Algeria, Jordan, Oman, Qatar, Saudi Arabia, Tunisia, United Arab Emirates, Bahrain, Egypt, Kuwait, Morocco) for the period 2007–2023. Table 1 presents the dependent and independent variables and their sources.

Table 1. Description of variables

Abbreviation	Variable name	Source
TRE	Total renewable energy	International Renewable Energy Agency (IRENA)
GII	Global Innovation Index	World Intellectual Property Organization (WIPO)
PT	Total patent applications	
GDPPC	GDP per capita	World Bank
EU	Energy use	
HDI	Human Development Index	UN Development Program

OR	Oil rents	World Bank
DC	Domestic credit to the private sector	
FDI	Foreign direct investment, net inflows	
GE	Government Effectiveness	

We apply the following model to our empirical investigation:

$$TRE_{it} = \beta_0 + \beta_1 GII_{it} + \beta_2 PT_{it} + \beta_3 GDPpc_{it} + \beta_4 EU_{it} + \beta_5 HDI_{it} + \beta_6 OR_{it} + \beta_7 DC_{it} + \beta_8 FDI_{it} + \beta_9 GE_{it} + \varepsilon_{it} \quad (1)$$

The traditional approach to panel data analysis, Ordinary Least Squares (OLS) with fixed effects, has been widely used for its simplicity and computational efficiency. This method effectively controls time-invariant unobserved heterogeneity but is limited to estimating effects on the conditional mean. In contrast, quantile regression for panel data aims to provide a more comprehensive view of the relationship between variables across quantiles of the conditional distribution. Quantile regression has become an essential tool in econometrics, allowing researchers to examine how covariates affect the entire distribution of the dependent variable, not just its mean. However, applying quantile regression to panel data, particularly with fixed effects, has posed significant challenges. A generalization of the quantile regression data-generating function can be written as follows:

$$y_i = \beta_0(\tau) + \beta_1(\tau)X_{i1} + \beta_2(\tau)X_{i2} + \cdots + \beta_k(\tau)X_{ik} \quad (2)$$

Based on this specification, a few characteristics should be considered:

- slopes $\beta_k(\tau)$vary across quantiles only if the model is heteroskedastic;
- quantile regression can be considered as a semi-parametric varying-coefficient model, with an unobserved running variable (τ);
- coefficients are percentile specific;
- It is possible to separate location effects (mean) from scale effects (deviation from the mean).

Quantile regressions are nonlinear models. Thus, one cannot just add dummies to address group fixed effects:

$$Q_\tau(y|x) = \beta_0(\tau) + \beta_1 X(\tau) + \sum \delta(\tau)_g \quad (3)$$

This creates an incidental parameter problem. Neither δ(τ)′s nor β′s would be consistently estimated. Koenker (2004) proposed the penalized quantile regression method as one of the first attempts to handle quantile regression in panel data. This method incorporates fixed effects via a penalty term, allowing for the estimation of quantile effects while controlling for unobserved heterogeneity. However, it can suffer from the incidental parameter problem when the number of fixed effects is large relative to the sample size. Koenker (2004) assumes fixed effects only have an impact on location and shrink individual effects:

$$y_i = \beta(\tau)X + \delta_g \quad (4)$$

Canay (2011) proposed a two-step approach: first, estimate fixed effects using a conditional mean model, and then perform quantile regression on the demeaned data. This method is intuitive and relatively simple to implement, but may introduce bias, particularly when the effects of covariates vary substantially across quantiles.

$$y = \beta X + \delta_g \quad (5)$$

$$Q_\tau\left(y - \delta_g \middle| X\right) = \beta(\tau) \quad (6)$$

The MM-QR approach, introduced by Machado and Silva (2019), represents a significant advancement in this field. MM-QR transforms the quantile regression problem into a set of moment conditions, allowing for efficient estimation even with high-dimensional fixed effects. This method avoids the incidental parameters problem and is computationally efficient for large datasets, addressing key limitations of previous approaches. This method was developed to incorporate individual fixed effects. In principle, it is an extension of a strategy to estimate quantile regression coefficients using a restricted location-scale model, assuming the following structure:

$$y_i = X_i\beta + \varepsilon X_i\gamma \quad (7)$$

Thus, the quantile regression model is given by:

$$Q_\tau(y|X) = X(\beta + F_\varepsilon^{-1}(\tau)\gamma) = X\beta(\tau) \quad (8)$$

OLS with fixed effects remains valuable for its simplicity and for its focus on average effects. Traditional quantile regression or Koenker's penalized approach may be preferred when the number of fixed effects is moderate. Canay's two-step method offers a straightforward alternative when the assumption of location shift (i.e., fixed effects affect all quantiles equally) is plausible. However, for researchers dealing with large panel datasets and interested in distributional effects, MM-QR offers significant advantages. Its ability to handle high-dimensional fixed effects efficiently, coupled with its robustness to outliers and non-normal errors, makes it a powerful tool in modern econometric analysis (Machado & Silva, 2019).

We investigate the impact of innovation on renewable energy across a panel of 11 Arab countries, using the MM-QR approach with panel fixed effects. We use the MM-QR approach to project the distribution of conditional economic growth, allowing us to account for heterogeneity. The model is as follows:

$$TRE_{it} = \alpha_i + X_{it}'\beta + (\delta_i + Z_{it}'\gamma)U_{it} \quad (9)$$

Where $P\{\delta_i + Z_{it}'\gamma > 0\} = 1$. Individual *i* fixed effects are denoted by (α_i, δ_i), i =1, 2, ..., n, and Z is a k-vector of transformations of the elements of X with probability 1 that are known to be differentiable. Model (09) could have the following expansions:

$$Q_{TRE}(\tau|X_{it}) = \left(\alpha_i + \delta_i q(\tau)\right) + Z_{it}'\gamma q(\tau) \quad (10)$$

X_{it} denotes the independent variables. Conditional on the location of explanatory variables, the response variable *TRE* has a quantile distribution denoted by $Q_{TRE}(\tau|X_{it})$. We define the τth quantile (0 < τ < 1) of the conditional distribution of the dependent variable, considering a set of independent variables X_{it}. The scalar coefficient *i* denotes the quantile-τ fixed effect, either for individual i or the distributional effect at τ. The distributional influence, unlike the habitual fixed effect, does not entail a change in location. As a result, the distributional effect replaces the influence of time-invariant individual traits, which, like other variables, could have different effects on different areas of *TRE*'s conditional distribution. Minimizing the following optimization yields the τ-th sample quantile estimate shown by $q(\tau)$:

$$\min_{q} \sum_i \sum_t \rho_\tau\left(\hat{R}_{it} - \left(\hat{\delta}_i + Z'_{it}\hat{\gamma}\right)q\right) \tag{11}$$

The check function is indicated by $\rho_\tau(A) = (\tau - 1)AI\{A \le 0\} + \tau AI\{A > 0\}$.

4 Results

Table 2 provides descriptive statistics for the variables analyzed in this study concerning renewable energy determinants across 11 Arab countries from 2007 to 2023.

Table 2. Descriptive statistics

Variable	Mean	Std. dev.	Min	Max
TRE	909.3476	1509.412	0	6709
GII	33.55316	7.32226	16.1	60.52
PT	1017.695	1058.546	12	7084
GDPpc	20618.53	19904.93	2540.615	81608.57
EU	5838.429	5221.251	495.4718	21456.07
HDI	0.7858396	0.076754	0.586	0.94
OR	16.85344	15.07444	-5.639278	58.36893
DC	62.713	28.62405	12.13019	144.2723
FDI	3.81e+09	5.49e+09	-2.81e+09	3.07e+10
GE	0.162813	0.5355018	-0.7829369	1.604282

Table 2 presents summary statistics, including the mean, standard deviation, minimum, and maximum, for the dependent variable TRE, along with the independent variables. The descriptive statistics indicate significant variability among the Arab economies, with TRE ranging from 0 to 6709 (mean 909.35), GDP per capita ranging from 2,541 to 81,609 (mean 20,618.53), and oil rents ranging from -5.6% to 58.36% of GDP (mean 16.9%). The statistics illustrate the varied economic structures and development levels within the sample, indicating that some countries are heavily reliant on oil while others possess more diversified economies. This foundational data justifies the use of MMQR to analyze heterogeneous effects across varying levels of renewable energy adoption.

Before commencing the analytical approach, econometric estimates must address multicollinearity doubts through correlation analysis and the variance inflation factor (VIF).

Table 3. Correlation matrix

	TRE	GII	PT	GDPpc	EU	HDI	OR	DC	FDI
TRE	1.00								
GII	-0.310	1.00							
PT	0.553	-0.130	1.00						
GDPpc	-0.342	0.618	-0.124	1.00					
EU	-0.432	0.578	-0.197	0.942	1.00				
HDI	-0.375	0.457	0.004	0.729	0.789	1.00			
OR	-0.394	0.328	-0.111	0.466	0.533	0.507	1.00		
DC	-0.193	0.289	-0.193	0.316	0.319	0.287	-0.184	1.00	
FDI	0.360	0.171	0.662	0.115	0.023	0.280	0.112	-0.101	1.00
GE	-0.257	0.665	0.0202	0.761	0.683	0.694	0.173	0.488	0.350

Table 3 displays the correlation matrix for all variables utilized in the study. The results demonstrate a significant correlation of 0.942 between EU and GDPPC, suggesting a potential multicollinearity issue that requires further diagnostic evaluation via the Variance Inflation Factor (VIF) analysis.

Table 4. VIF for independent variables

Variable	VIF	Tolerance
EU	15.65	0.063903
GDPpc	13.62	0.073423
GE	5.72	0.174854
HDI	4.31	0.231860
FDI	2.82	0.355115
OR	2.23	0.448515
GII	2.15	0.464234
PT	2.13	0.469697
DC	1.70	0.586671

Table 4 presents the VIF analysis for all independent variables in the renewable energy study, serving as a crucial diagnostic tool for detecting multicollinearity issues that could compromise the reliability of regression estimates. The VIF values reveal severe multicollinearity, with EU showing the highest VIF of 15.65 and GDPPC at 13.62, both substantially exceeding the commonly accepted threshold of 10, which indicates problematic multicollinearity. This finding is consistent with the strong correlation of 0.942 between EU and GDPPC observed in Table 3, suggesting these variables are nearly perfectly correlated and cannot be reliably included together in the regression model. This analysis necessitates excluding the EU variable and a subsequent retest.

Table 5. VIF for independent variables excluding EU

Variable	VIF	Tolerance
GE	5.50	0.181898
GDPpc	3.96	0.252481
HDI	3.13	0.319496
FDI	2.65	0.376655
OR	2.18	0.45774
GII	2.14	0.467965
PT	2.13	0.470346
DC	1.68	0.593996

Table 5 shows that after removing EU, which had a problematic VIF of 15.65, all remaining variables now have VIF values well below the critical threshold of 10, with the highest being GE at 5.50. This diagnostic step was necessary to ensure the robustness of the MM-QR analysis.

Table 6. The MMQR regression on TRE

	OLS		Quantile of TRE				
	Location	Scale	0.10	0.30	0.50	0.70	0.90
GII	-23.9145* (12.62453)	-11.7175 (8.74915)	-10.1439 (8.350769)	-14.8646* (8.774404)	-22.4074* (11.95343)	-32.9288* (18.1963)	-46.9521* (27.63633)
PT	-0.07905 (0.160607)	-0.003211 (0.111305)	-0.07528 (0.10716)	-0.076574 (0.111957)	-0.078641 (0.150203)	-0.081525 (0.23172)	-0.085369 (0.355312)
GDPPC	-0.03238** (0.01546)	-0.006757 (0.010715)	-0.02444** (0.01028)	-0.02717** (0.010766)	-0.03152** (0.014505)	-0.037587 (0.022294)	-0.045674 (0.034092)
HDI	20592.6*** (3138.66)	1959.59 (2175.185)	18289.7*** (2083.98)	19079.1*** (2184.161)	20340.5*** (2953.115)	22100.1*** (4524.718)	24445.3*** (6903.604)
OR	20.7749*** (7.004531)	4.18057 (4.854337)	15.8618*** (4.662909)	17.546*** (4.879296)	20.237*** (6.581024)	23.991** (10.10669)	28.9942* (15.45014)
DC	-14.159*** (4.208451)	-4.2777 (2.916575)	-9.1327*** (2.774901)	-10.856*** (2.9216)	-13.609*** (3.996753)	-17.45*** (6.061383)	-22.5702** (9.178923)
FDI	2.70e-08 (2.14e-08)	1.14e-08 (1.49e-08)	1.36e-08 (1.42e-08)	1.82e-08 (1.49e-08)	2.55e-08 (2.02e-08)	3.57e-08 (3.09e-08)	4.72e-08 (4.44e-08)
GE	473.798 (303.6979)	324.393 (210.4711)	92.5682 (200.8042)	223.256 (211.0755)	432.074 (288.4069)	723.354* (437.9827)	1111.58* (664.2374)
Cons	-13364*** (2280.525)	-3502.5** (1708.721)	-12765*** (1520.03)	-12970*** (1589.12)	-13299*** (2134.825)	-13756*** (3289.449)	-14367*** (5039.271)

Notes: The standard errors in parentheses. The statistical significance levels are as follows: *** at the 0.01 level, ** at the 0.05 level, and * at the 0.10 level.

Table 6 presents the MM-QR results examining the determinants of TRE across five quantiles (0.10, 0.30, 0.50, 0.70, 0.90) in 11 Arab countries from 2007 to 2023, alongside OLS estimates for comparison. The results reveal significant heterogeneity in how various factors influence renewable energy adoption across different levels of the TRE distribution.

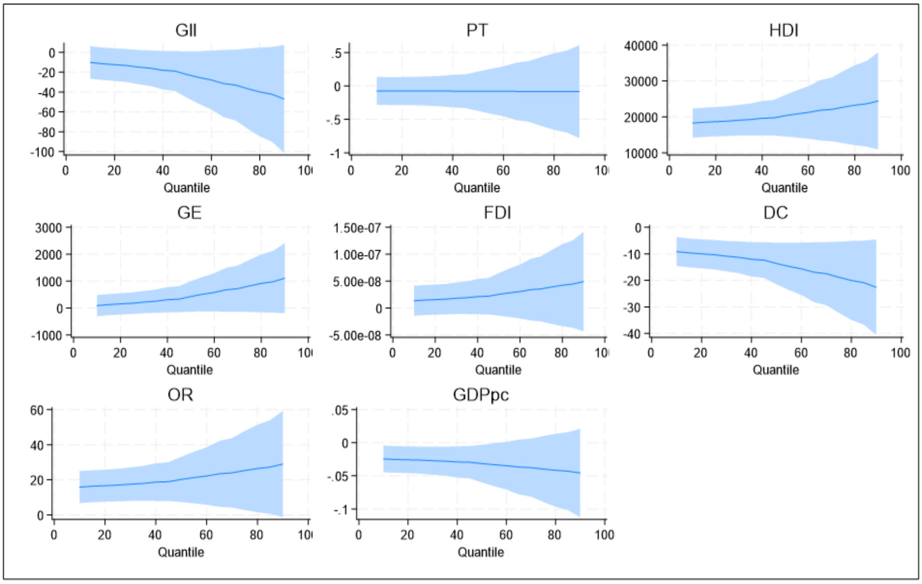

Fig. 1. Quantile estimation on TRE

Figure 1 provides a comprehensive graphical representation of the MM-QR results from Table 6, illustrating how the coefficients of eight independent variables affect TRE across different quantiles of the distribution. The figure contains eight panels, each showing the coefficient trajectory for a specific variable as it varies from the 10th percentile (left) to the 90th percentile (right) of the TRE distribution, with the blue-shaded areas representing 95% confidence intervals. The varying slopes and confidence interval widths across quantiles validate the MM-QR approach, demonstrating that the determinants of renewable energy adoption exhibit heterogeneous effects depending on a country's position in the TRE distribution, with some variables (such as HDI and GII) showing particularly strong quantile-dependent relationships.

Koenker and Bassett (1982) recommend using the Wald test to verify the equality of coefficients across quantiles.

Table 7. Wald test of homogeneity of the coefficients

	0.10				0.30			0.50		0.70
	0.30	0.50	0.70	0.90	0.50	0.70	0.90	0.70	0.90	0.90
GII	1.74 (0.187)	1.75 (0.185)	1.80 (0.179)	1.83 (0.176)	1.68 (0.195)	1.78 (0.181)	1.83 (0.176)	1.72 (0.189)	1.81 (0.178)	1.77 (0.183)
PT	0.14 (0.704)	0.14 (0.704)	0.14 (0.704)	0.14 (0.704)	0.14 (0.705)	0.14 (0.704)	0.14 (0.704)	0.14 (0.704)	0.14 (0.704)	0.14 (0.705)
GDPPC	0.40 (0.529)	0.40 (0.529)	0.40 (0.527)	0.40 (0.527)	0.39 (0.531)	0.40 (0.528)	0.40 (0.527)	0.39 (0.53)	0.40 (0.527)	0.40 (0.528)
HDI	0.80 (0.37)	0.80 (0.369)	0.81 (0.367)	0.82 (0.365)	0.79 (0.374)	0.81 (0.368)	0.82 (0.365)	0.80 (0.371)	0.82 (0.366)	0.81 (0.368)
OR	0.02 (0.891)	0.02 (0.891)	0.02 (0.891)	0.02 (0.891)	0.02 (0.891)	0.02 (0.891)	0.02 (0.891)	0.02 (0.891)	0.02 (0.891)	0.02 (0.891)
DC	1.70 (0.192)	1.72 (0.189)	1.78 (0.182)	1.79 (0.181)	1.59 (0.206)	1.76 (0.184)	1.78 (0.182)	1.73 (0.187)	1.76 (0.184)	1.64 (0.20)
FDI	1.59 (0.206)	1.60 (0.205)	1.65 (0.199)	1.66 (0.197)	1.48 (0.224)	1.63 (0.202)	1.65 (0.198)	1.61 (0.204)	1.64 (0.20)	1.54 (0.214)
GE	1.95 (0.162)	1.99 (0.158)	2.07 (0.15)	2.08 (0.148)	1.83 (0.176)	2.05 (0.152)	2.07 (0.15)	2.01 (0.156)	2.05 (0.152)	1.88 (0.17)

Koenker and Bassett (1982) recommend using the Wald test to verify the equality of coefficients across quantiles. Table 7 presents the Wald test results for coefficient homogeneity across quantiles, serving as a crucial diagnostic tool to determine whether the estimated coefficients from the MM-QR vary significantly across different quantiles of the RE distribution. The table displays Wald test statistics for pairwise comparisons between quantiles (0.10, 0.30, 0.50, 0.70, 0.90) for each of the eight independent variables (GII, PT, GDPPC, HDI, OR, DC, FDI, GE), with p-values shown in parentheses below each test statistic. The null hypothesis is that the coefficients are equal across quantiles, whereas the alternative hypothesis posits heterogeneous effects across the distribution. Examining the p-values reveals that all variables show p-values above 0.05 (ranging from approximately 0.15 to 0.89), indicating that the null hypothesis of coefficient equality cannot be rejected at the 5% significance level for any of the independent variables. This finding suggests that while the point estimates may appear to vary across quantiles in Table 6 and Figure 1, these differences are not statistically significant, implying that the relationships between the explanatory variables and renewable energy adoption are relatively homogeneous across different levels of the TRE distribution. However, this result should be interpreted carefully, as the Wald test's power may be limited by the relatively small sample size (11 countries × 17 years = 187 observations) and the MM-QR method's wide confidence intervals, which could mask true heterogeneous effects that are economically meaningful but not statistically detectable given the available data.

5 Discussion

The negative and statistically significant effects of the GII on renewable energy adoption across quantiles from 0.30 to 0.90 in Arab countries reflect a complex manifestation of the resource curse hypothesis, in which abundant hydrocarbon wealth systematically diverts innovation toward optimizing fossil fuel extraction and processing rather than promoting clean energy technologies (Sun et al., 2024; Topaloglu et al., 2025; Arab et al., 2025; Nchofoung & Ojöng, 2023). This pattern aligns with Cirera and Maloney (2017)'s "innovation paradox," which shows how technological innovation in developing countries can initially obstruct renewable energy deployment due to path dependency and sectoral misallocation of innovative resources. The quantile-specific pattern observed in Arab economies suggests that countries with higher overall innovation rankings paradoxically exhibit lower levels of renewable energy adoption because their elevated GII scores primarily capture innovation in traditional hydrocarbon sectors (Hurnyak et al., 2024; Al-Housani et al., 2024). This structural bias toward fossil fuel innovation is reinforced by the substantial financial returns from oil and gas industries, which create powerful incentives for continued investment in conventional energy technologies rather than renewable alternatives (Espinoza et al., 2022; Droste et al., 2024). The resource curse operates through multiple channels, including the crowding out of clean technology R&D, the entrenchment of fossil fuel-dependent institutional frameworks, and the systematic under-investment in human capital development for renewable energy sectors (Sun et al., 2024; Topaloglu et al., 2025).

Structural lock-in effects, characterized by entrenched fossil-fuel infrastructure that absorbs innovation inputs, further reinforce the negative association between GII and renewable energy adoption across higher quantiles in Arab countries (Topaloglu et al., 2025; Lombard & Ferreira, 2015; Moghadam & Karami, 2024). These path-dependent processes create self-reinforcing cycles in which existing hydrocarbon-based innovation systems become increasingly difficult to redirect toward clean energy technologies, as institutional capacity, research networks, and financial mechanisms remain oriented toward traditional energy sectors (Achakulwisut et al., 2023; Fan et al., 2024). The quantile-dependent reversal of innovation's expected positive effect on renewable energy deployment indicates that Arab countries with more developed innovation systems paradoxically face greater challenges in transitioning to clean energy due to deeper structural lock-ins (Hassan et al., 2025; Hurnyak et al., 2024). Addressing this innovation paradox requires comprehensive policy interventions that systematically realign innovation incentives through targeted clean technology R&D funding, enhanced institutional quality measures, and strategic diversification of innovation portfolios away from fossil-fuel dependence (Al-Housani et al., 2024; Meng et al., 2022; Hassan et al., 2025). These interventions must include establishing dedicated renewable energy innovation zones, implementing green technology transfer mechanisms, and developing regulatory frameworks that encourage private-sector investment in clean energy innovation while gradually reducing subsidies for conventional energy technologies (Huang et al., 2024; Hasan et al., 2024; Wang et al., 2025). Successfully overcoming the structural barriers identified in the quantile regression analysis will require coordinated efforts to break existing path dependencies and create new institutional arrangements that can harness Arab countries' innovation capabilities for sustainable energy transitions (Wan et al., 2022; Meng et al., 2022).

The HDI emerges as the most robust and consistent driver of renewable energy adoption in Arab countries, with highly significant positive coefficients at the 1% level across all TRE quantiles (10th to 90th). HDI's composite structure—encompassing education, health, and living standards—creates multiple pathways for deploying renewable energy, as higher human development not only enhances public awareness and technical skills but also strengthens institutional and financial capacity to implement and sustain clean energy projects (Jamshid et al., 2022). This bidirectional relationship, in which greater human development enables renewable energy adoption and, in turn, renewable energy supports further human development, is well documented in the literature (Azam et al., 2021). Empirical studies confirm that higher educational attainment significantly promotes renewable energy consumption, while improved health and income levels provide the resources and motivation for clean energy transitions (Jamshid et al., 2022; Musakwa & Odhiambo, 2022). Cross-country and regional analyses further highlight that countries with higher HDI not only have greater capacity to invest in and scale up modern renewable technologies but also benefit from a virtuous cycle in which clean energy and human development reinforce each other (Pervaiz et al., 2021; Metwally et al., 2024). Thus, the consistent and strong effect of HDI across the entire TRE distribution underscores the foundational role of human development in enabling the energy transition in the Arab region, supporting the view that policies advancing education, healthcare, and living standards yield significant co-benefits for renewable energy expansion.

High human development, as measured by the HDI, fosters robust innovation ecosystems crucial to advancing renewable energy transitions, despite the current study's finding that total patent applications (PT) show statistically insignificant effects across all quantiles in Arab countries. Stronger intellectual property (IP) protection, often found in higher-HDI contexts, incentivizes firms to invest in novel renewable energy technologies, driving increased production and deployment (Tee et al., 2021). Moreover, the technical complexity of the renewable energy sector, marked by advancements in robotics, automation, and 5G-enabled smart energy storage, necessitates a highly skilled workforce, which high human development cultivates (Iqbal et al., 2019). Parallel advances in digital finance platforms, driven by innovation, democratize access to capital for clean-tech ventures (Zhao & Zhao, 2023). While patent analyses globally demonstrate the critical role of performance-enhancing and cost-reducing innovations in scaling solar and wind technologies (Bayer et al., 2013), and environmental innovation positively drives renewable energy consumption in the EU and China, where political-institutional quality amplifies the impact of clean-tech innovation (Usman et al., 2022; Azam et al., 2022), the effectiveness of such innovations in the MENA region critically hinges on governance robustness (Awijen et al., 2022). This study suggests that while human development broadly nurtures innovation capacity, the specific translation of patenting activity into tangible renewable energy gains in Arab countries may be hindered by other contextual factors not fully captured by the current model's innovation variables.

Quantile regression analysis reveals heterogeneous effects of macroeconomic determinants on renewable energy consumption across the conditional distribution, offering a more nuanced perspective than mean regression (Balcilar et al., 2022). By estimating effects at specific quantiles, one can observe how drivers such as income, resource rents, financial intermediation, and governance quality vary in importance from low to high levels of renewable penetration. In Arab countries, GDPpc exerts a statistically significant negative influence on renewable energy consumption throughout the lower tail (Q10–Q50). This pattern reflects the well-documented resource dependence of early growth phases, in which fossil fuel extraction and consumption dominate investment and infrastructure spending, crowding out nascent renewable energy projects. In the Gulf Cooperation Council (GCC), for example, rising per capita income is initially channeled into expanding conventional energy systems rather than green technologies, yielding an inverse GDPpc–renewables nexus at low levels of renewable adoption (Al-Sarihi & Mansouri, 2022; Zheng et al., 2024). By contrast, oil rents (OR) maintain positive and significant coefficients across all quantiles of the renewable energy distribution. Hydrocarbon-derived fiscal revenues provide governments with stable capital buffers that can be recycled into large-scale solar, wind, and other renewable projects, regardless of baseline penetration. This "rent-recycling" mechanism underlies the consistent stimulative impact of OR on clean energy consumption across the entire conditional distribution in oil-rich Arab economies (Al-Sarihi & Mansouri, 2022; Bhatt, 2021). Domestic credit (DC) displays a robust negative effect on renewable energy uptake at all quantiles. Empirical evidence from the GCC banking sector indicates that credit expansion predominantly targets established fossil fuel, real estate, and public-sector projects, with minimal spillover to the renewable segment. Consequently, broader access to finance paradoxically suppresses clean energy investment across the distribution, reflecting sectoral allocation biases in financial intermediation (Elmonshid et al., 2024). Government effectiveness (GE) attains positive statistical significance only at the upper quantiles (Q70, Q90), reflecting the evolving institutional demands of the energy transition: in early phases, renewable uptake is shaped more by hydrocarbon rents and general financial conditions than by nuanced regulatory oversight, so incremental improvements in GE do not yield substantial gains. However, as renewable penetration deepens, further expansion depends on complex regulatory and administrative processes—such as transparent project tendering, grid integration, and enforcement of power purchase agreements—that require high institutional quality. At these advanced stages, improvements in policy stability, regulatory clarity, and bureaucratic efficiency remove critical barriers, enabling significant growth in renewables. Empirical evidence from the MENA region and beyond corroborates this threshold effect, showing that strong government effectiveness and governance quality become crucial for scaling renewable energy only once baseline consumption is high and market sophistication increases (Mahajan et al., 2024; Rahman & Sultana, 2024; Rafiq et al., 2024; Weng et al., 2024).

6 Conclusions

This study investigated the complex, often counterintuitive relationship between innovation and renewable energy adoption in Arab countries, using the MMQR to capture heterogeneous effects across the distribution of renewable energy consumption. Our central finding reveals a significant "innovation paradox" in the region: the Global Innovation Index (GII) has a statistically significant negative effect on renewable energy adoption across the middle and upper quantiles (0.30 to 0.90). This result provides robust empirical support for the resource curse hypothesis, suggesting that in these hydrocarbon-rich economies, innovation is systematically channeled toward optimizing the incumbent fossil fuel industry rather than fostering a transition to clean energy technologies. The structural lock-in created by entrenched hydrocarbon infrastructure and economic dependencies appears to absorb innovation capacity, paradoxically slowing the energy transition even as overall innovation metrics improve.

Our analysis further reveals a nuanced landscape of determinants shaping the region's future energy. While aggregate innovation indicators like the GII and patent applications show a negative or insignificant relationship with renewable energy, human development emerges as the most powerful and consistent driver of progress. The Human Development Index (HDI) was found to have a highly significant positive effect across all quantiles, underscoring that investments in education, health, and living standards create the foundational capacity, public demand, and technical skills necessary for a sustainable energy transition. Furthermore, our findings indicate that Arab countries are effectively engaging in rent-recycling, as oil rents positively and significantly correlate with renewable energy adoption across the entire distribution, demonstrating that hydrocarbon fiscal revenues are being used to finance clean energy projects. Conversely, domestic credit was found to have a consistently negative impact, reflecting a financial system that continues to prioritize traditional sectors over green investments.

The quantile regression approach also highlighted the evolving role of governance. Government effectiveness becomes a significant positive driver only at the upper quantiles (0.70 and 0.90), suggesting that strong institutional quality is most critical for navigating the complexities of advanced renewable energy integration, such as grid management and sophisticated regulatory frameworks. At lower levels of adoption, financial and resource-based factors are more dominant. This threshold effect provides a critical insight for policymakers: as countries advance their energy transition, the need for robust, transparent, and efficient governance becomes paramount to sustaining momentum.

Based on these findings, this paper offers several key policy recommendations. First, Arab nations must move beyond broad innovation support and implement targeted industrial and innovation policies that explicitly favor green technologies. This requires creating targeted incentives, R&D funding channels, and technology transfer mechanisms to break the fossil fuel sector's structural lock-in. Second, policymakers should recognize human development as a core pillar of their energy transition strategy, as it fosters the most reliable and broad-based support for renewable energy adoption. Third, financial sector reforms are needed to redirect credit flows toward clean energy projects, potentially through green bonds and dedicated credit lines. Finally, a sustained focus on improving government effectiveness is essential, as institutional capacity will become an increasingly important bottleneck as renewable energy systems mature.

This study contributes to the literature by providing the first empirical evidence on the innovation paradox in the Arab world using quantile regression. However, its limitations point to avenues for future research. The Wald test for coefficient equality is statistically insignificant—likely due to the relatively small sample size—suggesting that while the observed quantile patterns are economically meaningful, they warrant further investigation with larger datasets. Future studies should also use more granular, sector-specific data on green innovation to move beyond aggregate indices like the GII. Firm- or project-level analyses could further illuminate the micro-foundations of the innovation paradox and help design more effective policies to ensure that the innovation capabilities of Arab nations are fully harnessed to build a sustainable and prosperous energy future.

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