International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2026, 16(1), 965-973.

Digital Transformation and Renewable Energy Adoption in the MENA Region: An Econometric Analysis

Jihene Yemmen*

Department of Economics and Management Sciences, Manar University (FESGT Campus), Tunis, Tunisia.
*Email: jihene.yemmen@isgb.ucar.tn

Received: 05 August 2025 **Accepted:** 17 November 2025 **DOI:** https://doi.org/10.32479/ijeep.21874

ABSTRACT

This study examines the impact of digital transformation on the adoption of renewable energy sources. It employs the cross-sectionally augmented autoregressive distributed lag model and conducts robustness checks using the fully modified ordinary least squares approach to assess the potential influence of errors or random variations in the data. The analysis covers 12 countries in the MENA region from 2010 to 2023. The results indicate that digital transformation has a positive and statistically significant effect on the share of renewable energy. Governance quality emerges as a key determinant, whereas urbanization exhibits a negative correlation. This research contributes to the literature by providing novel empirical evidence for a region characterized by hydrocarbon dependency. It highlights the need for integrated policies that combine digital development, institutional strengthening, and the management of urban expansion to accelerate the energy transition.

Keywords: Energy Transition, Digital Transformation, Renewable Energy, Panel Econometrics, MENA Region
JEL Classifications: Q42, Q48, C23, O33

1. INTRODUCTION

Confronted with the progressive depletion of fossil fuel reserves and the growing urgency of climate change, the global energy transition has become an imperative. Countries in the Middle East and North Africa (MENA) region occupy a unique position in this landscape. Their economies have historically been heavily dependent on hydrocarbons, which constitute a critical source of economic rent and a foundation for fiscal stability in many states. However, this very dependence also renders them highly vulnerable to external shocks, whether arising from oil price volatility or the direct impacts of climate change, which disproportionately affect this region.

This distinctive energy and geopolitical context creates a specific environment for the adoption of digital transformation. In the MENA region, the digitalization of energy systems extends beyond mere technical efficiency gains; it is an integral part of a strategic agenda aimed at reducing hydrocarbon dependency, diversifying the energy mix, and enhancing economic resilience against global energy market fluctuations.

Consequently, the energy transition in the MENA region assumes a strategically vital role, particularly as it aligns with international commitments such as the Sustainable Development Goals (SDGs) and the recommendations of major climate conferences, which advocate for the accelerated deployment of renewable energy sources.

Within this framework, digital transformation emerges as a potentially decisive lever. The application of technologies such as artificial intelligence (AI), automated control systems, cloud computing, and energy optimization platforms enables more efficient management of energy systems. These tools facilitate the seamless integration of intermittent renewable sources, enhance energy efficiency, improve grid flexibility, and support decentralized models that are aligned with the ambitions of Sustainable Development Goal 7 (SDG 7) on "Affordable and Clean Energy."

Nevertheless, while digital transformation is often portrayed as a catalyst for sustainability, it is not without its challenges. It generates new energy and environmental costs (e.g., from data centers and equipment manufacturing), can increase technological dependencies, and may exacerbate existing social inequalities. Despite these caveats, the prevailing hypothesis in the recent empirical literature is that, on balance, digital transformation acts as a net positive driver for renewable energy adoption (REN) by helping to mitigate structural barriers related to integration costs and supply variability.

This study specifically aims to analyze the relationship between digital transformation (DIG) and renewable energy adoption (REN) in MENA countries. Utilizing a dataset covering the period 2010-2023 and applying robust econometric techniques namely the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) and fully modified ordinary least squares (FMOLS) methods the study examines the impact of digital transformation on renewable energy integration. The analysis controls for key variables, including foreign direct investment (FDI), economic growth, governance quality, and urbanization.

This methodological framework enables a threefold contribution:

Theoretical: Deepening the understanding of the role of digital technologies in energy transitions;

Empirical: Providing quantitative evidence for a region that remains understudied despite its structural dependence on fossil fuels;

Practical: Informing policymakers about strategies to reconcile energy transition, economic security, and social inclusion.

2. LITERATURE REVIEW: DIGITAL TRANSFORMATION AND RENEWABLE ENERGY ADOPTION

International scholarship increasingly underscores the contributions of digitalization to energy systems. According to the International Renewable Energy Agency (IRENA, 2025), the application of digital technologies such as artificial intelligence (AI), smart sensors, and digital twins extends beyond the optimization of energy production and consumption. These innovations also enhance grid flexibility while reducing the costs associated with integrating intermittent renewable energy sources. In this context, smart grids constitute essential tools for balancing supply and demand, facilitating storage solutions, and enabling the decentralized integration of local energy producers.

Empirical evidence substantiates this dynamic. A study of 18 Middle East and North African countries between 2000 and 2020 found that digital transformation exerts a positive effect on renewable energy adoption, interacting with both economic growth and institutional quality (Bekhet and Matar, 2023; Alshubiri et al., 2025). Similarly, recent research in the European Union confirms that digitalization amplifies the impact of renewable energy on sustainable development, primarily through enhanced energy efficiency and reduced greenhouse gas emissions (Sun et al., 2021; Zarrad et al.,2025).

Prospective analyses corroborate this trend. Kougias et al. (2025) emphasize the growing importance of digital solutions for renewable energy integration, highlighting the roles of energy markets, battery storage, microgrids, and demand-response systems (Kouveliotis et al., 2025). Furthermore, recent work on digital twins demonstrates their capacity to improve the accuracy and efficiency of investment decisions, underscoring the strategic function of digital tools in the energy transition (Li et al., 2024).

From a conceptual standpoint, two complementary theoretical frameworks elucidate the relationship between renewable energy adoption (REN) and digital transformation (DTR). Socio-technical transition theory (Rip and Kemp, 1998; Smith et al., 2005; Markard and Truffer, 2008) illuminates the multi-level dynamics of energy transitions, whereby digital technology niches progressively contribute to transforming fossil-fuel-dominated regimes. From this perspective, smart sensors, data platforms, and digital networks act as key vectors for the diffusion of renewables. The digital economy framework (Brynjolfsson and McAfee, 2014; Kusiak, 2017) complements this view by emphasizing how digital technologies reshape the structure and performance of energy systems.

A comprehensive meta-analysis by Ferdaus et al. (2024), which examined over 2,000 studies, assessed the impact of advanced digital technologies including artificial intelligence, blockchain, digital twins, cloud computing, the Internet of Things (IoT), and robotics on the transition toward carbon-neutral energy systems. The authors conclude that these technologies influence both technical and institutional dimensions, thereby facilitating the evolution of markets, business models, and regulatory frameworks.

Zhao et al. (2024) further demonstrate that the development of digital infrastructure and the digital economy stimulates technological innovation and patent creation, thereby advancing renewable energy adoption and improving carbon emission performance.

Multiple studies have investigated the combined impact of digital transformation and renewable energy adoption across diverse regional contexts. Hwang and Sánchez Díez (2024), for instance, find that in Latin American economies, the transition to renewable energy stimulates green economic growth, an effect moderated by national income levels and emissions. Complementing this, Alofaysan et al. (2024) show that in 22 European countries, digital investments coupled with renewable energy adoption enhance energy efficiency, although certain macroeconomic factors, such as GDP levels and energy price structures, can constrain these benefits.

Moreover, Hossain and Tabash (2024) emphasize that digital transformation fosters green innovation in emerging economies, contingent upon adequate institutional support, R&D investment, and appropriate green financing mechanisms. Finally, Behera and

Ghosh (2025) highlight that digital transformation strengthens green innovation, particularly in countries with higher R&D intensity and greater political stability.

Sectoral analyses yield complementary insights into the interactions between digital transformation and environmental performance. Sethi et al. (2022) demonstrate that the impact of information and communication technologies (ICTs) on the ecological footprint is highly contingent on existing institutional frameworks and environmental policies. In the manufacturing sector, Jin et al. (2020) find that digital transformation enhances carbon competitiveness by optimizing value chains and improving the energy mix. Similarly, Safi et al. (2021) emphasize that digital maturity, when supported by green financial instruments, significantly contributes to emission reductions, whereas unregulated technological experimentation may conversely exacerbate environmental pressures. These findings collectively underscore the necessity of tailored policies and regulations to maximize the environmental co-benefits of digitalization.

In oil-exporting countries, Sarabdeen et al. (2022) observe that access to digital technologies generally improves environmental quality, although the magnitude of this effect varies with the availability of internet and telecommunications infrastructure. Ullah et al. (2021) confirm that digital strategies support the transition to renewables and promote sustainable development, while noting significant regional variations.

Within the MENA region, several initiatives concretely illustrate the interplay between digital transformation and the energy transition. In the United Arab Emirates, the Smart Dubai program and the Shams Dubai project integrate smart meters and digital platforms to optimize residential solar self-consumption. Saudi Arabia's Vision 2030 strategy promotes the deployment of smart grids and digital storage solutions to support the expansion of renewable energy. Morocco, a regional pioneer, combines the Noor solar power plant with digital monitoring and management systems to enhance grid flexibility. In Egypt, the adoption of digital grid management systems helps reduce technical losses and facilitates the integration of solar and wind projects. These examples indicate that, despite substantial fossil fuel dependence, several MENA countries are actively leveraging digital tools to advance renewable energy integration, although systematic comparative studies remain scarce.

According to Alsuhaibany (2021), digital innovation, coupled with circular economy principles, enhances operational efficiency and sustainable resource consumption in Saudi Arabia's oil and gas sector. Liu et al. (2025) report that the deployment of industrial robots, alongside digital maturity, promotes ecological innovation within Chinese manufacturing firms, particularly in large enterprises and technology-intensive sectors. Zhang et al. (2022) further demonstrate that digital transformation fosters green innovation, especially in contexts characterized by stringent regulatory frameworks.

Research on education and green financing provides a complementary perspective. Ronaghi and Ronaghi (2023) demonstrate that the adoption of artificial intelligence (AI) in Middle Eastern universities strengthens institutional sustainability by enhancing both social equity and environmental management. In a similar vein, Twum et al. (2022) show that financial support moderates the relationship between ecological footprint and renewable energy adoption in Belt and Road Initiative (BRI) countries, underscoring the importance of aligning financing mechanisms with digital strategies.

Several recent empirical studies have sought to quantify the impact of digital transformation on renewable energy adoption across diverse regional contexts. For instance, Hwang (2024) employs panel data techniques to demonstrate that digitalization facilitates renewable energy integration in Latin American economies, with effects that are moderated by national income levels and energy intensity. Similarly, Alofaysan et al. (2024), applying Autoregressive Distributed Lag (ARDL) models to a panel of 22 European countries, find that digital investments significantly enhance the effectiveness of energy transition policies. These methodological approaches justify the use of robust econometric techniques, such as the Cross-Sectionally Augmented ARDL (CS-ARDL) and Fully Modified Ordinary Least Squares (FMOLS), to estimate the effect of digital transformation on renewable energy adoption in the MENA region, while controlling for the unique institutional, economic, and social specificities of each country.

In summary, the literature largely converges on the view that digital transformation serves as a pivotal tool for optimizing energy efficiency, fostering green innovation, and reducing carbon emissions, with its effectiveness being contingent upon institutional and regulatory frameworks. Nevertheless, empirical evidence remains fragmented across different regions, with a notable gap in the MENA context.

In light of this review, the following main hypothesis is proposed:

H_1: The integration of digital technologies in the energy sector significantly stimulates the adoption of renewable energy.

Within the MENA region, recent studies have established a strong correlation between digital advancement and the growth of renewable energy, underscoring their combined role in fostering a more sustainable economic model. Digital technologies encompassing energy efficiency solutions, smart management systems, and green innovation tools are increasingly recognized as pivotal levers for reducing carbon emissions and strengthening the resilience of local economies. Nevertheless, while the broader international literature largely confirms the positive influence of digital transformation on the energy transition, empirical research dedicated specifically to the MENA context remains scarce. This lacuna hinders a comprehensive understanding of the specific institutional, technological, and socio-economic mechanisms through which digitalization can accelerate renewable energy adoption in a region marked by a profound structural dependence on hydrocarbons.

3. RESEARCH METHODOLOGY

3.1. Data and Sample

The empirical analysis is based on a panel of MENA countries for which sufficiently comprehensive and consistent statistical data are available from 2010 to 2023. The selection of this timeframe was guided by several considerations. First, it aligns with the proliferation and maturation of pivotal digital technologies such as artificial intelligence, the internet of things, and big data and a concurrent shift in energy policies, characterized by the adoption of ambitious national diversification strategies (e.g., Saudi Arabia's Vision 2030 and Morocco's Solar Plan). Second, this 14-year span offers a sufficiently long observation period for the application of dynamic panel econometric techniques, allowing for the robust estimation of long-term relationships while mitigating biases associated with structural heterogeneity prevalent in earlier decades. Finally, this period captures significant exogenous shocks, particularly the COVID-19 pandemic and substantial oil price volatility; their inclusion strengthens the analytical rigor and policy relevance of the findings.

The sample composition was determined by data availability and continuity, particularly for the digital transformation variable. The study consequently comprises twelve countries: Morocco, Algeria, Tunisia, Egypt, Jordan, Lebanon, Saudi Arabia, Israel, Iran, the United Arab Emirates, Oman, and Bahrain. The use of this balanced panel ensures robust and comparable time series, which is essential for the reliable estimation of panel econometric models. Countries experiencing prolonged armed conflicts (e.g., Libya, Yemen, Syria) or those with significant data gaps were excluded to maintain the dataset's integrity and consistency.

Data were sourced from harmonized international databases. The share of renewable energy in total final energy consumption (REN) and real gross domestic product (GDP) were obtained from the World Bank's World Development Indicators (WDI). Data on imports of information and communication technology (ICT) goods and foreign direct investment (FDI) stocks in constant dollars were sourced from UNCTADstat.

Governance quality (GGI) is measured using the Worldwide Governance Indicators (WGI), which aggregate six key dimensions: Voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption. This composite index captures overall institutional performance, a critical factor for renewable energy diffusion and investment attractiveness. Finally, the urbanization rate (URBN), also retrieved from the WDI, measures the percentage of the population residing in urban areas, reflecting its significant influence on energy demand patterns and infrastructure requirements.

These standardized sources ensure the temporal and geographic comparability of the data, thereby underpinning the empirical robustness of the analysis. Table 1 presents the details of the respective variables, including measurement definitions, data sources, and summary statistics.

3.2. Variable Definitions

3.2.1. Dependent variable

Renewable energy (REN): The dependent variable in this study is the share of energy consumption from renewable sources. This indicator allows for the assessment of the degree of integration of sustainable and clean energy sources into a country's energy mix. A higher REN value reflects a stronger commitment to environmentally friendly energy alternatives, contributing both to reducing reliance on fossil fuels, enhancing energy security, and preserving ecosystems. The evolution of this variable depends on various economic, technological, and institutional factors, highlighting its central role in the energy transition process and in promoting sustainable development.

3.2.2. Independent variable

Digital transformation (DIG): This independent variable captures the degree of adoption and integration of digital technologies into a country's economic and social activities. In this study, it is measured by the value of ICT goods imports (computers, telecommunications equipment, and software) relative to total imports. A higher DIG value indicates an increased capacity to modernize production processes, improve energy efficiency, and promote the use of renewable energy. Through smart grids and data-driven decision-making, digital transformation thus contributes to the development and deployment of renewable energy sources within the economy.

3.2.3. Control variables

Foreign direct investment (INV): This variable reflects the contribution of international financial flows to the development of renewable energy by providing capital, technology, and infrastructure for energy projects. In this study, FDI is measured by the cumulative stock of foreign direct investment, expressed in constant thousand US dollars. This measure allows for comparisons of total foreign investment over time and across countries while controlling for inflation effects.

Economic growth (GDP): Economic growth is measured by

Table 1: Variable definitions and data sources

Variables	Définitions	Notations	Sources
Renewable energy	Percentage of total energy consumption derived from renewable sources	REN	World Development Indicators
Digital transformation	Share of imports of ICT-related goods (computers, telecommunications equipment, software) in total imports	DIG	UNCTADstat
FDI	Total inward foreign direct investment (FDI) stock, expressed in constant thousand US dollars	INV	UNCTADstat
Rate of economic growth	Real Gross Domestic Product (GDP), expressed in constant thousand US dollars	GDP	World Development Indicators
Governance	Global Governance Indicator	GGI	Worldwide Governance Indicators (WGI)
Urbanization rate	Share of urban population as a percentage of total population	URBN	World Development Indicators (WDI)

Source: Compiled by the author

gross domestic product (GDP) in constant thousand US dollars, representing inflation-adjusted national output. This indicator is widely used in econometric literature and is available for most MENA countries via World Bank data. It enables the assessment of real economic performance and examines the extent to which economic growth may facilitate investment in renewable energy projects and influence energy demand.

Governance (GGI): This control variable measures the overall effectiveness of public institutions. It is constructed as the arithmetic mean of the six dimensions of the worldwide governance indicators (WGI): political stability, rule of law, regulatory quality, policy coherence, control of corruption, and government effectiveness. The GGI thus synthesizes overall institutional performance and represents a key determinant in promoting renewable energy diffusion and enhancing the attractiveness of investments in the energy sector.

Urbanization (URBN): This variable is estimated based on the traditional urbanization rate, defined as the ratio of the population living in urban areas to the total population. Urbanization plays a crucial role in energy consumption, as urban areas generally have higher energy needs and benefit from better-designed infrastructure for energy production, distribution, and consumption.

3.3. Econometric Model

The relationship between the variables can be expressed by the following equation:

Equation (1):

$$REN_{it} = \beta_0 + \sum\lambda_1 \Delta REN_{it-1} + \sum\beta_1 \Delta DIG_{it-1} + \sum\gamma 1 \Delta INV_{it-1} + \sum\gamma 2 \Delta GDP_{it-1} + \sum\gamma 3 \Delta GGI_{it-1} + \sum\gamma 4 \Delta URBN_{it-1} + \psi 1 REN_{it-1} + \psi 2 DIGi_{it-1} + \psi 3 INVi_{it-1} + \psi 4 GDPi_{it-1} + \psi 5 GOVi_{it-1} + \psi 6 URBNit-1 + \mu_{it}$$

Equation (1) highlights the short-term and long-term effects of the variables included in the model. In this framework, REN denotes renewable energy adoption, DIG represents digital transformation, INV refers to international investment flows, GDP captures economic growth, GGI measures institutional quality, and URBN indicates the degree of urbanization. The coefficients λ, θ, ψ reflect the intensity of the relationships between the variables, while i and t correspond to the cross-sectional and temporal dimensions, respectively.

To ensure the robustness of the results, the CS-ARDL model is complemented by estimation using the Fully Modified Ordinary Least Squares (FMOLS) method. The corresponding equation can be expressed as follows:

Equation (2): FMOLS model

$$REN_{it} = \beta_0 + \lambda_1 DIG_{it} + \beta_1 INV_{it} + \beta_2 GDP_{it} + \beta_3\ GGI_{it} + \beta_4 URBN_{it} + \mu_{it}$$

Equation (2) allows for the analysis of long-term relationships between the dependent variable, renewable energy adoption (REN), and the explanatory variables. The primary focus is placed on the impact of digital transformation (DIG) on the energy transition, while the other variables (investment, economic growth, governance, and urbanization) serve as controls.

4. DESCRIPTIVE ANALYSIS

The descriptive statistics for the sample are presented in Table 2.

Table 2 presents a descriptive analysis summarizing the statistical properties of the variables under study. The share of renewable energy (REN) in total final energy consumption averages 5.12%, highlighting the still-marginal integration of sustainable resources into the regional energy mix. A minimum value approaching zero reflects the continued heavy reliance on fossil fuels in certain economies, whereas the maximum of 16.45% indicates that some countries are making more substantial progress in their energy transitions.

Digital transformation (DIG), proxied by the share of ICT goods imports, displays a mean of 6.35%. This suggests an intermediate level of digital adoption, with considerable heterogeneity across the sample. The minimum value (1.02%) signifies a still-nascent level of digital integration in some contexts, while the maximum (12.56%) reveals more advanced development in others.

Foreign direct investment stocks (INV), expressed as a percentage of GDP, average 3.47%. This points to a moderate role for FDI in the region's economies. The considerable dispersion ranging from 0.15% to 11.92% reveals pronounced structural disparities in investment attractiveness and the quality of the business environment among the sampled countries.

Economic growth (GDP) exhibits a mean annual rate of 2.85%, indicative of moderate regional expansion. The considerable dispersion, however, ranging from −6.30% to 9.85%, reveals pronounced macroeconomic volatility. This heterogeneity is likely driven by exogenous shocks, commodity price fluctuations, and episodes of political and institutional instability.

The composite governance indicator (GGI) has a slightly negative mean value of −0.152, signaling that institutional quality across the region, on average, falls below international benchmarks. The broad spectrum of values, from −1.22 to 0.88, highlights substantial cross-country divergence. This suggests a clear dichotomy between nations grappling with profound institutional

Table 2: Descriptive statistics

Variable	Observations	Mean	Standard deviation	Min.	Max.
REN	168	5.120	3.14	0.21	16.45
DIG	168	6.350	2.12	1.02	12.56
INV	168	3.470	2.26	0.15	11.92
GDP	168	2.850	3.05	−6.30	9.85
GGI	168	-	0.45	−1.22	0.88
URBN	168	67.84	13.27	38.20	92.44

Source: Authors' estimation

deficits and those with more robust and effective governance frameworks.

Finally, the urbanization rate (URBN) averages 67.84%, indicating that approximately two-thirds of the population in the sample resides in urban areas. This advanced stage of urbanization presents a dual role: It can serve as a catalyst for technological adoption and energy innovation, while simultaneously generating escalating demand and pressure on existing energy systems and ecological infrastructure.

Before proceeding with a deeper examination of the correlation coefficients, it is important to note that this stage constitutes a preliminary descriptive analysis, designed to assess the nature and strength of the interrelationships among the key variables of the model. The correlation matrix provides an initial overview of the potential interactions between digital transformation, renewable energy adoption, and the control factors (FDI, economic growth, governance, and urbanization). Although it does not allow for causal inference, this exploratory analysis is crucial for detecting significant associations, anticipating potential multicollinearity issues, and guiding the econometric specification of the panel models employed later in the study.

Table 3 reveals several notable correlations among the variables under consideration.

Digital transformation (DIG) exhibits a moderate positive correlation with renewable energy (REN), suggesting that higher levels of digitalization tend to be associated with a greater share of renewable energy sources. Governance (GGI) shows substantial positive correlations with both REN and DIG, underscoring the central role of institutional quality in shaping energy and digital dynamics. Foreign direct investment (INV) is positively correlated with DIG and GGI, but its association with REN remains very weak (r = 0.080), indicating that the contribution of FDI to the energy transition is limited and likely indirect.

Urbanization (URBN) is negatively associated with REN and GGI, reflecting the specific characteristics of highly urbanized MENA economies, historically dependent on hydrocarbons. Economic growth (GDP) shows only weak correlations, particularly with REN, suggesting that its relationship with the energy transition is more complex and mediated by other structural factors**.**

Taken together, these descriptive findings highlight the need for further investigation through robust multivariate econometric models (e.g., CS-ARDL, FMOLS) to identify the direct causal impact of digital transformation on renewable energy adoption, while accounting for the influence of additional determinants.

Table 3: Correlation analysis results

Variable	REN	DIG	INV	GDP	GGI	URBN
REN	1.000	0.427	0.080	−0.112	0.501	−0.283
DIG	0.427	1.000	0.382	0.241	0.467	0.105
INV	0.080	0.382	1.000	0.098	0.355	−0.198
GDP	−0.112	0.241	0.098	1.000	0.174	0.064
GGI	0.501	0.467	0.355	0.174	1.000	−0.231
URBN	−0.283	0.105	−0.198	0.064	−0.231	1.000

Source: Authors' calculation

4.1. Estimation Techniques

This study examines the influence of digital transformation on the development of renewable energy by employing econometric methods suited to panel data analysis. The empirical strategy is structured around three key methodological stages: Assessing cross-sectional dependence, testing the stationarity properties of the variables, and investigating long-term cointegration relationships.

4.2. Cross-Sectional Dependence Test

When residuals exhibit correlations across cross-sectional units, dependence tests are conducted, notably the Breusch-Pagan LM test and the Pesaran CD test. The results (Table 4) indicate statistically significant interdependence ($P < 0.001$), thereby justifying the use of the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) model. This framework captures both short- and long-term dynamics while explicitly accounting for cross-sectional dependence.

4.3. Panel Unit Root Analysis

Panel unit root tests, specifically the CIPS and CADF tests, were conducted to assess the stationarity properties of the series. The results (Table 5) indicate that some variables, such as renewable energy adoption (REN) and government effectiveness (GGI), become stationary only after first differencing (I(1)), whereas other variables, including digital transformation (DIG), foreign direct investment stocks (INV), economic growth (GDP), and urbanization (URBN), are stationary at levels (I(0)). This mix of variables integrated of different orders supports the use of the CS-ARDL model, which allows for the estimation of both short- and long-term relationships without requiring prior differencing of the series.

4.4. Long-Term Cointegration Analysis

To examine the presence of persistent long-term relationships, a cointegration test based on the Kao residuals approach was employed (Table 6).

Table 4: Cross-sectional dependence tests

Test	Statistique	P-value
Test de Breusch-Pagan LM	125.36	0.000
Test LM de Pesaran scaled	10.32	0.000
Pesaran CD	7.84	0.000

Source: Author's calculations

Table 5: Variable stationarity

Variable	CADF (level)	CADF (1re diff.)	CIPS (level)	CIPS (1re diff.)	Integration
REN	−1.72	−3.94***	−1.65	−3.87***	I (1)
DIG	−3.56***	—	−3.44***	—	I (0)
INV	−3.10**	—	−3.05**	—	I (0)
GDP	−3.21**	—	−3.15**	—	I (0)
GGI	−1.95	−4.05***	−1.88	−4.00***	I (1)
URBN	−3.11**	—	−3.06**	—	I (0)

Source: Author's calculations. ***P<0.01; *P<0.05; P<0.1

The test was applied to the full panel, including the variables REN, DIG, INV, GDP, GGI, and URBN. The Kao cointegration test (Table 6) yields an ADF statistic of 1.632 with a P = 0.065, indicating marginal significance. These results suggest a moderate long-term correlation among the examined variables in the panel. Although the level of significance is not particularly strong, it is sufficient to warrant the use of the CS-ARDL model, which enables the joint examination of short- and long-term interactions while accounting for the combination of variables stationary at levels (I(0)) and after first differencing (I(1)), as well as cross-sectional dependence across countries.

Finally, to enhance the robustness of long-term estimates and correct for potential endogeneity and autocorrelation issues, the fully modified ordinary least squares (FMOLS) method was employed as a complementary approach. This technique validates the estimated relationships and ensures a rigorous interpretation of long-term coefficients.

5. RESULTS

This section presents the empirical findings of the econometric estimations. The analysis begins with the main results obtained from the CS-ARDL model, followed by a robustness check using the FMOLS method.

5.1. Main Results from the CS-ARDL Model

Table 7 reports the estimation results of the CS-ARDL model, distinguishing between long-term and short-term effects.

Table 6: Long-term cointegration analysis

Kao Test	Statistique ADF	P-value
ADF	1.632	0.065

Source: Author's calculations. The marginal significance (P≈0.065) indicates cointegration at the 10% level, thereby justifying the use of the CS-ARDL model to estimate both short- and long-term relationships

Table 7: Impact of digital transformation (DIG) on renewable energy integration (REN), controlling for INV, GDP, GGI, and URBN

Variable	REN (dependent)	Coefficient	Standard error	T-statistic
Long-term Equation				
DIG	0.028***	0.007	3.698	0.000
INV	0.008***	0.002	3.795	0.000
GDP	0.008**	0.003	2.213	0.028
GGI	0.258***	0.032	8.041	0.000
URBN	−0.125***	0.030	−4.087	0.000
Short-term equation				
COINTEQ01	−0.340**	0.147	−2.302	0.022
ΔDIG	−0.020	0.059	−0.342	0.732
ΔINV	−0.004	0.038	−0.111	0.911
ΔGDP	−0.011	0.015	−0.769	0.442
ΔGGI	−0.188	0.532	−0.354	0.723
ΔURBN	−0.461	2.760	−0.167	0.867
Constante (C)	0.838*	0.441	1.896	0.059

Source: Author's calculations. ***P<0.01, *P<0.05, P<0.10; Δ denotes the first difference of the variables

The long-term results indicate that the coefficient of digital transformation (DIG) is positive (0.028) and statistically significant at the 1% level, suggesting a positive relationship between the adoption of digital technologies and the share of renewable energy in the energy mix. Among the control variables, foreign direct investment (INV) and economic growth (GDP) both exhibit positive and significant coefficients (0.008 each). Governance (GGI) displays the largest coefficient (0.258), significant at the 1% level, highlighting its critical role. In contrast, urbanization (URBN) shows a negative coefficient (−0.125), also significant at the 1% level.

In the short-term equation, only the error correction term (COINTEQ01) is significant and negative, confirming convergence toward the long-term equilibrium. The first differences of the other variables are not statistically significant in the short term.

5.2. Robustness Analysis using the FMOLS Model

To assess the robustness of the CS-ARDL model results, the fully modified ordinary least squares (FMOLS) method was employed. The estimation results are presented in Table 8.

The FMOLS estimates confirm the robustness of the previously identified long-term relationships. Digital transformation (DIG) retains a positive and significant impact (0.098) on renewable energy adoption. The significance and signs of the control variables (INV, GDP, GGI, URBN) are also confirmed, further reinforcing the reliability of the conclusions.

5.3. Discussion

The principal objective of this study was to investigate the impact of digital transformation on renewable energy adoption within the MENA region. The central hypothesis (H_1), postulating a positive and significant effect of digital transformation (DIG) on the renewable energy share (REN), is robustly validated by both the CS-ARDL and FMOLS estimators. This result aligns with the broader scholarly consensus. For instance, Ozcan et al. (2023) established that digitalization, through the optimization of smart grids and the deployment of the internet of things (IoT), significantly improves the efficiency and grid integration of renewables. Similarly, Usman et al. (2021) identified digital maturity as a critical driver of the energy transition, especially in emerging economies.

Table 8: Robustness analysis impact of digital transformation (DIG) on renewable energy adoption (REN) FMOLS results

Variable	Coefficient	Standard error	T-statistic	Prob.
DIG	0.098***	0.036	2.722	0.003
INV	0.198***	0.061	3.246	0.001
GDP	0.212***	0.058	3.655	0.000
GGI	0.189***	0.045	4.200	0.000
URBN	−0.107**	0.053	−2.021	0.044
Adjusted R-squared	**0.772**			
S.E. of regression	**1.612**			
Long-run variance	**5.031**			

Source: Author's calculations. ***P<0.01, *P<0.05, P<0.10

Concerning the control variables, the positive and significant coefficient for foreign direct investment (FDI) implies that international capital inflows play a complementary role by financing critical infrastructure and enabling the transfer of clean technologies. Although its marginal effect is smaller than that of digital transformation in the CS-ARDL specification, this finding is consistent with extant literature. Sadorsky (2013) underscored FDI's pivotal role in augmenting renewable energy capacity in developing nations, providing not just capital but also vital technical knowledge.

The positive association between economic growth (GDP) and renewable energy adoption lends support to the logic of the Environmental Kuznets Curve (EKC) within the energy sector. This suggests that upon reaching a certain developmental threshold, economic prosperity generates the requisite fiscal space for sustainable infrastructure investments and responds to growing societal demand for cleaner energy, a dynamic noted by Destek and Sarkodie (2019).

The particularly pronounced effect of governance (GGI) underscores that institutional quality is a fundamental determinant of the energy transition's pace. Sound institutions that guarantee the rule of law, policy predictability, and government effectiveness mitigate investment risks and create a conducive environment for long-term energy projects. This conclusion is widely corroborated. Bhattacharya et al. (2016) argued that in the absence of good governance, renewable energy policies often fail to achieve their objectives, while Al-Mulali et al. (2015) confirmed the indispensable role of political stability and regulatory quality in advancing the transition in MENA countries.

Conversely, the negative correlation between urbanization (URBN) and the renewable energy share reveals a distinct regional challenge. It suggests that, in the MENA context, rapid urban expansion is primarily associated with surging energy demand that is frequently met by incumbent fossil-based systems, a consequence of infrastructural inertia and path dependency. This phenomenon has been observed in other regions; for example, Salahuddin et al. (2019) demonstrated that unmanaged urbanization can impede renewable energy progress by overburdening existing networks and diverting investment from new sustainable infrastructure.

In conclusion, the findings of this study highlight a critical synergy between digital transformation and robust governance for accelerating the energy transition in the MENA region. They also affirm the enabling roles of foreign investment and sustained economic growth, while pinpointing the structural complications introduced by rapid urban development. These insights indicate that integrated policy frameworks which strategically combine digital advancement, institutional reinforcement, and targeted green investment are paramount for orchestrating a successful energy transition.

6. CONCLUSION

This study makes an original empirical contribution by addressing a significant gap in the quantitative literature on the MENA region, a critical arena in global energy geopolitics. By rigorously applying CS-ARDL and FMOLS econometric techniques to data from 2010 to 2023, it provides robust evidence of the catalytic effect of digital transformation on renewable energy adoption within economies historically dominated by hydrocarbons.

From a theoretical perspective, the findings validate and clarify the mechanisms of energy transitions in a fossil-fuel-dependent context. They underscore the predominant role of institutional quality as a pivotal determinant while identifying rapid urbanization as a significant structural impediment. Consequently, the results advocate for integrated policy frameworks that strategically combine targeted digital development, institutional strengthening, and sustainable urban planning.

Notwithstanding limitations related to data availability, this research opens promising avenues for future inquiry. Subsequent studies could investigate the specific conditions for a successful energy transition in rentier economies, particularly by exploring the micro-level channels of digital adoption and the political economy of institutional reform.

REFERENCES

Al-Mulali, U., Ozturk, I., Lean, H.H. (2015), The influence of economic growth, urbanization, trade openness, financial development, and renewable energy on pollution in Europe. Natural Hazards, 79(1), 621-644.

Alofaysan, H., Radulescu, M., Sarabdeen, M. (2024), The effect of digitalization and green technology innovation on energy efficiency in the European Union. Energy Policy, 195, 114344.

Alshubiri, F., Elheddad, M., Djellouli, N. (2025), Digital transformation and renewable energy adoption in the Middle East: The role of FDI and institutional quality. Energy Policy, 187, 114055.

Alsuhaibany, A.M. (2021), Digital innovation and circular economy in the oil and gas sector: A case study of Saudi Arabia. Resources Policy, 74, 102317.

Behera, P., Ghosh, S. (2025), Catalyzing the role of renewable energy, green growth, ICT, and political risk in achieving carbon neutrality target in the emerging economies. Amsterdam, Netherlands: Elsevier.

Bhattacharya, M., Churchill, S.A., Paramati, S.R. (2016), The dynamic impact of renewable energy and institutions on economic output and CO_2 emissions across regions. Renewable Energy, 111, 157-167.

Brynjolfsson, E., McAfee, A. (2014), The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies. New York: W. W. Norton & Company.

Bekhet, H. A., Matar, A. (2023), Digitalization and energy sustainability in MENA countries: The roles of financial development and institutional quality. Environmental Science and Pollution Research, 30(52), 112582-112601.

Destek, M.A., Sarkodie, S.A. (2019), Investigation of environmental Kuznets curve for ecological footprint: The role of energy and financial development. Science of the Total Environment, 650, 2483-2489.

Ferdaus, M.M., Dam, T., Anavatti, S. (2024), Digital technologies for a net-zero energy future: A comprehensive review. Renewable and Sustainable Energy Reviews, 202, 114681.

Hossain, M.I., Tabash, M.I. (2024), Empirical assessment of digital transformation and green innovation in emerging economies. Environmental Economics and Policy Studies, 26(2), 305-322.

Hwang, Y.K., Sánchez Díez, Á. (2024), Renewable energy transition and green growth nexus in Latin America. Renewable and Sustainable Energy Reviews, 198, 114431.

IRENA. (2025), Digitalisation for the Renewable Energy Transition. United Arab Emirates: International Renewable Energy Agency.

Jin, W., Zhang, H., Liu, S. (2020), Digital transformation and carbon competitiveness in the manufacturing sector. Journal of Environmental Management, 270, 110817.

Kouveliotis, K., Stergiou, D., Tsalikis, G. (2025), Digital solutions for renewable energy integration: The role of power purchase agreements, battery storage, and microgrids. Energy Reports, 15, 123-135.

Kougias, I., Gattringer, A., Segreto, L., Mondelli, N., Bi, C., Cano, J., Della Valle, N. (2025), Integration of renewable energy sources in the digital age: The crucial roles of energy markets, battery storage, microgrids and demand response systems. In International Energy Agency, Digitalisation and energy, 2024, 117-141.

Kusiak, A. (2017), Smart Manufacturing: Concepts and Methods. United States: John Wiley & Sons.

Li, X., Wang, Y., Zhang, Z. (2024), Digital twins for enhancing investment efficiency in renewable energy projects. Applied Energy, 353, 122058.

Liu, Y., Chen, J., Zhao, X. (2025), Industrial robots, digital maturity, and green innovation in Chinese manufacturing firms. Technovation, 131, 102956.

Markard, J., Truffer, B. (2008), Technological innovation systems and the multi-level perspective: Towards an integrated framework. Research Policy, 37(4), 596-615.

Ozcan, B., Usman, M., Godil, D.I. (2023), The role of digitalization in energy efficiency and renewable energy deployment. Energy Economics, 125, 106855.

Rip, A., Kemp, R. (1998), Technological change. In: Rayner, S., Malone, E.L., editors. Human Choice and Climate Change. Vol. 2. Florida: Battelle Press. p327-399.

Ronaghi, M., Ronaghi, M. (2023), The impact of artificial intelligence adoption on sustainability in Middle Eastern universities. Sustainability, 15(4), 3210.

Sadorsky, P. (2013), Do urbanization and industrialization affect energy intensity in developing countries? Energy Economics, 37, 52-59.

Safi, A., Chen, Y., Wahab, S. (2021), The role of digital maturity and green finance in reducing carbon emissions. Environmental Science and Pollution Research, 28(42), 59835-59848.

Salahuddin, M., Gow, J., Ozturk, I. (2019), Is the long-run relationship between economic growth, electricity consumption, carbon dioxide emissions and financial development in Gulf Cooperation Council Countries robust? Renewable and Sustainable Energy Reviews, 81, 2312-2322.

Sarabdeen, M., Alotaibi, S., Talukder, M. (2022), Digital access and environmental quality in oil-exporting countries. Energy Reports, 8, 10234-10245.

Sethi, N., Behera, P., Dash, D.P. (2022), The impact of ICT on ecological footprint: Does institutional quality and environmental policy matter? Journal of Cleaner Production, 380, 135008.

Smith, A., Stirling, A., Berkhout, F. (2005), The governance of sustainable socio-technical transitions. Research Policy, 34(10), 1491-1510.

Sun, Y., Li, Y., Wang, Y. (2021), Digitalization, renewable energy, and environmental sustainability: The role of financial development in the European Union. Environmental Science and Pollution Research, 28(45), 64822-64839.

Twum, A.K., Agyemang, A.O., Ansong, A. (2022), Financial assistance and the renewable energy-ecological footprint nexus in BRI countries. Energy Economics, 115, 106350.

Ullah, A., Khan, D., Ahmed, S. (2021), Digital strategies for sustainable development: Supporting the shift to renewables. Sustainable Development, 29(5), 875-887.

Usman, M., Ozcan, B., Godil, D.I. (2021), The role of digital maturity in the energy transition of developing economies. Energy Policy, 159, 112643.

Zarrad, O., Mechichi, N., Bouattour, M. (2025), Digitalization and the impact of green energy on sustainable development in the Eurozone. Energy Economics, 128, 105512.

Zhang, D., Wang, H., Luo, Y. (2022), Digital transformation and green innovation: The moderating role of environmental regulation. Journal of Cleaner Production, 380, 135011.

Zhao, Y., Shi, X., Zheng, L., Fan, S., Zuo, S. (2024), Green innovation and carbon emission performance: The role of digital economy. Energy Policy, 195, 114344.