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Digitalization and Energy Transition for Sustainable Development in North Africa: New Evidence from the CS-ARDL Approach

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ABSTRACT

This paper examines the impact of digitalization and energy transition on economic growth in North African countries from a sustainable development perspective. Using the CS-ARDL model, we distinguish between short-run dynamic adjustments and long-run structural relationships that reflect the combined influence of fixed capital investment, renewable and non-renewable energy consumption, and the diffusion of information and communication technologies (ICT). Our results suggest that in the short run, productive investment and fossil fuel dependence stimulate economic activity. In the long run, the gradual integration of renewable energy and the improvement of digital infrastructure promote more inclusive and resilient growth in line with the Sustainable Development Goals. The analysis also reveals significant structural and regional disparities, underscoring the need for differentiated and coordinated public policies to optimize the synergy between digitalization and energy transition.

Keywords: Digitalization, Renewable Energy, ICT, Energy Transition, Economic Growth, Sustainable Development, North Africa, CS-ARDL
JEL Classifications: O33, Q41, E31, L86, C23

1. INTRODUCTION

In the face of escalating fossil fuel resource depletion, worsening environmental degradation, and persistent socioeconomic inequalities, digital transformation and energy transition are emerging as strategic levers to rethink traditional development models in North Africa. These twin transitions serve as integral pathways to modernize economies while reducing their carbon footprints. The Sustainable Development Goals, as defined by the United Nations (2015), provide a normative framework that encourages the adoption of new technologies and innovative solutions to promote inclusive and environmentally sustainable growth.

Historically, economic research has focused primarily on the role of energy in production, as evidenced by the pioneering work of Kraft and Kraft (1978). However, recent transformative developments, such as the rapid expansion of information and communication technologies (ICTs), the emergence of artificial intelligence, the deployment of Industry 4.0 technologies, the emergence of Industry 5.0 paradigms, and the widespread integration of connected devices, combined with a significant shift toward renewable energy sources, call for a broadened analytical perspective. For example, Fambeu and Yomi (2024) show that the expansion of digital services stimulates renewable energy consumption in economies undergoing structural change, while Becha et al. (2023) show that positive shocks related to ICT imports have a statistically significant amplifying effect on economic growth. These findings imply that improving the digital infrastructure and optimizing the energy mix are essential prerequisites for achieving resilient economic growth.

Moreover, empirical evidence from studies by Chi et al. (2023) and Benali and Benabbou (2023) suggests that the rapid adoption of low-carbon technologies plays a critical role in reducing environmental footprints and sustaining long-term growth. In this context, digitalization is not only a catalyst for industrial modernization, but also a driver of innovation that addresses environmental challenges. Advances in emerging technologies, particularly artificial intelligence, offer new opportunities to improve energy efficiency and accelerate the shift to production systems that emit fewer greenhouse gases. These goals are in line with the ambitions of the Sustainable Development Goals.

Considering this evolving landscape, our study employs the CS ARDL approach to quantify both the short-term dynamic adjustments and the long-term structural relationships between digitalization, energy consumption (both renewable and non-renewable), and economic growth in North African countries. This method is well suited to account for regional interdependencies and structural heterogeneity among these economies. The primary objective of this research is to provide robust empirical evidence that will inform policy recommendations tailored to specific national contexts, while promoting effective regional coordination. In doing so, the study contributes to the broader discourse on sustainable development by clarifying the interplay between investments in productive capital, energy consumption patterns and the diffusion of digital technologies.

The paper is organized as follows. Section 2 provides a critical synthesis of previous research, highlighting both the advances and the gaps that remain in our understanding of the interactions among digitalization, energy transition, and economic growth. Section 3 outlines the theoretical framework and methodology, with particular emphasis on the specification of the CS-ARDL model and the characteristics of the panel data used. Section 4 presents our empirical results, distinguishing between short-term adjustments and long-term structural effects, and compares these results with recent studies in literature. Finally, Section 5 discusses the policy implications of our findings and offers targeted recommendations for North African economies, while suggesting directions for future research aimed at further elucidating the twin transitions that underpin sustainable development in the region.

2. LITERATURE REVIEW

Since the seminal work of Kraft and Kraft (1978), the study of energy's role in production has formed the foundation of debates on economic growth. Over time, faced with the challenges posed by the depletion of energy resources and the worsening of environmental degradation, research has gradually expanded its scope to include digitalization and energy transition as potential levers for sustainable development. In this context, the impact of information and communication technologies (ICT) on the transformation of energy systems and environmental quality has attracted growing interest, particularly in North Africa.

Fambeu and Yomi (2024) demonstrate that the expansion of Internet services and the export of ICT services stimulate renewable energy consumption, especially in rapidly growing economies undergoing structural transformation. Their analysis highlights the moderating effect of economic growth and transformation processes on the optimization of the energy mix. Similarly, Becha et al. (2023) investigate both the symmetric and asymmetric effects of digitalization, revealing that positive shocks related to ICT imports can significantly boost economic growth while negative shocks do not have an equivalent effect. These findings underscore the need to reinforce digital infrastructure to ensure autonomous and resilient growth.

In the North African context, the significance of renewable energy is widely recognized. Chi et al. (2023) show that the energy trilemma index, which incorporates environmental sustainability, energy security, and affordability, plays a determining role in the region's economic progress. They position the accelerated adoption of low-carbon energy technologies as a key driver for sustainable growth. At the same time, Benali and Benabbou (2023) provide empirical evidence from Morocco that investments in renewable energy infrastructure not only enhance long-term growth but also contribute to substantial reductions in carbon emissions, thereby illustrating the economic potential of the energy transition.

The environmental dimension of energy transition is central in recent studies. Charfeddine et al. (2024) show that an efficient digital management system, measured by a composite digitalization index, contributes to improved environmental quality by alleviating pressures on natural resources, despite the variability of individual ICT indicators. Moreover, Dahmani and Mabrouki (2025) employ the CS-ARDL model to examine the influence of human capital, innovation, and governance on growth in the MENA region. Their results indicate that short-term and long-term effects vary according to resource endowments and institutional structures, thereby distinguishing resource-rich economies from those less endowed with natural resources. In addition, the work by Ben Youssef and Dahmani (2024a; 2024b; 2024c) explores the interaction among environmental policies, urbanization, and digitalization. Their advanced econometric approach shows that implementing environmental taxes in conjunction with strategies to promote sustainable productive capacities fosters convergence toward improved environmental quality. This convergence manifests itself in reduced carbon emissions and enhanced energy sustainability, despite short-term fluctuations. Finally, research by Dahmani and Ben Youssef (2023) and Dahmani et al. (2022a; 2022b; 2023) further deepens these findings in the Tunisian context by revealing that the impact of ICT on value added varies significantly across different economic sectors. Consequently, it is imperative to tailor organizational reforms and sector-specific strategies to optimize the benefits of digitalization within the framework of energy transition.

Institutional and educational factors also play a decisive role. Yahyaoui (2024) demonstrates that the impact of ICT on CO_2 emissions varies with national policies, suggesting that optimal management of digital technologies can mitigate adverse environmental effects while inadequate planning may exacerbate them. In a similar vein, Abu Alfoul et al. (2024) emphasize the importance of educational attainment in maximizing the benefits of ICT, indicating that a robust educational system not only strengthens digital competencies but also limits negative effects such as brain drain, which undermines innovation and the efficiency of investments.

Beyond the purely digital aspects, several studies focus on investments in the energy transition. Evans (2024) highlights how fluctuations in oil prices directly influence renewable energy investments through substitution effects. Bergougui and Meziane (2025) find that technological innovation and economic complexity play a moderating role in energy performance, particularly in economies heavily dependent on hydrocarbons such as Algeria. Moreover, Arbia and Sobhi (2024) examine how foreign direct investment, in interaction with ICT infrastructure, can affect economic growth in North African countries, emphasizing the importance of digital inclusion policies. These findings suggest that strategies aimed at strengthening digitalization and improving ICT infrastructure, in synergy with rigorous resource management, can stimulate investments in clean technologies.

Regional integration emerges as another critical factor. Ullah et al. (2024) demonstrate that cooperation among countries through regional integration mechanisms can amplify the positive impacts of renewable energy transitions on sustainable development. At the same time, Sarabdeen et al. (2024) show that digital transformation can facilitate the shift toward a low-carbon economy by coordinating efforts to combat climate change and promoting environmentally friendly development models.

Research on emerging technologies adds an innovative dimension to this debate. Lee et al. (2024) explore the potential of artificial intelligence to accelerate the energy transition. Their findings indicate that advancements in AI, combined with digitalization, enhance the capacity of economies to adopt clean technologies and optimize energy efficiency. Similarly, Shouwu et al. (2024) report that the integration of environmental technologies into the energy mix reduces dependence on fossil fuels and improves overall environmental quality. Systematic contributions by Blimpo et al. (2024) and Sarsar and Echaoui (2024) offer macroeconomic perspectives by analyzing how economic complexity and policy integration affect energy transition and growth, advocating for nuanced policy frameworks that consider contextual specificities.

Furthermore, Alariqi et al. (2023) stress the need for integrated policies that promote low-carbon technologies while reducing subsidies for fossil fuels, a strategy that would bolster long-term growth potential in line with global environmental objectives. Concurrently, Iddrisu and Chen (2024) show that digitalization, when supported by adequate financial sector development, can significantly contribute to economic growth, though its effects are conditioned by education levels and the ability of countries to retain talent.

Collectively, these studies, which utilize advanced econometric techniques such as CS-ARDL and other panel methods, demonstrate the diversity of approaches used to analyze the synergy among digitalization, energy transition, and sustainable development. They underscore the critical importance of coordinated energy and digital policies, supported by sustained investments in education and innovation, to address the challenges of transitioning to a greener and more inclusive economy.

3. METHODOLOGICAL FRAMEWORK AND ANALYTICAL STRATEGY

3.1. Method of Econometric Analysis

3.1.1. Theoretical framework and model specification

This paper analyzes the impact of energy consumption and digitalization on economic growth in North African countries using the neoclassical growth model originally developed by Solow (1956) and extended by Mankiw et al. (1992). This theoretical framework posits that economic growth is generated by a Cobb-Douglas production function that simultaneously incorporates physical capital, energy, and information and communication technologies (ICT). The production function is usually expressed as follows

$$Y_{it} = A_t \prod_{k=1}^{K} X_{kit}^{\alpha_k}, \quad \text{with } 0 < \alpha_k < 1 \tag{1}$$

where Y_{it} is the real Gross Domestic Product (GDP) of country i at time t and X_{kit} is the vector of K explanatory variables, namely physical capital, energy consumption and ICT. The term A_t symbolizes the technological progress common to all countries and α_k represents the elasticities associated with the different explanatory variables. To facilitate the econometric estimation and to allow a direct interpretation of the coefficients as elasticities, the model is linearized by taking its natural logarithm, which results in the following equation:

$$\ln(Y_{it}) = \ln(A_t) + \sum_{k=1}^{K} \alpha_k \ln(X_{kit}). \tag{2}$$

In this context, i covers the five North African countries under study (Algeria, Egypt, Mauritania, Morocco, and Tunisia), t represents the period from 1990 to 2022, and K indexes the five selected explanatory variables. To capture the interactions between digitalization, energy consumption and economic growth, the model is specified as follows:

$$\begin{aligned} &\ln(GDP\_CAP_{it}) = \beta_0 + \beta_1 \ln(GFCF\_CAP_{it}) \\ &+\beta_2 \ln(NONREV\_\_ENERGY\_CAP_{it}) \\ &+\beta_3 \ln(REV\_\_ENERGY\_CAP_{it}) + \beta_4 \ln(ICT_{it}) + \varepsilon_{it} \end{aligned} \tag{3}$$

In this specification, In(GDP_CAP_{it}) is the natural logarithm of GDP per capita, which serves as the dependent variable. In($GFCF\_CAP_{it}$) is the natural logarithm of gross fixed capital formation per capita, which reflects the stock of physical capital. Similarly, In($NONREV\_ENERGY\_CAP_{it}$) measures the natural logarithm of non-renewable energy consumption per capita, capturing dependence on fossil fuels, while In($REV\_ENERGY\_CAP_{it}$) represents the natural logarithm of renewable energy consumption per capita, illustrating energy transition efforts. Furthermore, In(ICT_{it}) is the natural logarithm of the ICT index and serves as an indicator of the level of digitalization. Technological progress, denoted by ln(A_1), is assumed to be constant and is included at the intercept β_0.

The estimated coefficients $\beta_1 \beta_2 \beta_3$ and β_4 have clear economic interpretations: A positive β_1 indicates that an increase in fixed capital investment per capita promotes proportional economic growth; β_2 indicates that non-renewable energy consumption contributes positively to economic growth despite its negative environmental externalities; β_3 suggests that renewable energy consumption supports sustainable growth, although its effectiveness may be constrained by limited infrastructure; and $\beta_4 > 0$ implies that digitalization, as measured by the ICT index, improves economic efficiency, fosters innovation, and thus contributes positively to growth. This methodological framework provides a robust analytical basis for exploring how digitalization and energy consumption interactively shape economic trajectories within the North African region.

3.1.2. Data and descriptive statistics

The empirical analysis in this study is based primarily on data from the World Bank's World Development Indicators (WDI, 2025) and the US Energy Information Administration (EIA, 2025). These databases were selected because of their proven reliability, comprehensive coverage, and comparability of economic, energy, and technology indicators. Consequently, the selected variables effectively capture critical dimensions of the energy transition and economic growth dynamics in the North African countries studied.

Specifically, the dataset includes indicators such as real GDP per capita, gross fixed capital formation per capita, non-renewable and renewable energy consumption per capita, and an ICT development index. These variables have been carefully selected to assess the complex interplay between economic performance, productive investment, energy dependence and digitalization in the region. The economic variables (GDP per capita and gross fixed capital formation per capita) are measured in constant 2015 U.S. dollars to control for inflationary effects and to facilitate meaningful comparisons across countries and over time. Non-renewable energy consumption per capita, measured in tons of oil equivalent, effectively captures the region's dependence on fossil fuels, while renewable energy consumption per capita serves as an indicator of progress toward a sustainable energy transition. In addition, the ICT Index is constructed as a composite measure derived from fixed telephone subscriptions, mobile phone subscriptions (per 100 inhabitants), and internet penetration, providing an integrated perspective on the region's progress towards digitalization.

The descriptive statistics for the study variables presented in Table 1 illustrate significant differences in economic, energy, and technological indicators across North African countries over the period 1990-2022. For example, the average GDP per capita across these countries is approximately \$2,821.49, with a substantial standard deviation of \$1,024.57, indicating considerable economic heterogeneity. Similarly, gross fixed capital formation per capita averages \$703.42, with a significant standard deviation of \$408.42, underscoring differences in productive investment capacity. In terms of energy consumption, non-renewable energy per capita averages 0.70 tons of oil equivalent, highlighting continued dependence on fossil fuels. In contrast, renewable energy consumption remains significantly low, averaging only 0.008 tons of oil equivalent per capita, underscoring the relatively slow pace of the region's transition to renewable energy sources. In addition, the ICT index has an average score of 26.97, with a standard deviation of 25.09, reflecting the considerable differences in digital infrastructure and access to technology among these North African economies.

The evolution of GDP per capita as observed in the dataset indicates significant progress in most of the countries considered, albeit with highly variable growth rates. At the same time, the overall upward trend in gross fixed capital formation and the persistently high level of non-renewable energy consumption highlight the continued dependence on fossil fuels and the continued reliance on traditional growth drivers. In contrast, the limited deployment of renewable energy sources underscores the challenges in achieving the desired energy transition, while the varying levels of digital technology integration illustrate the uneven path to digital transformation.

3.1.3. Theoretical framework and model specification

This study examines the impact of energy consumption and digitalization on economic growth in North Africa using the Cross-Sectional Augmented Autoregressive Distributed Lag (CS-ARDL) model. This model was chosen because of its methodological suitability for panel data and its ability to meet the objectives of our research. The CS-ARDL approach extends the traditional ARDL framework by incorporating a linear combination of

Table 1: Variable definitions and descriptive statistics

Variable	GDP_CAP	GFCF_HAB	NONREN_ ENERGY_CAP	REN_ENERGY_ CAP	ICT
Definition	Gross domestic product per capita (constant 2015 USD)	Gross fixed capital formation per capita (constant 2015 USD)	Total non-renewable energy consumption per capita (tons of oil equivalent)	Total renewable energy consumption per capita (tons of oil equivalent)	ICT Development Index: Average of fixed telephone subscriptions, mobile subscriptions (per 100 inhabitants), and Internet users (%)
Source	WDI	WDI	EIA	EIA	WDI
Observations	165	165	165	165	165
Mean	2 821.49	703.42	0.7	0.008	26.97
Standard deviation	1 024.57	408.42	0.35	0.006	25.09
Minimum	1 252.10	81.94	0.16	0.0002	0.1
Maximum	4 768.73	2 019.83	1.52	0.026	77.56

cross-sectional averages of both dependent and independent variables. This inclusion allows for an effective correction for error correlations across countries, as demonstrated by Chudik and Pesaran (2015). Moreover, the inclusion of a 1-year lag of the dependent variable in the error correction process, which is treated as weakly exogenous, improves the robustness of the estimation, in line with the findings of Islam et al. (2022).

The CS-ARDL model is also characterized by its ability to significantly control unobserved factors that influence long-term effects. This provides a comprehensive analytical framework for the simultaneous evaluation of short-run dynamics and long-run structural relationships related to digitalization and energy transition. This approach is particularly relevant in contexts characterized by strong cross-sectional dependencies in both the short and long run, as demonstrated in the works of Chudik et al. (2016; 2017) and Dahmani and Mabrouki (2025). In addition, Pesaran (2015; 2021) advocates the use of the cross-sectional dependence (CD) test to detect and quantify potential co-correlation effects arising from strong economic linkages between countries. Ben Youssef and Dahmani (2024a; 2024b; 2024c) further emphasize the importance of estimating the dependence between panel units. These considerations fully justify our choice of the CS-ARDL model, which allows us to simultaneously model both short-run dynamics and long-run structural relationships, while accounting for structural interactions and regional interdependencies among the North African countries under study.

The econometric specification of the CS-ARDL model employed in this study is as follows:

$$\begin{aligned} &\ln(GDP\_CAP_{it}) = \alpha_i \\ &+\sum_{j=1}^{p}\beta_{ij}(\ln(GDP\_CAP_{it-j}) - \overline{\ln(GDP\_CAP_{t-j})}) \\ &+\sum_{k=1}^{q}\gamma_{ik}(X_{kit} - \overline{X_{kt}}) + \delta D_t + \mu_i + \varepsilon_{\text{it}} \end{aligned} \tag{4}$$

In this specification, In(GDP_CAP_{it}) denotes the natural log of GDP per capita for country i in year t, which is the dependent variable. The term α_i captures country-specific fixed effects. The coefficients β_{ij} and γ_{ik} measure the lagged effects of the dependent variable and the explanatory variables, respectively. The cross-sectional averages of the lagged dependent and independent variables, denoted by $\overline{\ln(GDP\_CAP_{t-j})}$ and X_{kt}, respectively, are included to capture cross-country interactions and global influences. The term δD represents time-fixed effects such as global shocks or common trends, while μ_i and ε_{it} denote the country-specific time-invariant effects and the random error term, respectively.

The strength of the CS-ARDL model lies in its flexibility regarding the orders of integration of the variables. It allows the inclusion of integrated series of different orders (I(0) and I(1)) and simultaneously models both short-run dynamics and long-run relationships, which is critical for capturing the lagged effects of economic policies related to digitalization and energy transition. Moreover, its robustness to small samples makes it an appropriate choice for a comparative study involving only five North African countries.

The estimation procedure used in this study includes several preliminary tests to ensure the reliability of the empirical results. First, the cross-sectional dependence test of Pesaran (2015) is used to identify dependencies among countries, followed by the test of Pesaran and Yamagata (2008) to account for heterogeneity in structural relationships among panel units. To ensure the stationarity of the series, we use the Cross-Sectionally Augmented Im, Pesaran, and Shin (CIPS) test, which allows for cross-sectional interactions. Next, the panel cointegration test of Westerlund (2007) is applied to confirm the existence of stable long-run relationships among the variables. Once these conditions are met, the CS-ARDL model is estimated to accurately distinguish between short-run dynamics and long-run structural relationships, thereby capturing the true impact of digitalization and energy transition policies on economic growth. This comprehensive approach ensures a rigorous analysis of causal interactions in a context characterized by strong regional interdependencies and country-specific structural characteristics.

3.2. Estimation Methodology

3.2.1. Cross-sectional dependence test

The analysis of the interactions between digitalization, energy consumption, and economic growth in North Africa requires special attention to the structural and economic interdependencies among the countries under study. The concept of cross-sectional dependence, as defined by Baltagi (2015), refers to the correlation between the residuals of different panel units due to common economic shocks or shared characteristics across countries. Accounting for this cross-sectional dependence is essential to ensure the robustness of econometric estimates, as its absence could bias the estimated impact of the explanatory variables on growth and energy consumption, leading to a misinterpretation of the effects of digitalization and energy policies.

To detect and capture this interdependence, we apply the cross-sectional dependence test proposed by Pesaran (2015; 2021) to the residuals of the main variables in our analysis. This test assesses whether the unobserved errors across countries are correlated, indicating the presence of economic interactions or common shocks that affect several countries simultaneously. The results presented in Table 2 show that all the main variables, namely the natural logarithm of GDP per capita (LnGDP_CAP), gross fixed capital formation (LnGFCF_CAP), non-renewable energy consumption (LnNONREN_ENERGY_CAP), renewable

Table 2: Results of cross-sectional dependence analysis

Variable	CD
GDP per capita (LnGDP_CAP)	15.30***
Gross fixed capital formation (LnGFCF_CAP)	13.95***
Non-renewable energy consumption (LnNONREN_ ENERGY_CAP)	4.98***
Renewable energy consumption (LnREN_ENERGY_ CAP)	3.92***
ICT index (LnICT)	17.99***

***Indicates significance at the 1 percent level energy consumption (LnREN_ENERGY_CAP) and the ICT index (LnICT), exhibit statistically significant cross-sectional dependence at the 1% level. These results demonstrate the mutual influence of economic and technological dynamics among the countries studied and underscore that a country's economic and technological policies cannot be analyzed in isolation.

Moreover, these results underscore the importance of a regional approach to energy and digital policy development. Close coordination between countries, through joint initiatives or strategic partnerships, could increase the effectiveness of individual policies for energy transition and sustainable development, and thus improve overall economic and environmental performance. These considerations fully justify the use of econometric models that correct for cross-sectional dependence, such as the CS-ARDL model used in this study, which accounts for both short-run dynamics and long-run relationships while capturing regional interactions and interdependencies among North African countries.

Integrating these dimensions allows for a better understanding of the complex relationships among digitalization, energy transition, and economic growth, thereby facilitating the formulation of policy recommendations tailored to the regional context.

3.2.2. Heterogeneity test

After confirming the existence of cross-sectional dependence among North African countries, we found that the heterogeneity of the slopes in the panel data analysis can significantly affect the final conclusions. This finding highlights the importance of considering the unique structural characteristics of each country, as imposing homogeneous coefficients would not capture the differences in the impact of the explanatory variables on economic growth. In fact, the development trajectories vary considerably from one country to another, as evidenced by the differences observed in energy policies and levels of digitalization. The application of the slope homogeneity test developed by Pesaran and Yamagata (2008) allowed us to reject the hypothesis of homogeneous slopes, revealing that the responses of countries to factors such as gross fixed capital formation, renewable energy consumption and the ICT index are significantly different. The results presented in Table 3 show a delta statistic of 16.838 and an adjusted delta statistic of 18.616, both associated with a P = 0.000.

These findings clearly demonstrate the need to use flexible econometric models that incorporate both structural disparities and regional interdependencies. By taking these heterogeneities into account, it becomes possible to formulate policy recommendations tailored to each country's specific characteristics, while also exploring opportunities for regional cooperation to optimize the economic and environmental benefits of energy transition and digitalization.

Table 3: Heterogeneity test results

	Δ Statistic	P-value
Test delta	16.838	0.000
Adjusted delta	18.616	0.000

3.2.3. Unit root tests in panel data

Ensuring the stationarity of the time series is a fundamental step to guarantee the validity of econometric results, since non-stationarity can lead to spurious correlations and undermine the robustness of the conclusions. In our analysis, it is essential to verify that the series reflect genuine dynamics rather than uncontrolled stochastic trends. Given the confirmed cross-sectional dependence in our data, we opted for the Cross-Sectionally Augmented Im-Pesaran-Shin (CIPS) test developed by Pesaran (2007), which provides enhanced robustness in the presence of interdependencies among panel units.

The results of the unit root tests presented in Table 4 indicate that certain variables, such as gross fixed capital formation (LnGFCF_CAP) and the ICT index (LnICT), are stationary at the level (integrated of order zero, I(0)), which means that their fluctuations are mainly explained by short-term fluctuations without a long-term stochastic trend. In contrast, GDP per capita (LnGDP_CAP), non-renewable energy consumption (LnNONREN_ENERGY_CAP) and renewable energy consumption (LnREN_ENERGY_CAP) are not stationary in levels, but become stationary after first differencing, indicating that they are integrated of order one (I(1)). These findings confirm that most series require differencing to achieve stationarity.

This observation justifies the use of appropriate econometric techniques, such as cointegration analysis, to examine the long-run relationships between variables. Cointegration analysis allows us to identify stable structural relationships between variables integrated at the first order (namely GDP per capita, non-renewable energy consumption, and renewable energy consumption) and those integrated at the zero order (such as gross fixed capital formation and the ICT index). These long-run relationships are essential for understanding how digitalization, investment in energy infrastructure, and energy consumption interact and influence economic growth in the region.

The results obtained are strategically important for policymakers, as they indicate that short-run and long-run dynamics should be analyzed separately to formulate tailored policy recommendations. For example, some energy and digital policies may have an immediate impact in some countries, while in others their effects may be felt over a longer period. Incorporating these dynamics into our analytical framework thus provides a comprehensive understanding of the economic and energy interactions in North African countries and a solid basis for developing energy transition and digitalization strategies that are adapted to regional specificities.

Incorporating these results into our analysis will later allow us to address cointegration relationships, which are critical for examining the long-term structural impact of digitalization and energy transition on economic growth in North Africa.

3.2.4. Cointegration tests

Identifying long-run relationships between the selected economic and energy variables is necessary for understanding the structural dynamics underlying economic growth and energy transition

Table 4: Results of unit root tests in panel data

Variables	Level		First difference		Order
	No trend	With trend	No trend	With trend	
LnGDP_CAP	−1.908	−2.607	−4.907***	−5.218***	I (1)
LnGFCF_CAP	−3.617***	−3.466***	−4.500***	−4.268***	I (0)
LnNONREN_ENERGY_CAP	−0.877	−1.614	−5.926***	−6.056***	I (1)
LnREN_ENERGY_CAP	−1.739	−2.071	−5.655***	−5.783***	I (1)
LnICT	−4.108***	−3.930***	−5.024***	−5.227 ***	I (0)

***Indicates statistical significance at the 1% level

in North Africa. In a context characterized by economic interdependencies and the non-stationarity of some time series, the application of a cointegration test is an indispensable step in the empirical analysis. Cointegration analysis allows us to determine whether the variables evolve together in a stable manner over the long run, despite short-term fluctuations. This analytical framework is particularly relevant in the North African context, where fiscal and energy policies, while having immediate effects, pursue consistent long-term objectives in terms of energy transition and sustainable development.

To examine these relationships, we use the panel cointegration test developed by Westerlund (2007). This test is characterized by its ability to incorporate heterogeneous coefficients across countries as well as cross-sectional dependence due to common shocks or shared structural characteristics. The unique characteristics of each country in terms of energy mix, digital infrastructure and economic strategies warrant a methodological approach that reconciles regional convergence with country-specific differences. The Westerlund test is based on the analysis of residuals from cointegration models; the stationarity of these residuals indicates that the variables move together in the long run. The $G\tau$, $G\alpha$, $P\tau$ and $P\alpha$ tests, which allow us to distinguish between a relationship that is common to all countries and one that is country-specific, provide a comprehensive assessment of cointegration.

The results presented in Table 5 confirm the existence of stable long-run relationships among the variables. The cointegration statistics are significant at the 1% level, with P-values below 0.01 for each of the tests ($G\tau$, $G\alpha$, $P\tau$, and $P\alpha$). These results lead us to reject the null hypothesis of no cointegration and indicate that variables such as GDP per capita, gross fixed capital formation, renewable energy consumption, non-renewable energy consumption, and the ICT index converge toward a common long-run dynamic. This convergence implies that economic and energy policies aimed at increasing the share of renewable energy, strengthening digital infrastructure, or intensifying investment in physical capital have measurable and consistent effects over time, despite short-term fluctuations.

The policy implications of these results are significant. The presence of cointegration among the variables shows that short-term fluctuations, such as economic or energy crises, do not necessarily impede the achievement of long-term sustainable growth and energy transition goals. It is therefore imperative that North African governments adopt coherent and sustained long-term policies to avoid short-term adjustments that could disrupt the observed positive trajectory.

Table 5: Results of the cointegration tests

Statistic	Value	Z-value	P-value
$G\tau$	−5.751	−8.201	0.000
$G\alpha$	−18.768	−2.795	0.003
$P\tau$	−15.175	−9.125	0.000
$P\alpha$	−23.290	−5.253	0.000

4. RESULTS AND DISCUSSION

4.1. Estimation of Short- and Long-Term Relationships: The CS-ARDL Model

The present empirical analysis is based on the estimation of a CS-ARDL model using panel data from North African countries to assess the impact of digitalization and energy consumption on economic growth from a sustainable development perspective. This model distinguishes between short-run dynamics, which reflect rapid adjustments towards the long-run equilibrium, and long-run structural relationships, which capture the cumulative effects of implemented policies. The results, summarized in Table 6, reveal an effective adjustment mechanism. A coefficient on the error correction term of −0.883 indicates that almost 88 percent of deviations from long-run equilibrium are corrected within 1 year.

In the short run, gross fixed capital formation per capita (LnGFCF_CAP) has a statistically significant positive effect (coefficient = 0.189, $p = 0.001$), underscoring the critical role of infrastructure investment in stimulating economic activity. This result is in line with the findings of Dahmani et al. (2022a) and Iddrisu and Chen (2024), who emphasize the importance of productive investment in strengthening growth. Moreover, non-renewable energy consumption per capita (LnNONREN_ENERGY_CAP) also has a significant positive impact (coefficient = 0.142, $p = 0.002$), confirming that reliance on fossil fuels continues to support short-term economic expansion, consistent with the energy growth hypothesis outlined by Chen et al. (2016) and Le and Quah (2018). Renewable energy consumption per capita (LnREN_ENERGY_CAP) exerts a moderate positive effect (coefficient = 0.030, $p = 0.026$), suggesting that while renewable energy sources are gradually being integrated into the energy mix, their immediate impact remains limited. In contrast, the ICT index (LnICT) has a positive coefficient of 0.017 in the short run, but this effect does not reach statistical significance ($p = 0.190$), suggesting that the economic benefits of digitalization may require a longer time horizon to materialize.

In the long run, the results show the robustness of structural effects. Gross fixed capital formation per capita continues to play

Table 6: CS-ARDL panel data estimates: short- and long-run results

	Coefficient	Standard Error	Z-Statistic	P-value
Short-run results				
ECT (-1)	−0.883	0.157	−5.63	0.000
LnGFCF_CAP	0.189	0.056	3.70	0.001
LnNONREN_ENERGY_CAP	0.142	0.047	3.04	0.002
LnREN_ENERGY_CAP	0.030	0.013	2.23	0.026
LnICT	0.017	0.024	1.35	0.190
Long-run results				
LnGFCF_CAP	0.217	0.060	2.93	0.003
LnNONREN_ENERGY_CAP	0.169	0.039	4.29	0.000
LnREN_ENERGY_CAP	0.053	0.025	3.64	0.000
LnICT	0.082	0.038	2.15	0.043
Cross-sectional dependence statistic (CD)	0.36			0.718

an important role (coefficient = 0.217, p = 0.003), confirming the importance of infrastructure investment as a driver of sustainable growth, in line with the findings of Ben Youssef and Dahmani (2024a). Non-renewable energy consumption remains a significant positive determinant (coefficient = 0.169, p = 0.000), illustrating that despite efforts to diversify energy sources, the region remains dependent on fossil fuels. However, the integration of renewable energy into the energy mix has a significant positive effect in the long run (coefficient = 0.053, p = 0.000), which is consistent with the conclusions of Chi et al. (2023) and Benali and Benabbou (2023), who identify the accelerated adoption of low-carbon technologies as essential for sustainable growth. Moreover, the ICT index becomes significant in the long run (coefficient = 0.082, p = 0.043), indicating that digitalization contributes to improved economic efficiency and innovation, a result that confirms the findings of Dahmani et al. (2023) and Abu Alfoul et al. (2024).

Table 6 provides a clear summary of these results, and the cross-sectional dependence (CD) statistic, with a value of 0.36 (p = 0.718), confirms that the CS-ARDL model adequately accounts for the structural heterogeneity and regional interdependencies inherent in North African economies. These estimates provide a solid basis for comparing our results with recent literature that emphasizes the importance of an integrated strategy combining digitalization and energy transition to promote sustainable development. They also pave the way for a more detailed discussion of their policy implications in a later section.

4.2. Discussion

The results, both in the short and long run, illustrate the complex interplay between digitalization, energy consumption and economic growth in North African countries. In the short run, the importance of investment in fixed capital is evident, as indicated by the positive coefficient on LnGFCF_CAP, which confirms that improvements in infrastructure are important for stimulating immediate economic activity. Moreover, the significant positive effect of non-renewable energy consumption suggests that, despite environmental concerns, reliance on fossil fuels continues to support economic growth in the short run. The moderate effect of renewable energy consumption, on the other hand, suggests that the integration of renewable energy sources, while progressing, remains limited in the short run. These observations are consistent with the findings of Chi et al. (2023) and Benali and Benabbou (2023), who argue that the accelerated deployment of low-carbon technologies, while promising, requires substantial structural changes.

With respect to ICT, the lack of a significant short-run impact suggests that the economic benefits of digitalization may take time to materialize. In contrast, the long-run analysis reveals a significant positive impact of ICT on economic growth, consistent with Dahmani et al. (2023), which suggests that the diffusion of digital technologies promotes innovation and improves industrial processes over a longer period of time. This time lag reinforces the notion that a successful energy transition integrated with digitalization requires long-term strategies that include investments in human capital and digital infrastructure.

Long-term results also show a persistent positive effect of renewable energy consumption, albeit modest, suggesting that energy transition policies are gradually improving environmental sustainability. The persistent positive effect of non-renewable energy consumption underscores that North African economies are still in a transition phase, where diversifying the energy mix remains a key challenge. These findings are in line with Benali and Benabbou (2023), who show that investments in renewable energy infrastructure generate lasting economic benefits and contribute to reducing carbon emissions.

The robustness of the CS-ARDL model, which simultaneously captures short- and long-term effects while accounting for regional interdependencies, allows us to compare our results with recent studies that advocate an integrated approach to digitalization and energy transition in support of sustainable development. Studies by Dahmani and Mabrouki (2025) and Ben Youssef and Dahmani (2024a; 2024b; 2024c) and Dahmani (2024) highlight the complexity of the interactions between digitalization, productive investment, and environmental policies. Our analysis suggests that to maximize the benefits of digital transformation and energy transition, long-term strategies tailored to the unique structural characteristics of each North African economy are essential.

Table 6 clearly illustrates these complex dynamics and provides a robust empirical basis for the debate on the effectiveness of digitalization and energy transition policies in promoting sustainable development in the region. The observed differences between the short-run effects, where digitalization appears to require a lag before translating into significant economic growth, and the long-run effects, which reveal a positive and structurally significant impact of ICT, support the argument that integrating digital transformation with renewable energy adoption is a key lever for building an inclusive and environmentally sustainable growth model.

4.3. Policy Implications and Recommendations

The results of our study suggest that digitalization and energy transition offer complementary levers to enhance economic sustainability in North Africa, provided that policy strategies are tailored to specific national contexts and effective regional coordination is promoted. In this context, the implementation of policies that encourage investment in ICT infrastructure is essential to improve access to digital services and optimize the energy mix, as shown by the work of Fambeu and Yomi (2024) and Becha et al. (2023). Such initiatives help increase renewable energy consumption and stimulate more resilient economic growth, while facilitating the transition to lower-carbon technologies, as noted by Chi et al. (2023) and Benali and Benabbou (2023).

From an institutional perspective, effective management of ICTs, supported by a robust education system, is key to minimizing negative externalities and fostering innovation. The findings of Yahyaoui (2024) and Abu Alfoul et al. (2024) underscore the importance of developing digital skills and strengthening educational frameworks to mitigate brain drain and ensure that investments in digitalization yield long-term benefits for both growth and environmental quality.

Energy transition policies must also address market volatility and structural constraints. Analyses by Evans (2024) and Bergougui and Meziane (2025) show that stabilizing oil prices and supporting investment in renewable energy are essential to diversify the energy mix and reduce reliance on fossil fuels. In addition, encouraging foreign direct investment through inclusive digital policies can enhance the competitiveness of the region's economies, as shown by Arbia and Sobhi (2024).

Regional integration emerges as a strategic lever to maximize the impact of digitalization and energy transition policies. Integration mechanisms, as studied by Ullah et al. (2024) and Sarabdeen et al. (2024), facilitate the sharing of best practices and the pooling of resources, thereby enabling economies of scale and harmonizing national efforts to achieve sustainable development goals.

At the national level, specific recommendations emerge. In Tunisia, it would be beneficial to strengthen the use of ICTs in strategic sectors, while implementing reforms in the informal sector to improve organizational efficiency and promoting investment in solar energy to diversify the energy mix. Morocco should focus on expanding digital infrastructure in agriculture and water management, building on the experience of integrated projects to support the competitiveness of SMEs and accelerate the uptake of clean energy. Algeria should prioritize diversifying its non-oil economy through digitalization and technological innovation, redirecting oil revenues to investments in renewable energy technologies and advanced ICT infrastructure. In Egypt, modernizing both digital and energy infrastructure through public-private partnerships is essential to reduce territorial disparities and stimulate local economic activity. Finally, in Mauritania, efforts should be made to increase rural electrification through the development of solar energy, while gradually integrating ICTs into public services and education, with increased cooperation with international partners.

These policy orientations, based on a detailed analysis of the interactions between digitalization and the energy transition, provide a framework for rethinking development strategies in North Africa. They show that an integrated approach combining investments in digital and energy infrastructure, institutional strengthening, and regional cooperation is essential to address today's challenges and promote inclusive, sustainable growth in the region.

5. CONCLUSION

This study has provided an in-depth exploration of the complex interactions between digitalization, energy consumption and economic growth in North African countries using an integrated sustainable development approach. Using second-generation panel data econometric models, in particular the CS-ARDL model, our analysis shows that digitalization and energy transition act as transformation levers; however, their effects are strongly moderated by national and regional specificities. The results underline the strategic role of investments in digital infrastructure and the gradual integration of renewable energy, which together stimulate economic growth while improving environmental quality.

In the short run, the positive effects of fixed capital formation and the continued reliance on non-renewable energy highlight the importance of supporting immediate economic activity, even though these mechanisms put pressure on the environment and pose challenges for sustainability. In the long term, the analysis shows that greater use of renewable energy, combined with increased digitalization, can generate significant structural benefits by reducing carbon emissions and improving economic efficiency. These observations underscore the need for an overhaul of the energy mix and a sustained deployment of digital technologies to support inclusive and resilient growth.

Despite the insights provided by our study, certain limitations remain. The variability of data across countries and the challenges of accurately measuring some indicators of digitalization and energy transition call for caution in interpreting the results. Although the CS-ARDL model allows for the integration of both short- and long-term dynamics, the structural complexity of North African economies suggests that additional variables, such as institutional and educational factors, could be included to further refine the analysis. Future research should explore the impact of these additional dimensions, as well as the evolution of interactions in a context of rapid technological change and accelerated energy transition.

Furthermore, the generalization of the results to all North African economies requires further confirmation, opening the way for comparative studies with other regions facing similar challenges. Future research could also use nonlinear modeling techniques and explore asymmetric effects to better capture the differentiated responses of economies to exogenous technological or energy shocks.

These findings offer important avenues for the development of coordinated public policies. A harmonious integration of digitalization and energy transition, supported by strategic investments in education, innovation, and infrastructure upgrading, appears to be a promising way to address current and future sustainable development challenges in North Africa.

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