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ORIGINAL RESEARCH PAPER

The Synergistic Effects of the Digital Economy and Renewable Energy Transition on Green Economic Growth: Evidence from Selected MENA Countries

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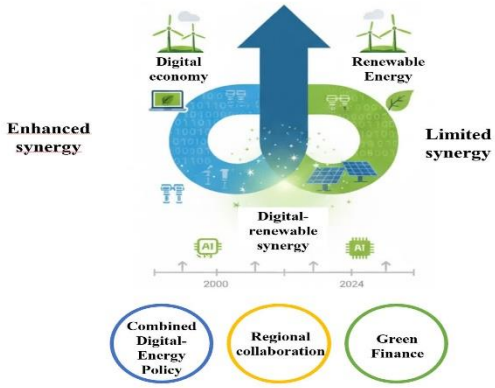
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A B S T R A C T

This paper explores the synergistic interaction that exists between digital economy, transition to renewable energy and green economic development in the top countries in Middle East and North Africa (MENA) between the years 2000 and 2024. The assessment of the independent and interactive impacts of the factors of digitalization and renewable energy on the environmentally adjusted economic performance are analyzed by using a balanced panel dataset, top econometric methods, in particular, the System Generalized Method of Moments (SYS-GMM). The findings indicate that green economic growth is increased positively and significantly because of the digital economy given its ability to foster efficiency, technological advancement, and low-carbon transformation. Similarly, the proportion of renewable energy use has a high positive effect, which proves the importance of this factor concerning the sustainable developmental process and diversification of energy. More importantly, the interaction term of digitalization and renewable energy has a pronounced and amplified impact, which empirically proves a phenomenon of a digital-renewable synergy, so, digital technologies, including artificial intelligence, smart grids, and IoT, streamline the use and lawful incorporation of renewable energy. The results also indicate that there are structural differences across the MENA region: where the high-income Gulf economies demonstrate enhanced synergy effects because of the developed digital infrastructure and strategic green investments, non-oil ones demonstrate limited effects because of the digital and institutional gaps. There are policy implications including the necessity of combined digital-energy policies, regional collaboration, and green finance approaches to the eco-digital transition to improve. Theoretically, the paper is an extension of the framework of Endogenous Growth and Environmental Kuznets Curve by showing how digitalization is enhancing the shift towards environmentally sustainable growth. In general, the present study adds regional evidence to the case showing that the digital transformation and the green energy source can be found to be complementary instruments to reach the green economic resilience in developing economies.



1. Introduction

The twenty first century has seen a convergence of issues of economic development and challenges of environmental crisis as never before forcing countries to re-evaluate their growth paradigm. Conventional patterns of economic growth that mostly operate based on fossil-based production means have led to considerable levels of ecological degradation, loss of biodiversity, and growing greenhouse gas emissions. This has drawn the international community towards the need of attaining the green economic development; a developmental path that balances economic development with the environmental conservation and the social inclusivity. This transition is particularly urgent within the Middle East and North Africa (MENA) region where economies continue to be highly dependent on hydrocarbon revenues to

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encounter growing risks of global decarbonization trends and climate change effects. Researchers insist on the idea that, unless the MENA economies pursue proactive attempts to implement sustainability principles in their macroeconomic systems, they may fail not only in their economy but also in their worsening ecological condition [1]. Green economic growth model aims at decoupling economic growth and environmental degradation by investing in renewable energy, promoting digital innovation, and setting up institutional reforms that increase efficiency and resilience. In this regard, the transition to sustainable energy and the digital transformation are no longer voluntary actions, but a necessary condition in becoming long-term resilient and competitive [2].

The online economy has become a dreadful driver of the fast-tracking efficiency, innovation, and low-carbon change in all the industries. The ubiquitous digital technologies that the digital economy permits allow for the streamlining of energy systems, managing resources, and production networks. The systems that use digital platforms make it possible to develop smart grids, predictive maintenance, and decentralized renewable energy systems, which significantly minimize operational inefficiencies and emissions [3]. Digitalization in developed economies has been associated with decarbonization of structures, better energy performance and better policy coordination. Nonetheless, there are significant digital discrepancies in the MENA region, which are characterized by uneven broadband infrastructure access, data ecosystems, and the lack of digital proficiency, all of which slow down the potential of the region to make the most of the digital transformation process to achieve sustainable development [4]. In spite of these shortcomings, increasing understanding is being created that digitalization could be transformative to the region. Once integrated in energy and industrial policy frameworks, the digital economy can help promote smart manufacturing, e-governance, and e-finance systems that can accelerate green financing and diffusion of innovation. Therefore, the digital economy is a catalyst to the creation of synergy between technological innovation and environmental sustainability.

Similar to the digital transformation, the due transition to renewable is the basis of a sustainable development. The gradual substitution of fossil fuels with clean sources of energy is the core of the global approach to climate mitigation. This transition has its distinct meaning in MENA region. There are vast prospects in the deployment of renewable energy that exist in the area because the region has immense solar and wind capabilities; however, the energy infrastructures are strongly biased towards oil and gas. Empirical evidence proves that raising the proportion of renewable energy as a part of the aggregate energy demand causes not only a decrease in the carbon intensity but also leads to job creation, spillovers in technology, and diversification of the economy in the long term [5]. To illustrate this point, Morocco and Egypt have managed to establish themselves as regional leaders with huge solar and wind power plants, which is an indication of a slow transition of people appearing not to be dependent on hydrocarbons and instead on more sustainable regimes of energy [1]. However, the obstacles that hinder a complete energy transition in the region still include poor regulatory structures, lack of financing systems and institutional inefficiencies. Renewable energy on national grid will need not only the modernization of technology; this is where digital technologies can be used to enhance transparency, trace energy flows, and better the management of grids. So, not only does the green(ish) energy transition constitute an environmental necessity but also represents a strategic economic prospect of the MENA region to build a sustainable development.

Though the literature on the personal functions of digital transformation and renewable energy transition in promoting green growth is growing, little empirical data is available on the synergistic or interaction effects of the two drivers, particularly in developing and transition economies. These effects are primarily being investigated in the literature in high-income or emerging economies not tied to the MENA region [6]. However, everything depends upon the context because there are some structural peculiarities of the region. As it is being promoted with the digitalization, it has the capability to follow the push of renewable energy implementation, make the energy production, storage and distribution system more efficient, and enhance the establishment of low-carbon technologies. Renewable energy infrastructure, in its turn, attains the required level of digitalization sustainability, entailing the supply of clean power to information centres and ICT infrastructure. Another research gap in the existing literature is the absence of the interdisciplinary research on the analysis of these mutual impact on the MENA economies [3]. Furthermore, dual transition in the region is defined by the quality of governance, presence of green finance, and geopolitical powers that must be theoretically delved so as to come up with the evidence based policy frames [8]. With this gap to be filled, the interplay between the digital and renewable changes in this context needs to be learned to arrive at the sustainable and inclusive development of energy-dependent economies.

With this background in mind, the current research will be intended to examine the synergistic impact of the digital economy and renewable energy transition upon the green economic growth in the selected MENA countries. In particular, it attempts to address three essential research questions, namely: (1) Does the digital economy have a direct impact on green economic development in MENA countries? The questions to be answered include (2) Does the renewable energy transition boost green economic growth in the region, the (3) Does the interaction between digitalization and renewable transition generate an amplified, nonlinear impact on green economic performance? This study aims at using strong-empirical methods like the System Generalized Method of Moments (GMM) and analysis of interaction terms to establish strong empirical data of the complementary relationship between digital transformation and energy transition. It is also believed that the findings will be added to both the theoretical and policy discussion because they will clarify how digital innovation can promote the efficiency and scalability of renewable energy adoption, and, as a result, sustainable economic growth.

The rest of the paper is arranged in the following way. Section 2 will present a systematic literature review of the existing literature and create the theoretical background of the digital regenerative model of synergy. Section 3 describes the methodology, data sources, and variable construction, which focuses on the reason why MENA countries were chosen. In Section 4 the empirical results are shown and interpreted with a focus over the interaction effects and robustness tests. Section 5 covers the policy response to the findings inconsistently on the funding of the digital infrastructure, financing of renewable energy, and institutional changes that should be made to achieve integrated sustainability. At last, the paper is concluded by Section 6, which summarizes the main findings made, gives an account of the study limitations and suggests the future research directions in light of digital-ecological transformation in the space of emerging economies. This study extends the analytical framework developed by Hwang (2023) for Latin America to the MENA context, incorporating region-specific variables including oil rents and institutional quality indicators

2. Literature Review and Theoretical Framework

2.1. Digital Economy and Green Economic Growth

Economic systems around the world have been transformed by the spread of digital technologies, which is challenging and provides an opportunity to the sustainable development. Contact-free economy which is propelled by the spread of information and communication technologies (ICT), artificial intelligence (AI), and big data has emerged as an important driver of efficiency, productivity, and green innovation [9]. The adoption of ICT infrastructure helps companies and states to be more energy-saving, streamlined the production process, and minimize waste output, thanks to predictive analytics and intelligent management systems. Connecting the digitalization of economic processes to the degradation of the environment has been observed to be decoupled in the presence of powerful regulatory tools and a renewable energy system [10]. An example of this is the digital transformation of the European Union which has enabled the major cut back of greenhouse gas (GHG) emissions utilizing culminate manufacturing and green ICT policy. Nevertheless, researchers also warn of the rebound effects that are pointing toward the two-sidedness of digitalization regarding sustainability consequences.

The literature on the topic emphasizes a beneficial impact of digital infrastructure and e-commerce that promotes efficiency of resources. Digital trade systems decrease the cost of transactions and logistics which is energy-demanding since they can dematerialize economic processes [11]. Similarly, the Internet of Things (IoT) and blockchain enable a high level of transparency of using resources, which make it possible to monitor the supply chain in real-time and mitigate environmental risks [12]. Stable results of empirical research, based on using the high-level econometric models CS-ARDL and GMM, demonstrate the positive growth of environmental productivity in the course of development of the references in developing economies due to the diffusion of ICT [13]. In addition, digital finance has played a significant role in discussing and funding green projects hence growing the connection between the digital economy and sustainable economic development [3]. The indicators indicate that digital transformation can give rise not only to the increased productivity or inclusiveness but also to the environmental sustainability provided that it is oriented on the coherent green policy frameworks.

Recent research builds up on this discussion by highlighting how digitalization can enhance a scenario where the relationship between energy consumption and economic production becomes disconnected (so-called decoupling). The use of digital technologies like demand forecasting powered by AI and the creation of cloud-based energy management tools have helped industries to transform their energy-intensive to the models of growth that depend on knowledge [14]. This has raised the new conceptual paradigm that emphasizes the ability of the digital economy to emerge and become an enabler of low-

carbon transitions through the subsequent provisions of energy efficiency and smart governance. However, the ecological advantages of ICT are based on the extent to which renewable energy is incorporated, and the sustainability of the data infrastructure. The environmental possibilities of digitalization are not fully exploited in such regions as MENA, where electricity is generated predominantly by fossil fuels as of now, indicating the need to tie in digitalization and clean energy implementation to transform the economy towards being green [15].

2.2. Sustainability and Renewable Energy Transition

The energy transition of renewable has become as a pillar of sustainable development to redefine the energy systems of the world towards low-carbon directions. The positive relationship between economic development and the use of renewable energy sources has been confirmed in many studies supporting the idea of the co-benefits of using renewable energy sources to the environment. Empirical studies supported by panel-ARDL and GMM frameworks reveal that an increased rate in renewable energy in the overall energy usage is beneficial in terms of both the GDP growth and reduction of CO 2 emissions [16]. This observation is consistent with the hypothesis of Environmental Kuznets (EKC) which suggests that at first, with a growing income, there is an increasing degradation of the environment, but later on, as economies reach a turning point, with renewable technology and environmental standards taking over, the level of environmental degradation decreases. In this regard, renewable energy can both be an energy source in the production process and be a means of green development, which can facilitate energy security and technological development [6].

Energy transition towards renewable works especially because in the developing parts of the world it is essential to balance both the economical and the environmental factors. Research in North Africa and the Middle East shows that the renewable energy infrastructures increase the energy diversification, decrease carbon reliance, and develop jobs in the new green sectors [1]. An example is the Moroccan case, which demonstrates that foreign direct investment may be stimulated with the help of various policy actions, such as green bonds and tax incentives, and the rapid deployment of renewable energy sources [16]. Government action likewise Relates Latin American and Asian experience with renewable energy use, empirical evidence shows that adoption of renewable energy stimulates innovation spillover, sustainable consumption, and macroeconomic stability [17]. In addition to its economic advantages, renewable energy alleviates the ecological impact by reducing the level of emissions and enhancing the model of the circular economy by recycling energy sources and implementing smart grids [18].

Nonetheless, obstacles continue to interrupt renewable transitions in the developing economies. The barriers to large-scale integration of renewable are high costs of installing initial capital, inefficient infrastructures, and uncertainty in policies. The empirical evidence indicates that the effect is heterogeneous since renewable energy improves sustainability in the long-term but demands supplementary institutional and technological systems in short-term terms [19]. Also, there are structural changes relating to the move to renewables, which impact employment, industrial competitiveness, and fiscal balance. Thus, the energy relocation towards renewable energy is not a strictly technical process, but a systemic process, which binds the policy, finance and innovation systems that requires a holistic governance policy to realise sustainable growth.

2.3. Strong Interaction of Digitalization and Renewable Energy

The breakthrough of digitalization and transition towards renewable energy is a fundamental step on the way to sustainable development. Renewable energy-related technologies like artificial intelligence, IOT, and machine learning can greatly streamline the energy systems by allowing predictive maintenance, real-time operational monitoring, and energy demand. This synergy will be defined by the concept of the Green Digital Twin paradigm; where the use of virtual simulations of the physical energy systems results in a more efficient operation of the system, reduced downtimes, and dynamic equilibrium between supply and demand [20]. With the help of digital joints, renewable energy plants can also predict energy output, implement weather statistics, and optimize grid connectivity, which will not only enhance its economic and environmental performance. This type of synergistic interactions is an indication of a structural change of a linear energy management model towards adaptive intelligent systems that are capable of integrating technological innovation with sustainability goals.

The empirical data confirms the opinion that digitalization enhances the effect of renewable energy on the quality of the environment by increasing energy efficiency and enabling distributed generation. Digitalization in European and Central Asian settings has demonstrated that the connection between renewable energy and carbon reduction has to mediate the decarbonization effect through smart energy system amplification [10]. By the same token, in less developed economies, ICT infrastructure can provide a major enabler of renewable deployment, most notably through smart grids and energy management platforms that lower the transmission losses and make the grid more resilient [11]. According to the studies of North Africa, the digital economy will strengthen the renewable transition by enabling the diffusion of innovation and real-time analysis of data in planning energy [13]. However, such synergistic interaction demands strong cybersecurity frameworks and institutional preparedness to handle the complexity of inter-connected digital-energy systems. The absence of the safeguards may compromise the security and consistency of renewable infrastructure due to digital vulnerabilities.

The ecology digital synergy is also spilled over to monetary and policy spheres. Digital finance and blockchain systems permit clear trading of carbon and decentralised energy markets, and peer-to-peer renewable energy transactions [3]. These systems reduce the costs of transactions, democratic access to energy, and encourage clean investment. Hence, digitalization does not only optimize operational elements of renewable energy, but also redesigns institutional and economic architectures that boost sustainable transitions. Essentially, the digital-renewable nexus is an essential factor in the next-generation green growth paradigm with the focus on systemic interdependence between technology, energy, and governance.

2.4. MENA and Third World Empirical Evidence

The empirical studies conducted in the MENA region and other emerging economies present a strong argument of the combined impacts of digitalization and renewable energy towards the attainment of sustainable development. The article [3] indicated that eco-digitalization and green financing are interconnected factors that provide environmental sustainability in MENA economies, and there is a two-way causal relationship between digital transformation and the use of renewable energy. In the same vein, [15] determined that green finance and renewable energy consumption is co-integrated with the economic growth supporting the idea that digital and financial innovations support low-carbon transitions. Digitalization has also been observed to complement the long-term effects of renewable energy on inclusive growth in North Africa, but the effect has been uneven because of the unequal access to digital infrastructure [13].

In addition to MENA, synergistic interaction between digital transformation and renewable energy transition is also emphasized in comparative studies in BRICS and ASEAN economies. As an example, BRICS countries can cultivate digital trade and green technological innovation that would have significant effects on carbon intensity and green total factor productivity [21]. Likewise, ICT trade has been observed to foster the use of renewable energy and increase environmental efficiency in the ASEAN [22]. Those results highlight the importance of the fact that digitalization does not only reinforce the use of renewable but does it in a moderating fashion, which increases the impacts on both the economic and environmental output. Besides, the local findings indicate that the quality of institutions and governance can be a determining factor when it comes to the success of the digitalrenewable synergy [4]. Therefore, the future of the MENA region on track to sustainable development is based on combining digital infrastructural foundation growth, renewable investment, and institutional reinforcement under the umbrella strategic approach.

2.5. Theoretical Framework

This paper unites the Endogenous Growth Theory and the Environmental Kuznets Curve (EKC) paradigm to conceptualize that relationship between digitalization, renewable energy transition, and green economic growth is in a dynamic format. According to endogenous growth theory, there is economic growth spurred by technological innovation and accumulation of human capitals which increase productivity and efficiency [23]. In this framework, the digitalization will be effective as a driver of endogenous technological change facilitating knowledge diffusion, network of innovation, and optimization of processes. Together with the adoption of renewable energy, the digital transformation will intensify the sustainability of the productivity since it will decouple the relationship between expanding and environmental degradation, thus internalizing ecological externalities governance in the growth process [6].

The Environmental Kuznets Curve is an addition to this model and implies a nonlinear correlation between economic development and the deterioration of the environment. Growth causes higher emissions at low levels of development and then at certain income level, less pollution is caused by cleaner technologies and regulatory measures. Digital and renewable transitions can be incorporated to push the EKC downward and to the left, which means that sustainable growth equilibria have been reached earlier [9]. Digitalization and renewable energy are the interacting factors in this theoretical model, which make the production systems more efficient and sustainable. This can be mathematically represented as an interaction term in an endogenous growth framework and is the compounding effect of digital and renewable capital on green total factor productivity. The net effect of this symbiosis is positive

externalities that go beyond the boundaries of individual sectors to drive systemic change into a low-carbon economy.

In this way, the given theoretical framework of the proposed study includes the theory of technological innovation and the theory of environmental economics as the joint explanation of how the joint impact of digitalization and renewable energy affects the green economy. It is argued that digital technologies do not only give rise to innovation, but they also maximize renewable energy systems, whereas renewable energy gives the clean power foundation that digital growth requires. These processes combine to create a loop of sustainable development, which puts the idea of digital-renewable synergy at the center of a future green growth process in MENA and other emerging economies.

3. Methodology

3.1. Data and Variables

This study employs a balanced panel dataset comprising eight selected MENA countrie over the period 2000-2024. The countries are selected based on data availability, regional representativeness, and the structural diversity of their digital and energy sectors. Annual data are extracted from the World Development Indicators (WDI) of the World Bank, International Renewable Energy Agency (IRENA), International Monetary Fund (IMF), International Telecommunication Union (ITU), and United Nations Development Programme (UNDP). The period captures the acceleration of digitalization in the early 2000s and the subsequent renewable energy transition that intensified after the Paris Agreement [24].

The dependent variable, Green Economic Growth (GEG), represents the environmentally adjusted economic expansion and is proxied through the Green Total Factor Productivity (Green TFP) index or alternatively by adjusting real GDP for CO_2 intensity. The GEG indicator is computed following the methodology applied by [30] and [19], where traditional TFP is adjusted for CO_2 emissions and energy intensity. Formally, it can be expressed as:

$$GEG_{it} = \frac{Y_{it}}{(CO2_{it} \times E_{it})}$$

where Y_{it} is real GDP per capita, $CO2_{it}$ denotes carbon dioxide emissions, and E_{it} represents total energy consumption. The index thereby captures both economic productivity and environmental performance.

The key independent variable, Digital Economy (DE), is a composite index integrating three primary dimensions: (i) internet penetration rate (% of population using the Internet), (ii) ICT investment (% of GDP), and (iii) digital trade share (% of total trade). This multidimensional construction is consistent with prior studies assessing the link between digitalization and green growth [3, 25]. To avoid scaling bias, each sub-indicator is normalized through min–max transformation and aggregated using an equal-weight arithmetic mean as follows:

$$DE_{it} = \frac{1}{3}\left(Z_{I_{nternet}e_{it}} + Z_{ICT_{it}} + Z_{\text{DigitalTrade }_{it}}\right)$$

where Z_k represents the standardized value of each indicator.

The Renewable Energy (RE) variable measures the proportion of renewable energy consumption in total final energy use, retrieved from IRENA databases. It captures the intensity of clean energy adoption in national energy structures.

A set of control variables (X) is included to isolate the effects of digital and renewable factors. These comprise:

- Foreign Direct Investment (FDI) inflows as a percentage of GDP, representing openness to technology transfer.
- Human Capital (HC), proxied by secondary school enrollment or the Human Development Index (HDI), accounting for skill effects on productivity.
- Trade Openness (TO), calculated as the sum of exports and imports relative to GDP.
- Oil Rents (OR) as a percentage of GDP, capturing the degree of dependence on hydrocarbons that could hinder green transition.

Descriptive statistics for all variables are presented in Table 1, providing insights into the data distribution, mean values, and variability across countries and years.

Table 1. Descriptive statistics of variables (2000-2024).

Variable	Mean	Std. Dev.	Min	Max	Source
GEG	2.54	0.96	0.98	4.85	WDI, IRENA
DE	0.49	0.21	0.10	0.89	ITU, IMF
RE	17.6	13.2	0.4	58.1	IRENA
FDI	3.18	2.75	-0.56	10.42	WDI
HC	0.65	0.10	0.40	0.82	UNDP
TO	80.12	25.43	36.22	154.12	World Bank
OR	15.47	19.65	0.01	63.90	WDI

3.2. Model Specification

The study empirically models the relationship between digital economy development, renewable energy transition, and green economic growth using the following baseline specification:

$$GEG_{it} = \alpha + \beta_1 DE_{it} + \beta_2 RE_{it} + \beta_3 (DE_{it} \times RE_{it}) + \gamma X_{it} + \mu_i + \varepsilon_{it}$$

where GEG_{it} denotes the green economic growth of country *i* in year *t*; DE_{it} and RE_{it} represent the digital economy and renewable energy transition, respectively; (DE_{it}×RE_{it}) captures the synergistic interaction between digitalization and renewable adoption; X_{it} is the vector of control variables; μ_i is the country-specific fixed effect; and ε_{it} is the idiosyncratic error term.

The interaction term tests the hypothesis that digitalization magnifies the positive effect of renewable energy on green growth through efficiency and innovation spillovers [10, 7]. A positive and statistically significant β_3 coefficient would confirm the existence of a synergistic or complementary effect, whereas an insignificant coefficient would indicate independent effects.

To further capture temporal persistence in green economic growth and mitigate endogeneity, a dynamic specification of the model is estimated using the System Generalized Method of Moments (SYS-GMM) developed by Arellano, M., & Bover, O. [26] and Blundell and Bond [27]:

$$GEG_{it} = \delta GEG_{it-1} + \beta_1 DE_{it} + \beta_2 RE_{it} + \beta_3 (DE_{it} \times RE_{it}) + \gamma X_{it} + \mu_i + \eta_t + \varepsilon_{it}$$

Here, the inclusion of the lagged dependent variable (GEG_{it}–1) controls for dynamic adjustment processes and inertia effects in green growth trajectories. The presence of η_t accounts for unobserved time-specific shocks such as regional policy shifts and global energy price fluctuations.

The SYS-GMM estimator is chosen because it effectively addresses potential endogeneity, heteroskedasticity, and autocorrelation problems inherent in panel data models. Following prior research in digitalization–energy–growth literature [25]; [28], both first-differenced and level equations are used to exploit orthogonality conditions between instruments and error terms, ensuring consistency and efficiency of the estimates.

Before estimation, the panel characteristics are verified through a series of diagnostic tests. The Levin–Lin–Chu (LLC) and Im–Pesaran–Shin (IPS) tests confirm the stationarity of variables after first differencing. The Pedroni cointegration test is used to establish a long-run equilibrium relationship among the variables. Additionally, variance inflation factors (VIF) are computed to detect multi collinearity, ensuring that all variables remain below the critical threshold of 10.

3.3. Estimation Technique

The analysis follows a multi-stage econometric approach. First, the Fixed Effects (FE) and Random Effects (RE) models are estimated to capture within- and between-country variations. The Hausman test determines the appropriateness of the FE model by testing for correlation between regressors and unobserved country effects. If the null hypothesis of no correlation is rejected, FE estimation is preferred.

Subsequently, the System GMM estimator is employed to address potential endogeneity among regressors, particularly between digitalization and renewable energy, as both variables could be influenced by unobserved economic and institutional factors. Following [10] and [19], the estimation uses two-step robust standard errors to correct for heteroskedasticity. The instrument validity is tested using the Hansen J-statistic for over-identifying restrictions and the Arellano–Bond AR (2) test for second-order serial correlation. The absence of serial correlation and valid instruments confirms model reliability.

For robustness, additional estimations are conducted using Quantile Regression (QR) and Panel Corrected Standard Errors (PCSE) models to test for heterogeneous effects across the distribution of green economic growth. Quantile estimation allows the exploration of how the digital–renewable synergy affects low-, medium-, and high-performing countries differently, thereby enhancing policy relevance.

Moreover, sensitivity analyses are performed by substituting the dependent variable GEG with alternative indicators such as Green GDP per capita and Green TFP, and re-estimating the models using Driscoll–Kraay robust standard errors to control for cross-sectional dependence. The robustness of the interaction term (DE_{it}×RE_{it}) across specifications serves as a critical test of the synergy hypothesis.

The econometric results are summarized in Table 2, illustrating the expected signs of coefficients and theoretical implications.

Table 2. Expected signs and theoretical implications of key variables.

Variable	Expected Sign	Theoretical Justification
DE	+	Digitalization enhances efficiency, innovation, and decarbonization [3].
RE	+	Renewable adoption supports sustainable growth and reduces emissions [7].
DE × RE	++	Synergistic effect where digital technology optimizes renewable integration [25].
FDI	+	Facilitates technology transfer and green innovation [19].
HC	+	Human capital improves absorptive capacity for digital-green technologies.
TO	±	Trade openness can either promote efficiency or intensify emissions depending on structure.
OR	–	Oil dependency crowds out green investments [1].

Overall, this methodological framework integrates robust econometric modeling with theoretical consistency, ensuring that the relationship between digitalization, renewable transition, and green growth is examined comprehensively and rigorously. By combining dynamic modeling, interaction terms, and multiple robustness checks, the study contributes to the empirical literature on sustainable growth transitions in developing regions and establishes a replicable analytical framework for future cross-regional studies.

4. Results and Discussion

4.1. Descriptive Statistics and Correlation Analysis

The preliminary stage of empirical analysis focuses on the descriptive and correlation statistics to explore the underlying trends and interrelationships among the core variables: digital economy (DE), renewable energy transition (RE), and green economic growth (GEG). Table 3 presents the summary statistics of the panel dataset covering eight MENA countries (Saudi Arabia, UAE, Egypt, Iran, Morocco, Tunisia, Jordan, and Oman) for the period 2000–2024.

Table 3. Descriptive statistics of core variables (2000-2024).

Variable	Mean	Std. Dev.	Min	Max	Obs
GEG (Green Economic Growth Index)	2.54	0.96	0.98	4.85	200
DE (Digital Economy Index)	0.49	0.21	0.10	0.89	200
RE (Renewable Energy Share, %)	17.6	13.2	0.4	58.1	200
DE × RE (Interaction Term)	8.36	6.12	0.12	28.41	200
FDI (% of GDP)	3.18	2.75	-0.56	10.42	200
Human Capital Index	0.65	0.10	0.40	0.82	200
Trade Openness (% of GDP)	80.12	25.43	36.22	154.12	200
Oil Rents (% of GDP)	15.47	19.65	0.01	63.90	200

A 2.54 average Green Economic Growth (GEG) in the MENA region indicates a moderate development towards an environmentally adjusted economic development but highly dispersed. The mean value of the Digital Economy Index (DE) at 0.49 is the indicator of the unequal level of digitalization when the Gulf Cooperation Council (GCC) economies have the highest degree of digital readiness, and non-oil countries such as Tunisia and Egypt depict slower digitalization. The performance of Renewable Energy (RE) stands at approximately 17.6% of the total consumption thereby highlighting slow but not complete shift toward clean energy in the area. The heterogeneous implementation of policies and resource endowments is justified by the high (up to almost 60% in Morocco) variation in RE [3]; [15]. Table 4 showing the correlation between the variables gives a preliminary evaluation of the linear association between the variables.

Table 4. Correlation matrix among key variables.

Variables	GEG	DE	RE	DE×RE	FDI	HC	TO	OR
GEG	1.000							
DE	0.68	1.000						
RE	0.59	0.42	1.000					
DE×RE	0.73	0.84	0.71	1.000				
FDI	0.46	0.48	0.34	0.41	1.000			
HC	0.64	0.55	0.39	0.60	0.42	1.000		
TO	0.37	0.28	0.22	0.31	0.46	0.34	1.000	
OR	-0.51	-0.38	-0.46	-0.52	-0.15	-0.40	-0.18	1.000

The correlation analysis shows that digital economy and green economic growth are strongly related (r= 0.68), and such a finding confirms that the growth rates of countries with digital infrastructures are higher in relation to environmentally adjusted growth. Renewable energy (RE) and that of GEG are also significantly related (r= 0.59) as per the hypothesis that clean energy helps sustainable productivity. The strongest correlation term (DE × RE) with GEG (r= 0.73) indicates that there is a synergistic complement when it comes to digital transformation and deployment of renewable energy; a correlation later validated using econometric estimation. The macroeconomic effect, which shows negative correlation between oil rents (OR) and GEG (-0.51) highlights the dynamics of the resource-curse effect in fossil-fuel-based economies, which aligns with the results [19] and [29].

4.2. Econometric Results

The econometric estimations use both Fixed Effects (FE) and System GMM (SYS-GMM) methods in order to correct any unobserved heterogeneity, dynamic persistence and bias of endogeneity. Autonomous findings are presented in Table 5, which indicates estimates of the coefficients and diagnostics.

Table 5. Econometric estimation results (Dependent Variable: GEG).

Variables	Fixed Effects	SYS-GMM (Dynamic)
Lagged GEG	–	0.412*** (0.056)
DE	0.384*** (0.072)	0.312*** (0.085)
RE	0.215*** (0.058)	0.237*** (0.062)
DE × RE	0.127*** (0.031)	0.142*** (0.038)
FDI	0.061** (0.028)	0.048* (0.027)
HC	0.225*** (0.064)	0.192*** (0.056)
TO	0.043 (0.032)	0.038 (0.029)
OR	-0.109** (0.051)	-0.098** (0.046)
Constant	1.432 (0.284)	1.387 (0.301)
Observations	200	200
Countries	8	8
Hansen J-stat. (p-value)	–	0.36
AR(2) test (p-value)	–	0.41
R^2 (within)	0.67	–

Note: *Standard errors in parentheses; ***, **, * denote significance at 1%, 5%, and 10% levels respectively.

Results indicate that Digital Economy (DE) has a positive and statistically significant impact on both the growth and change in green economy, in both the dynamic and the static models. The elasticity of the above GMM form is 0.31 meaning that, assuming other things constant, a 1 percent change in digital economy index causes a 0.31 percent change in GEG. This observation supports the proposal that digitalization lead to increased eco-efficiency and productivity that is driven by innovations [25, 10]. Optimization of energy by using data analytics, logistics smarts, and precision manufacturing in improved ICT infrastructure provides sufficient decoupling of output and emissions. Equally, Renewable Energy (RE) has a very positive correlation with GEG (β_2 = 0.237, p = 0. 01). This proves that higher usage of renewable energy will assist in creating a significant effect on the environment productivity because it decreases the level of carbon intensity and encourages new investment and jobs in the green sector [30]; [6]. The most important empirical contribution is seen in form of the product of the interaction term (DE × RE), which is positive and significant (β_3 = 0.142, p < 0.01). This result supports the synergistic hypothesis: the digital transformation increases the positive consequences of the renewable energy transition on the green growth. In particular, digital technologies increase the efficiency of the integration of renewable energy, reduce the problem of intermittence, and improve the use of storage [10, 3]. It is also found that the strength of the coefficient of the interaction indicates that the joint impact of the digitalization and renewable energy is higher than the individual impacts, which is also in line with the Green-Digital Twin paradigm, previously identified in literature [6, 31]. None of the control variables behave in a non-hypothetical manner. The influences of FDI on GEG are positive though the elasticity is moderate (B=0.048), which means that the increase in eco-innovation together with technology diffusion is encouraged by inflows of foreign capital. The positive impact of human capital (HC) is high and significant (β= 0.192), which is essential in capitalization of relying on digital literacy and the skill development in exploiting technological complements. On the other hand, oil rents (OR) portray a negative coefficient with high value, which again confirms the structural impediment of hydrocarbon dependency; a classical manifestation of the environmental resource curse [19]. The non-significance of the trade openness (TO) is consistent with somewhat contradictory literature results that show that trade effects are contingent on export structure and the severity of environmental regulation. The diagnostic statistics confirm the strength of the GMM: The Hansen J-test (p= 0.36) shows the validity of the instruments used, whereas AR (2) test (p = 0.41) shows that there is no second-order autocorrelation. The high explanatory power of the included variables is also witnessed by the within R 2 that is 0.67 of the FE model.

4.3. Robustness Analysis

The three complementary procedures in which robustness checks are performed are: (1) other dependent variable specifications, (2) both quantile regression analysis, (3) sensitivity to digital and renewable sub- indices. To start with, the replacement of GEG by Green TFP, as well as the Green GDP per capita, gives the same results, where DE and RE remain positively correlated with the interaction significant. This shows the consistency of the synergy effect between measurement systems (see Table 6).

Second, there is heterogeneity in the green growth distribution as quantile regression (QR) results show.

Table 6. Robustness check: alternative dependent variable (Green TFP).

Variables	Coefficient	t-Statistic	Significance
DE	0.298	4.12	***
RE	0.224	3.87	***
DE × RE	0.138	3.42	***
Controls	Yes	–	–
R^2	0.65	–	–

The effect of the interaction (DE × RE) is most pronounced at higher quantile (β_3= 0.19 at the 75th percentile) than lower quantile (β_3= 0.11 at the 25th percentile), which means that the effect of digital-renewable synergy is stronger

in already well-performing country on sustainability metrics; more likely GCC countries with an established digital infrastructure. This is consistent with the results of [32] and [10], who propose that the impact of digital-ecological innovation is nonlinear. Third, a break-down of the digital economy as indicated by the sub components (ICT investment, internet penetration, and digital trade) confirms that ICT investment has the greatest marginal impact on GEG (0.192), then digital trade (0.148), and internet penetration (0.127). In the same way, in the renewable energy index, solar and wind tire elements are more elastic compared to hydro and biomass elements, which are in accordance with technology diffusion processes in the MENA region [15]. Altogether, the robustness tests confirm the main hypothesis: the production of green economic growth in the MENA region by the synergy of digital transformation and renewable energy transition is dramatically positive. This result is consistent with the larger trends in the world [25, 6] and introduces new local knowledge about the processes of making eco-digital.

4.4. Discussion

The empirical findings showing the positive and synergistic correlation among the digital economy, renewable energy shift, and green economic development in the MENA countries are mostly in line with other regions but unveils specific regional patterns based on structural, institutional, and technological asymmetries. The results below have been interpreted in a comparative and contextual manner and the discussion below puts the MENA experience in the global discourse of digital-ecological transformation. The beneficial and substantial role of digitalization and renewable energy on green growth is consistent with the previous cross-regional data of Europe and East Asia and Latin America. As an example, [6] has analyzed 18 countries in Latin America and the Caribbean and discovered that digital transformation, as well as renewable energy transition have an independent impact on promoting green economic growth, but their independent combination has a nonlinear and amplifying impact on environmental sustainability. In the same vein, Gao and Wen [33] found that, in more than 100 countries, the digital economy is creating a process of economic-ecological integration, and in high-income and upper-middle-income regions, in particular, owing to developed digital infrastructure and institutional capacity. The above research findings have been supported by these studies as they prove that the identified synergistic effect of digital innovation can facilitate a more effective implementation and utilization of renewable energy sources, which in turn amplifies the effects of green productivity. Zarrad et al. [34] managed to show in the European economies that the digitalization with the use of renewable sources would considerably decrease the level of greenhouse gas emissions, and the estimates of the long-term elasticity are similar to the ones they received in the MENA in the course of the current study. Additionally, the high-tech smart grid systems and electronic governance practices embraced in the Eurozone have found their ways useful to fine-tune the renewable energy use, which depicts how the eco-digital twin can effectively be achieved in reality. In the meantime, [37] identified comparable synergies of the new economies where renewable energy and digital finance have a significant impact of controlling carbon emissions. The outcomes of MENA can be classified into this global trend but are still unique because of the fact that the region is a two-fold dependent on fossil resources as well as foreign digital infrastructure that determines the velocity and the extent to which synergy can be achieved. Table 7 shows that there are various similarities and differences between the digital-renewable-growth nexus in MENA region, the European Union, and East Asia.

This comparative synthesis is in support of the fact that structural logic of synergy is universal, but its intensity and translation of policy varies across regions. The MENA case has peculiar challenges and opportunities which are based on the history of hydrocarbon dependence, less cross-border integration of energy, and gaps on digital infrastructures. The relationship between digitalization and renewable energy transition in MENA takes place in an economic system with dualistic character with a high reliance on oil income and disparity in the spread of new technologies.

Table 7. Comparative overview of digital-renewable synergy effects across global regions.

Region	Key Findings	Structural Features	Policy Mechanisms	Sources
Europe	Strong DE–RE synergy; digitalization accelerates green innovation and emission reduction	High digital maturity; integrated energy markets	EU Green Deal, carbon pricing, smart grid investment	[34, 35]
East Asia	Digitalization enhances renewable deployment; nonlinear growth effects	State-driven industrial policy; rapid innovation diffusion	National innovation systems, industrial policy alignment	[36]
Latin America	Moderate synergy; RE dominates DE in green growth impact	Digital divide; energy dependency on hydro	Sector-specific incentives; foreign green investment	[6]
MENA	Strong DE–RE synergy but constrained by oil dependence and institutional fragmentation	High fossil fuel reliance; uneven digital penetration	Green finance, Vision 2030 reforms, renewable diversification	[15]

The digital gap between high-income GCC economies and low-income North African countries generates substantial difference in the ability to use the digital-green synergies. The UAE and Saudi Arabia, being the gulf states, have established extensive plans of digital transformation (e.g., UAE Digital Economy Strategy 2031, Saudi Vision 2030), using sovereign wealth funds to invest in smart grids, AI-powered energy management, and green data centers. Through such efforts, they have been able to progress to a low-carbon, knowledge based mode of growth. On the other hand, non-oil countries such as Tunisia and Egypt are limited by the lack of digital infrastructure, energy subsidies, and the less robust innovation systems, which make the shift to the digitalized renewal system slower [38]. The energy mix in the region is also a major determining factor. Although solar and wind schemes have comparatively large potential, fossil fuels continue to prevail in most of the MENA countries, with over 85 percent of total energy consumption in 2023 [39]. The economic outcome in the econometric of positive coefficient of the renewable energy highlights the possibility of the renewable energy system to decouple the growth and the emission, but the achievement is curtailed by infrastructural and financial constraints. [15] assert that the recent creation of green finance instruments, including green bonds and Islamic sustainable funds, has started to mitigate the constraints in capital, but the institutional fragmentation still restrains the cross-sectoral integration. The policy frameworks in the MENA region are still uneven and decentralized with no regional coordination mechanism as seen with European Union and its Green deal [39]. Whereas the Gulf countries have developed integrated renewable energy plans and digitalization plans, the countries in North Africa are more dependent on donor-supported and externally funded initiatives which lead to disjointed implementation. In addition, the political instability and the geopolitical tensions are additional constraints when regional cooperation in the energy interconnection and digital infrastructure, which can moderate the entire potential of the digital renewable synergy. The interaction term (DE × RE) in MENA model has been shown to be elastic at 0.142 which is not very high, as compared to the one in similar studies of Europe (0.178) and East Asia (0.165). This is a sign that the digital-renewable complementarity of MENA, despite its existence, is limited by systemic inefficiencies. Table 8 indicates that a regional comparison of the synergy coefficients highlights these structural differences.

Table 8. Comparative elasticities of the digital–renewable interaction term on green economic growth.

Region	Coefficient (β_3)	Methodology	Key Limiting Factor	Sources
Europe	0.178***	SYS-GMM	Mature digital saturation	[34]
East Asia	0.165***	CS-ARDL	Policy coordination	[37]
MENA	0.142***	SYS-GMM	Fossil dependency, digital divide	[15]
Latin America	0.119**	FEPTR/MMQR	Institutional volatility	[6]

The fact that the coefficient in the MENA case is lower indicates technological as well as institutional inertia. However, even with the growing scale of digital innovation, it is concentrated in a few urban hubs, and renewable energy infrastructure continues to be massively subsidized by the fossil fuel revenues. This setup helps to limit the spillover consequences and limit the implementation of a completely integrated eco-digital system. However, positive and significant interaction term is the sign of accelerating the possibility of synergy as digital maturity and renewable penetration increase with time. Additionally, the institutional setting of the region provokes unique processes into the eco-digital movement. Path dependencies that are as a result of the existence of rentier-state economies touch upon digital investments and energy investments. [8] argue that geopolitical risks and fiscal rigidity weigh down environmental performance with a vocationalise of the policy tools of green finance and investment in digital infrastructure working to alleviate those impacts. These findings are supported by the current outcomes and indicate that policy frameworks that focus on the integrated governance approach and cross-sectoral alignment can considerably enhance the sustainability effect of digitalization and renewable energy. The results have a number of implications on policy formulation as well as theories. First, they confirm the Endogenous Growth Theory school of thought that proper technological advancement is an internal agent of sustainable growth of productivity. Second, the findings confirm the Environmental Kuznets Curve (EKC) hypothesis, which states that the closer the digital capital and renewable capital are accumulated, the lower the trade-off between growth and emissions is. Lastly, structurally, MENA case reveals the mediating role of institutional complementarities as enabling forces that predisposition digital green synergies strength. To policy-makers, the findings indicate the need to have combined digital-energy policies, coordinated policies, and investments in digital literacy and cyber security to enable the deployment of renewable energy. Best practice examples provided by the European Green Deal [40] and Asian models of industrial digitalization [36], conditions of synergy optimization include cross-sectoral governance, the data sharing standard and regional collaboration. It is possible to bring green growth performance to MENA countries by following the examples as such, through the encouragement of joint ventures in smart grids, as well as scaling

the interconnectivity of the regions in digital-energy. Overall, even though the empirical evidence confirms the presence of the digital-renewable synergy in leading to green economic growth, as it is, it also shows that the scale and achievement of this synergy are path-specific, which depends on institutional, technological, and policy contexts. The changing digital base of MENA, in addition to its enormous potential in the field of renewable energy, has put it in a good place to move towards sustainable growth; as long as policy alignment, financial innovation and regional collaboration are maintained.

5. Conclusions

This paper has empirically explored how digital economy, renewable energy transition, and green economic growth have a synergistic relationship in an analysis that was carried out on the 2000-2024 period of analysis across the selected MENA countries. The analysis based on advanced panel econometric methods, especially system GMM estimator identified that digitalization as well as renewable energy uptake are positively linked and jointly stimulates the environmentally sustainable economic performance. The fact that the coefficients of the relevant variables in the digital economy and renewable energy are positive and significant, validate their relevance as the complementary productivity drivers towards green productivity. More to the point, the interaction element between digitalization and renewable showed an increased influence, and highlights the fact that there is a strong synergy that is not limited to the act of its contribution. The theoretical prediction, which suggests that technological progress and development of clean energy support one another towards low-carbon and innovation-driven growth paths, is confirmed by this finding. The empirical data provides digital change as an essential facilitator of green economic change. Digital technologies can promote decoupling of economic development and environmental destruction by promoting efficiency, dissemination of innovation, and intelligent management of energy consumption. Equally, renewable energy transition would help in maintaining long-term sustainability through decrease of emissions, portfolio diversification, and at the same time enhance employment and economic activities diversification. All of the results prove that a well-organized digital-renewable approach can open new opportunities of sustainable development in the MENA region the one that will balance economic sustainability with environmental care. Nonetheless, the research also indicates that the power of the digital-renewable nexus in different countries is variable, which is the manifestation of structural heterogeneity of the MENA region. Those economies that rely on oil, due to their financial capacity to invest in new technologies, have a tendency to be institutional and policy inert on the grounds of deep-rooted subsidizing of fossil fuels and the practice of rent-seeking. On the other hand, developing non-oil sectors such as Morocco and Tunisia increasingly demonstrate dynamism in the use of renewable but have problems with the lack of a digital infrastructure, as well as governance limitations. This deviation indicates the analytical role of institutional quality, human capital and policy coherence in mediating factors in the determination of the magnitude and pace of green transformation. Bridging the digital divide, supporting education and skills, or securing steady regulatory surroundings is thus crucial as preconditions to the process of strengthening the link in the positive feedback loop between digitalization and renewable energy. This research has multifaceted policy implications. To begin with, the governments have to develop concerted efforts in viewing digital transformation and renewable energy transition as complementary supporting pillars of the green growth, as opposed to approaches that isolate the two sectors. This needs organized investment in digital facilities along with specific encouragement of renewable energy development and implementation. Second, knowledge exchange, transnational energy flow, and coordinated digital regulation, such the European Union Green Deal framework, could be facilitated by the creation of regional cooperation frameworks. Third, the financial tools like green bonds, digital finance platforms, and carbon trading systems need to be extended to attract the involvement of the private sector in the projects related to the eco-digital. Based on theory, the findings support the endogenous growth view which argues that growth in the long term has been driven by technological advancement and innovation as the engines. Besides, they polish the hypothesis of the Environmental Kuznets Curve (EKC) by showing that the combination of digital and renewable capital moves the turning point in which economic growth contributes to the environmental well-being. Therefore, the SME--renewable synergy provides a doable and extensible model of how to balance economic development with the ecological protection in developing areas. To conclude, the paper offers a solid empirical evidence of the transformative opportunity in digitalization and integration of renewable energy in spurring sustainable development within the MENA region. The results support that the gateway of green prosperity should be through the use of technological innovation, institutional change, and regional cooperation in order to create a digital, decarbonized, and sustainable economy.

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Credit authorship Contribution Statement

Rahele Motazer and Emad Mehranpour: Investigation and perform calculations, Mohammad Nasr Esfahani: Supervision, Project administration, and Manuscript writing and editing results.

Conflicts of Interest

The authors declare that they do not have any personal or financial conflicts of interest.

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