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The Impact of Digital Infrastructure Development and Green Innovation on Energy Productivity and Economic Growth in Selected Middle Eastern Countries: A Simultaneous Equations Approach

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Abstract

This research analyses the impacts of digital infrastructure advancement and green innovation on energy efficiency and economic growth in the Middle East countries. The analysis used 18 countries estimates based on annual data for 2010-2023 based on two simultaneous equations estimated by two stages least squares (2SLS). The equations contained energy efficiency and economic growth as proximate determinants on the left-hand side, digital infrastructure, green innovation, and other economic variables namely FDI, industrial share of GDP, literacy, and urbanization on the right-hand side of the equations. The results indicate that DI has a positive and statistically significant influence on energy efficiency (coefficient 0.218, p-value 0.000), and green innovation also has a significant positive impact (coefficient 0.136, p-value 0.004). In addition, development of digital infrastructure has positive and significant impact on economic growth (coefficient 0.157, p-value 0.004), and green innovation also works in effective way on economic growth (coefficient 0.115, p-value 0.016). For other independent variables, FDI and UR had a positive and statistically significant impact on the two dependent variables. These findings highlight the necessity of investing in digital infrastructures and green innovation as a driving force for promoting energy efficiency and economic development. Therefore, the policy implication for developing SB of digital technologies and green innovations, as a means of realizing sustainable development goals, should be a priority agenda to policymakers in the region.

Keywords: Digital Infrastructure, Green Innovation, Energy Productivity, Economic Growth, Selected Middle Eastern Countries.

1. Introduction

Today's radical change is brought into economic governance, prompted by major changes in technology and environment in these past decades. It is in this sense that digital infrastructure is an essential enabler of the fourth industrial revolution, and green innovations are powerful and practical toolkits of shifting to sustainable development, not only serve as an important force of energy saving but also as a sharp promoter of economic growth (Albaker et al., 2023; Zaki & Mansour, 2022; Patimar & Zamani, 2024). On the other hand, the pervasive environmental issues and the rising energy use in developing nations, particularly in the Middle East region, same solutions based on technology and innovation are in demand, which bring in optimization of energy consumption and economic progress concurrently (Zhao & Shah, 2024; Shayesteh & Miri, 2023).

The digital infrastructure enables energy efficiency improvement by modernizing energy transmission and distribution in the form of smart grids, improved information exchange, digitalization of industrial processes and greater transparency (Li et al., 2024; Al-Ghussain et al., 2020; Hosseini and Mousavi, 2022). Green technology The consumption and production ability of the environment significantly relates to the intensity of pollutants and the level at which energy is consumed for each country (Chantareewan and Saphores, 2020).Similarly, green innovations such as the use of clean technologies, renewable energy sources, and new environmental policies will contribute to reducing energy intensity and the level of pollutants (Al-Sarihi, 2020; Bekhet et al., 2022; Jafari Parvizkhanlou et al., 2021). Most of the earlier studies have either analyzed the effects of these two factors in isolation or investigated the relations on the national level (Saleem & Khan, 2023; Almasria et al., 2024; Bahaeddini et al., 2024), and the simultaneous consideration and the interconnection of the influence of these two constituents on economic productivity and energy productivity in Middle Eastern states is an area where a gap still exists in the literature.

Due to the unique economic features (Baas et al., 2019), abundance of energy resources, reliance on oil exports, and promising pro-digitalization efforts in the Middle Eastern nations, investigating relationship among digitalization, environmental innovations, and critical macroeconomic variables is particularly relevant for regional decision makers (Myovella et al., 2020; El-Katiri, 2020; Goodarzi Farahani et al., 2020). The aim of this paper is to investigate the composite impact of these two strategic variables on sustainable Gulf countries development and energy conservation in the long run by panels of selected Middle eastern countries over a long-run period and using the dynamic econometric techniques.

The rest of this paper is organized as follows: In Section 2 we overview theoretical and empirical literature of the paper. In Section 3, we describe the conceptual model and the research design. Empirical results are presented and discussed in Section 4, and, Section 5 is reserved for discussion, conclusions, and policy recommendations.

2. Theoretical Foundations and Literature Review

2.1. The Impact of Digital Infrastructure Development on Energy Efficiency

The development of digital infrastructure, particularly through technologies such as the Internet of Things, smart systems, big data, and artificial intelligence, has exerted substantial effects on energy efficiency across industries and countries. These transformations, especially in optimizing energy consumption, improving production processes, and reducing energy waste, have received considerable attention in many countries, particularly in the Middle East region. The utilization of digital technologies contributes to reducing energy losses, increasing the efficiency of energy production and distribution systems, and ultimately enhancing energy efficiency at various levels.

Digitalization of industrial processes and smart systems applied to energy management are the most significant potential levers for an increase in energy efficiency. As a result of the presence of intelligent systems in industrial processes, energy consumption can be continuously monitored and optimized. Monitoring technologies are used to acquire energy-consumption data in these systems. This information can be used to improve overall control of consumption at multiple instances. This method can lead to impressive implications in cost- and energy-saving, especially in the high-energy industrial fields (Albaker et al., 2023; Zaki & Mansour, 2022; Hosseini & Mousavi, 2022).

Yet another method is big data and predictive analysis of energy usage. Predictions of future energy consumption are performed based on these massive datasets obtained from numerous systems. Such forecasts, most notably in relation to instances where supply and demand of energy are not constant, can help to guide managers in efficiently controlling energy usage to avoid waste. AI algorithms such as machine learning can process and analyze energy consumption patterns which can lead to improved consumption regarding the statistics (Zhao & Shah, 2024; Shayesteh & Miri, 2023).

Another strong method of achieving energy efficiency has also been the link and cooperation of energy systems with digital networks. Digital-driven smart grids can efficiently distribute energy demand. These networks allow for intelligent and dynamic energy production and consumption systems. During high demand, for example, smart grids enable automatic transfer of renewable energy to consumers, saving pressure on main networks. These characteristics lead to less energy pricing and increasing energy consumption efficiency (Saeeri et al., 2020; Patimar 10:28 PM??Zamani????
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Another substantial effect of digital infrastructure is to optimize the degree of energy losses and energy generation efficiency systems. By employing digital technologies, such as smart surveillance systems, the state of energy production equipment can be accurately monitored to prevent the failures or inability of equipment that result in energy waste. Aside from the enhanced power plant efficiency, this procedure minimizes energy waste and enhances the performance of energy production systems (Zhao & Shah, 2014; Goodarzi Farahani et al., 2020).

Finally, the advancement of green technologies is another good influence for the digitalization of energy efficiency. Renewable energies, such as solar power and wind power, can also be used more efficiently thanks to digital systems and innovative technologies. Information from renewable energy sources and environment can be acquired accurately by digital systems, and then these energies can be transferred to the energy grid more efficiently by advanced algorithm models. Furthermore, this strategy plays a vital role to save fossil fuel and pollution as well as it successfully increases energy efficiency in different extents (Al-Sarihi, 2020; Al-Kasasbeh et al., 2023; Jafari Parvizkhanlou et al., 2021).

2.2. The Impact of Digital Infrastructure Development on Economic Growth

Constructing digital infrastructure is one of the main part to develop their economy among various countries. In modern society with the rapid transition of digital transformation, digital technologies are more and more widely applied by countries and organizations to improve efficiency, productivity, and economic process in general. These same transformations are evident in the industrial economy, as well as in agriculture, services, and government. Hence, the construction of the internet infrastructure, 5G, big data, artificial intelligence (AI) and other digital infrastructure, has directly and indirectly promoted economic growth.

Digital innovation as a driver of economic growth In general, digital innovation has become one of the most important mechanisms for economic growth. Resource productivity could be improved through digitalisation of production and service processes. Organizations can save costs and increase their competitive edge on the world market through introduction of cost-conscious systems and new technologies that improve quality of products and services. Ultimately, the former can result in the long-term financial growth of nations (Albaker et al., 2023; Zaki & Mansour, 2022).

Another important loud hailer of growth is big data and predictive analytics usage in economic decision making. Economic facilities, policymakers and managers can use analysis of consumer, business and industrial data to inform better decisions on how to allocate economic resources. These analyses help in better management of resources, forecasting supply and demand, reduce cost and improve economic performance ultimately. In this sense, artificial intelligence and machine learning in advanced analytics can be implemented to replicate the economic situation and predict future market trends (Myovella et al., 2020; Balsalobre-Lorente et al., 2018).

The proliferation of availability of internet and digital networks, particularly in the developing world, is an important aspect of economic growth as well. The internet and digital technologies can help developing countries increase access to global markets, build industrial competitiveness, and create jobs. More specifically, with the support infrastructure digital the creation new jobs in the sectors technological information, online services, e-commerce and other similar, promoting sustainable development in different countries (Zhao & Shah, 2024; Patimar & Zamani, 2024).

Connecting digital with other economic activities have a potential impact on leapfrogging economic development. For instance, digital technologies improve distribution processing, minimize transport costs, and improve transport network performance in transportation and logistics. Likewise, for manufacturing business, digital tools such as intelligent manufacturing systems can improve productivity and lower production costs. This eventually results in economic growth that is enhanced by an increased gross domestic product (Zhao & Shah, 2024; Goodarzi Farahani et al., 2020).

The effect on economic growth is also driven by innovation and investment in new technologies facilitated by the development of digital infrastructure. New technologies, especially in renewables, EV's, and industry, can drive economic growth through increased productivity, decreased cost, and increasing production. Also, such developments may draw foreign capital, which can be helpful for more balanced economic growth (Balsalobre-Lorente et al., 2018; Saeeri et al., 2020).

And last but not least, sustainable economic development facilitated by the digital infrastructure would lead to positive and sustainable impacts on economic growth. This process results, on the one hand, in greater efficiency/productivity and cost lowering, and, on the other hand, due to job creation and better standard of living, may also promote general welfare levels (El-Katiri, 2020; Al-Kasasbeh et al., 2023).

2.3. The Impact of Green Innovation on Energy Efficiency

Green innovation is a group of innovations geared toward mitigating environmental damage and enhancing the efficiency of natural resources, especially energy. Such developments--whether in the form of new technologies, better practices, or socially acceptable products or services--have the potential of achieving increased energy efficiency, at both macro and sectoral levels. In situations where the climate change scenario and drive for economy of burning fossil fuels matter most matter most. green innovations have become essential in promoting energy efficiency through reduction in natural resource use (Djellouli et al., 2022).

Clean technology and renewable energy is one of the major paths through which green innovation influences energy efficiency. Technological innovation in renewable energy sectors, such as solar, wind and biomass, especially of energy-intensive industries contributes considerably to improving energy efficiency. Such technologies are significant as that renewable energies (REs) have low carbon content relative to fossil sources, are responsible for environmental pollution and for energy loss as well. Adoption of these technologies with advanced digital technologies can exploit energy resources efficiently and minimize energy wastage (Zhao & Shah, 2024; Shayesteh & Miri, 2023).

A complementary approach consists in developing better sustainable products and processes that have a clear relevance from the point of view of energy efficiency. Green process innovation in production and industrial processes can lead to betterous system efficiency and energy consumption. For instance, employing smart systems in power consumption control is another renewable source in a variety of industry processes, each stage in each of them is reduced for purposes of minimizing power usage. This is particularly useful for the metal production, cement and petrochemical industries, where energy intensity is relatively high so that costs decreases and productivity increase accordingly (Balsalobre-Lorente et al., 2018; Hosseini & Mousavi, 2022).

Another effect of green innovation on energy efficiency is the use of economic models that rely on the efficiency of natural resources. These are models in which green technologies are used to enhance the use of natural resources and alleviate the environmental.

The relationship between green innovation and environmental and management policies is another significant aspect of green innovation's effect on energy efficiency. These advances are especially important in the mitigation of pollutants and greenhouse gases. The supportive policies for the diffusion and creation of green innovations and improved adoption offer the most potential to promote industries to adopt energy-saving technology and decrease energy use. In the less developed coun- tries that have weaker economic capabilities, the green technology could efficiently raise energy efficiency and reduce the long-term energy cost (Zhao & Shah, 2024; Bahaeddi- ni et al., 2024).

Energy efficiency can also be significantly impacted by the introduction of green transport and urban systems. Electric vehicles, green public transportation, and smart systems for traffic and transportation management are potential means for achieving energy saving in the transportation sector. Such optimisations, which lead to lower fossil fuel use and enhanced system efficiency, can make substantial contribution to national energy efficiency (Goodarzi Farahani et al., 2020; Al-Kasasbeh et al., 2023).

Studies have shown that green innovation can promote increases in energy system efficiency in developing economies. These nations, usually resource-poor and infrastructure-challenged, can earn much more environmental and economic benefits through the application of green technologies in enhancing energy efficiency. These developments, especially in SMEs, which are frequently less and less exposed to advanced technological developments, can be transformed towards enabling more optimised energy consumption (Jafari Parvizkhanlou et al., 2021; Sadeghi et al., 2015).

2.4. The Impact of Green Innovation on Economic Growth

Green innovation is a series of innovations that contribute directly or indirectly to environmental protection and natural resources efficiency. These innovations, including new technologies and processes or sustainable products and energy production and consumption techniques, have significant impacts on economic development. In the present era when we are coping with environmental crises and climate change has already been accepted as one of the biggest challenges, green innovations might act as a locomotive towards sustainable economic development. These new developments promote economic growth by lowering the costs of energy and natural resources, and by growing productivity and innovative sectors of the economy.

Productivity of natural resource input green innovation plays a role in raising natural resource productivity and cutting production costs. Green technologies such as energy, transportation, and production are being used to minimize the use of natural resources and minimize waste. The use of green methodologies in different industrial sectors can lead to lower energy dependency on fossil fuels as well via cost production reduction. The lower the cost the more competitive our industry on the global stage the more gross domestic product . Moreover, at the lower cost, firms can generate and present superior quality and lower priced products and services resultantly to sustain economic growth in an economy (Balsalobre-Lorente et al., 2018; Hosseini & Mousavi, 2022).

Green innovation can also draw new investments and improve industrial competitiveness. Green innovation and clean technology policies, for renewable energy, greener industries and sustainable transport, have mobilized new investments, both from companies and from governments, in many countries. Such investments could result in new technologies, increased reliance on green infastructure, and job growth in renewable energy and green technology industries. So, the development in innovative sectors will bring forth economic expansion and job mitigation at macro level (Zhao & Shah, 2024).

Encouraging innovation in renewable energy areas, such as growth in developing nations, promotes economic development. They are usually economically challenged and resources constrained and the introduction and development of emerging technologies in renewable energy can offer new sources of revenue and employment. Moreover, such solutions support the lowering of such countries' dependency on imported energy and the related costs. Hence, the progress and expansion of these technologies can help sustainable economic growth in developing countries (El-Katiri, 2020; Shayesteh and Miri, 2023).

Growing transportation and green sectors is another channel through which green innovation influences economic growth. Application of electric vehicles, construction of ecological transportation systems and perfection of traffic management and facilities have the potential to save fossil fuel and decrease energy consumption of transportation. This change of state can result in decreases in operational costs and enhancements in the urban quality of life, which in turn would contribute to the macroeconomic growth (Goodarzi Farahani et al., 2020; Al-Kasasbeh et al., 2023).

Green innovation, as the vital driver of sustainable development, can lessen negative environmental and social impacts. Pollution reduction, improvement of environmental quality and improved quality of life in communities can be realized by the development and application of green innovations by countries. This action not only helps in saving the environment but contributes directly and indirectly to economic growth in different sectors. Especially for developing countries, green innovation can act as a driving force for sustainable economic growth (Zhao and Shah, 2024; Bahaeddini et al., 2024).

Another dimension to the contribution that green innovation can make to economic growth are the jobs it could create and the entrepreneurship it could bring about. Use of Green Technology stimulates the job creation to bring the latest vision and science to the use of renewable energy, management of natural resources, and electric vehicle industries and encourage new entrepreneurships. Particularly in human resource-rich countries, such innovations can result in sustainable job creation and lower unemployment and promote economic growth and sustainable development (Sadeghi et al., 2015; Al-Ghussain et al., 2020).

2.5. Literature Review

As for the domestic sources, Patimar and Zamani (2024) investigated the influence of technology gaps and green innovations on international trade between developing and developed countries, arguing that green technological innovations is likely to increase export competitiveness and economic sustainability. Faraj and Tarpagada, 2013, also showed that strict environmental laws could enhance green productivity in Iranian regions. PhotoBavab et al. Ghorbani et al. (2024) studied the effect of green technology on the sustainability performance of knowledge-based companies, indicating that smart logistics and green governance enhance the relationship between green innovation and sustainability performance. Karimi and Rezaei (2023) investigated the effect of digital infrastructure on industrial energy efficiency in Iran, whereby they posit that digital technologies foster improvement in energy efficiency. Shayesteh and Miri (2023) indicated that DIGI facilitates economic growth in some Middle eastern countries by its reducing the EYEN. Hosseini, M., & Mousavi, M. (2022) showed that being supportive of the green innovations results in the increased sustainable economic growth and better sustainability indicators in Iran.

From the international sphere, Zhao and Shah (2024) studied the interrelationship between green energy, economic growth, and innovations for sustainable development in OECD countries, finding that investment in renewable energies and technologies will yield good results in economic development and GHG reductions. Almasria et al. (2024) examined the Middle East and discussed that by lowering oil price volatility, oil-exporting countries can improve economic growth and suggested that the policymakers should take measures to reduce the impact of oil price volatility. Li et al. (2024) have also shown that renewable energy and technology innovation in the OECD countries and its emerging economies are engines of growth and energy efficiency. Albaker et al. (2023) investigated the effects of renewable energy and green innovation on the carbon emissions in the MENA countries, and they argued that the renewable energy and green innovation might help reduce the level of GHGs. Saleem and Khan (2023) studied the effects of government effectiveness and innovation on sustainable economic growth and CO2 emissions reduction in the Middle East and found strong connections between these variables. Al-Kasasbeh et al. (2023) revealed that renewable energy use encourages to the economic growth in Jordan. Zaki and Mansour (2022) found that the development of digital technologies in the ICT field has positive effects on CO_2 reduction and green economic growth in the Middle East. Bekhet et al. (2022) addressed the role of supportive policies for clean energies and improved government performance in achieving carbon neutrality goals in the Middle East region.

Based on the literature review, although numerous studies at the international level have examined the impact of digital infrastructure or green innovations individually on economic growth or energy efficiency (such as the study by Li et al., 2024), and some domestic research has also addressed the role of information technology, energy investment, and environmental innovation in Iran's economy or developing countries (such as Shayesteh & Miri, 2023; Hosseini & Mousavi, 2022), no comprehensive study has yet been conducted that simultaneously examines the combined effect of digital infrastructure development and green innovation on the two key variables of energy efficiency and economic growth within the regional context of selected Middle Eastern countries. The innovation of the present research lies in combining two areas of digital and environmental policymaking to simultaneously analyze the direct and indirect effects of these two components on economic growth and energy efficiency. By utilizing dynamic panel econometric methods, it provides a novel framework for synergistic policymaking between digital transformation and sustainable development in the Middle East region.

3. Research Methodology

To examine the impact of digital infrastructure development and green innovation on energy efficiency and economic growth in selected Middle Eastern countries, following Li et al. (2024) and Zhao and Shah (2024), the estimation of the following simultaneous equation system is employed. This model enables the simultaneous examination of mutual relationships and direct and indirect effects of key research variables, leading to a more comprehensive understanding of the dynamics between digital, environmental, and economic variables:

$$EP_{it} = c_0 + c_1 DIG_{it} + c_2 DIG_{it} + c_3 GI_{it} + c_4 IND_{it} + c_5 FDI_{it} + c_6 URB_{it} + e_{it}$$

$$GDP_{it} = c_0 + c_1 EP_{it} + c_2 DIG_{it} + c_3 DIG_{it} + c_4 GI_{it} + c_5 EDU_{it} + c_6 INF_{it} + c_7 GOV_{it} + e_{it}$$

Where:

Energy Productivity (EP): The ratio of gross domestic product (in constant US dollars) to total energy consumption (in crude oil equivalent tons). Data for this variable is extracted from the World Bank database (WDI).

Economic Growth (GDP): The annual growth rate of real gross domestic product based on constant US dollars. Data for this variable is extracted from the World Bank database.

Digital Infrastructure Development (DIG): A composite of indicators including number of internet users per 100 people, number of mobile phone subscriptions, international internet bandwidth, and access to digital technologies. Data for this variable is extracted from the International Telecommunication Union database. Principal Component Analysis (PCA) is used to combine these indicators:

Table 1. Principal Component Analysis (PCA) Results for Digital Infrastructure Development

Component	Internet Users	Mobile Subscriptions	International Bandwidth	Digital Technology Access	Explained Variance Ratio
Component 1	-0.505	0.399	0.506	-0.574	30.13%

Component 2	0.530	0.762	0.245	0.280	24.36%
Component 3	0.385	-0.510	0.770	-0.015	23.28%
Component 4	0.562	-0.010	-0.303	-0.769	22.23%

Source: Research findings

The results of the principal component analysis indicate that the first component, with high factor loadings on international bandwidth (0.506) and mobile subscriptions (0.399) while simultaneously having negative loadings for internet users and digital technology access, explains approximately 30% of the total variance. This component is selected as the main composite representative of digital infrastructure development and is used in the final model, as it has the largest share in explaining data variance and indicates strong correlation between different dimensions of digital technology.

Green Innovation (GI): Research and development expenditure on environmental technologies as a ratio of gross domestic product. Data for this variable is extracted from the Organization for Economic Cooperation and Development (OECD) and World Intellectual Property Organization (WIPO) databases.

Industrial Share of Gross Domestic Product (IND): The ratio of industrial sector value added (including mining, manufacturing, water, and electricity) to total gross domestic product. Data for this variable is extracted from the World Bank database (WDI).

Foreign Direct Investment (FDI): Net inflow of foreign direct investment as a percentage of gross domestic product. Data for this variable is extracted from the United Nations Conference on Trade and Development (UNCTAD) and World Bank databases.

Urbanization Rate (URB): Percentage of population residing in urban areas relative to the total country population. Data for this variable is extracted from the World Bank database (WDI).

Education Level (EDU): Average years of schooling for individuals aged 25 and above or gross enrollment rate in higher education. Data for this variable is extracted from the United Nations Development Programme database (UNDP Human Development Reports).

Physical Infrastructure Development (INF): A composite index including access to roads, electricity, clean water, and transportation services, or percentage of population with access to basic infrastructure services. Principal Component Analysis (PCA) is used to combine these indicators. Data for this variable is extracted from the World Bank and African Development Bank databases.

Table 2. Principal Component Analysis (PCA) Results for Physical Infrastructure Development

Component	**Road Access**	**Electricity Access**	**Clean Water Access**	**Public Transportation Services**	**Explained Variance Ratio**
Component 1	0.580	0.511	0.482	0.399	34.72%
Component 2	0.050	-0.154	0.614	-0.769	27.41%
Component 3	0.762	-0.313	-0.334	0.456	22.55%
Component 4	-0.274	0.781	-0.528	-0.145	15.32%

Source: Research findings

Based on the above table, the first component with high factor loadings on all four main indicators particularly road access (0.580) and electricity access (0.511) explain the highest variance (34.72%) and is selected as the main representative of physical infrastructure in the final model. This component effectively demonstrates the structural coherence between different infrastructure service indicators and constitutes a strong component for measuring physical infrastructure development in the countries studied.

Governance Quality (GOV): Average of governance indicators including government effectiveness, control of corruption, and rule of law. Data for this variable is extracted from the World Bank database (Worldwide Governance Indicators – WGI).

The use of a simultaneous equation system model in this research is fully justifiable based on theoretical and empirical foundations. According to endogenous growth theory, innovation and digital technologies are simultaneously both functions of economic growth and drivers of it. Furthermore, studies such as Li et al. (2024), Zhao and Shah (2024), and Bahaeddini et al. (2024) have also pointed to the existence of bidirectional relationships between green innovation, digital infrastructure, and economic growth. On the other hand, energy efficiency is not only influenced by innovation and digitalization but can also affect economic growth through consumption optimization and production cost reduction (Shayesteh & Miri, 2023; Hosseini & Mousavi, 2022). Therefore, the relationships between variables are mutual and simultaneous, and the use of the simultaneous equation system method is an appropriate and necessary approach to prevent bias in estimates and provide a more realistic reflection of intra-system relationships.

The statistical population of the research includes Middle Eastern countries, and considering data accessibility, 18 countries—Iran, Turkey, Saudi Arabia, UAE, Qatar, Kuwait, Oman, Bahrain, Jordan, Lebanon, Iraq, Syria, Palestine, Yemen, Egypt, Israel, Cyprus, and Pakistan—have been selected as the final sample. The time period under study is set from 2010 to 2023, which provides the opportunity to analyze and examine the effects of digital transformation and environmental policies. Finally, it should be noted that data analysis and simultaneous equation estimation will be conducted using EViews software version 13. This software provides the capability to accurately execute panel econometric models, simultaneous analyses, and diagnostic tests.

4. Data Analysis

4.1. Pesaran Cross-Sectional Dependence Test

In studies conducted with panel data involving multiple countries or geographical regions, examining the assumption of cross-sectional independence among cross-sectional units (countries) is a prerequisite for many econometric tests and estimations. If there exists structural correlation or common dependence on global, regional, or institutional shocks among countries, the assumption of cross-sectional independence is violated, and the results of analyses that ignore this may be biased and inefficient. Therefore, the Pesaran cross-sectional dependence test is used as one of the valid tests for identifying the existence of this dependence in panel data:

Table 3: Results of Pesaran Cross-Sectional Dependence Test for Simultaneous Equation System Variables

Variables	**Pesaran Test Statistic Value**	**P-value**
Economic Growth (GDP)	4.823	0.0000
Digital Infrastructure (DIG)	5.276	0.0000
Green Innovation (GI)	3.998	0.0001
Industrial Share (IND)	4.516	0.0000
Foreign Direct Investment (FDI)	3.721	0.0002
Urbanization Rate (URB)	2.864	0.0042
Education Level (EDU)	4.113	0.0000
Physical Infrastructure (INF)	3.554	0.0004
Governance Quality (GOV)	4.302	0.0000
Energy Productivity (EP)	3.786	0.0002

Source: Research findings

The findings of the above table indicate that all variables under study exhibit significant cross-sectional dependence among selected Middle Eastern countries at the 99% confidence level. In other words, the probability value (p-value) in all cases is significantly less than 0.01, indicating rejection of the null hypothesis of no cross-sectional dependence. This dependence may result from mutual influence of economic policies, technological developments, convergence in environmental policies, or occurrence of international shocks at the regional level. Therefore, in subsequent analyses, methods that account for this structural characteristic should be employed, such as dynamic panel models, panel data with cross-sectional dependence, or simultaneous equation system methods, which is the focus of this research.

4.2. Unit Root Test

When cross-sectional dependence in panel data is confirmed, the use of conventional panel unit root methods such as Levin and Lin (LL), Im, Pesaran and Shin (IPS) tests will increase the probability of spurious unit root results. To address this problem, several tests such as the Pesaran unit root test (2007) and the Hadri and Rao unit root test (2008) exist for examining stationarity. The advantage of the Hadri and Rao (2008) stationarity test over the Pesaran unit root test is that it simultaneously considers structural breaks and cross-sectional dependence. Therefore, this study employs the Hadri and Rao (2008) unit root test:

Table 4: Results of Hadri and Rao (2008) Unit Root Test for Simultaneous Equation System Variables

Variables	**Hadri and Rao Statistic Value**	**P-value**	**Test Result**
Economic Growth (GDP)	6.741	0.0000	Stationary
Digital Infrastructure (DIG)	5.916	0.0000	Stationary
Green Innovation (GI)	4.382	0.0001	Stationary

Industrial Share (IND)	6.213	0.0000	Stationary
Foreign Direct Investment (FDI)	3.898	0.0002	Stationary
Urbanization Rate (URB)	5.002	0.0000	Stationary
Education Level (EDU)	4.776	0.0000	Stationary
Physical Infrastructure (INF)	5.884	0.0000	Stationary
Governance Quality (GOV)	6.045	0.0000	Stationary
Energy Productivity (EP)	5.392	0.0000	Stationary

Source: Research findings

Based on the results of the above table, the Hadri and Rao test statistic for all research variables is statistically significant, and their probability values are much less than the 0.05 level. Therefore, the null hypothesis of this test regarding the existence of a unit root is rejected, and the variables are stationary at level. This result indicates that the simultaneous equation system model can be estimated without concern about time series instability, and there is no need for differencing or cointegration testing in the first stage.

4.3. Equation Identification Test

In simultaneous equation systems, before model estimation, the equation identifiability must be determined. For equation identification, order condition and rank condition are used:

Table 5: Identification Test Results for Simultaneous Equation System Variables

Equation Number	Dependent Variable	Total Variables in	Variables Included	Excluded Variable	Identification Condition (K - K' ≥	Test Result

		System (K)	in Equation (K')	s (K - K')	Number of Endogenous Variables in System – 1)	
First	EP	10	6	4	First equation	Identifiable
Second	GDP	10	7	3	Second equation	Identifiable

Source: Research findings

Based on the results of the above table, both model equations satisfy the minimum identification conditions based on the order condition, such that the number of variables excluded from each equation is greater than or equal to one (i.e., number of equations - 1). Therefore, the structural coefficients of these equations are estimable.

4.4. Simultaneous Equation System Estimation Results

Given the theoretical model structure of the research and the existence of mutual relationships among key variables such as energy productivity and economic growth, the simultaneous equation system method was used to estimate coefficients. This method enables accurate estimation of mutual and simultaneous effects of endogenous and exogenous variables. To address the bias problem arising from equation collinearity, the two-stage least squares (2SLS) method was employed to estimate structural coefficients. The model estimation results are presented in Table 6.

Table 6: Simultaneous Equation System Estimation Results

Variable	**Coefficient**	**Standard Error**	**t-statistic**	**P-value**
First Equation: Energy Productivity				
DIG	0.218	0.055	3.91	0.000
GI	0.136	0.047	2.88	0.004
IND	-0.092	0.044	-2.11	0.036
FDI	0.057	0.032	1.78	0.076
URB	0.123	0.042	2.95	0.003
c	0.447	0.073	6.12	0.000
Second Equation: Economic Growth				
EP	0.198	0.054	3.67	0.000
DIG	0.157	0.054	2.92	0.004
GI	0.115	0.048	2.41	0.016
EDU	0.176	0.056	3.14	0.002
INF	0.103	0.050	2.06	0.041
GOV	0.089	0.047	1.91	0.059
c	0.532	0.093	5.71	0.000

Source: Research findings

Analysis of the first equation results (Energy Productivity) indicates that:

The estimation results of the first equation demonstrate that digital infrastructure development (DIG) has a positive and significant effect on energy productivity, with a coefficient of 0.218 and a probability value of 0.000. This result indicates that the expansion of digital technologies plays an effective role in enhancing energy productivity through energy consumption optimization and demand management improvement. Another factor is green innovation (GI), which has positive statutory significance on energy productivity with a coefficient of 0.136 (P = 0.004). This result indicates that investment in clean and new technologies may encourage the reduction in energy intensity and enable to enhance productivity. On the other hand, industrial share of gross domestic product (IND) with a coefficient of -0.092 and probability value of 0.036 has also had negative and significant effect on energy productivity. It means enhancing the proportion of industrial high energy-intensive industry to reduce energy efficiency at the national level. There is also the FDI (coefficient 0.057, p-value = 0.076) significant at 90% confidence level (positive role in energy productivity). Finally, urbanization rate (URB) with a coefficient of 0.123 and a probability value of 0.003, indicates that the progress of urban development may enhance the energy productivity due to modern infrastructure and possible optimal consumption.

From the second equation we have: (Economic Growth) 0 > M > - C > D.

The outcomes of the coefficients of the 2nd equation indicate that energy productivity (EP) effects economic growth positively and significantly with a coefficient (0.198) and probability values of (0.000). This result consistently illustrates the significance of energy consumption minimization in production costs minimizing and economic productivity maximization process. Digital infrastructure development (DIG) also exerts a positive and significant effect on economic growth at 0.157 with probability value of 0.004, highlighting the potential of ICTs in increasing productivity, employment and innovation in the economy. Green innovation (GI) has a positive and significant effect with a coefficient 0.115 and p-value 0.016, which confirms the impact of environmental innovations toward sustainable growth opportunities. for education level (EDU) is significant at 0.002, indicating the significance of human capital in influencing economic growth. Physical infrastructure development (INF) is given coefficient value of 0.103 and probability value of 0.041, and quality of governance (GOV) which is given coefficient value of 0.089 and probability value of 0.059 have a positive and quite significant influence on economic growth. These findings highlight the need for better infrastructure, as well as a reinforcement of the institutional environment to achieve sustainable economic development.

4.5. Inspection of classical linear regression assumptions

To interpret results from the model of simultaneous equations estimations, the classical econometric assumptions should be checked. These assumptions consist of the normality of residuals, homoscedasticity, no-autocorrelation, and no-multicollinearity among independent variables. Any departure of these assumptions will result in the biased estimates and misleading conclusions. Results of applicable tests are reported in this section and discussed:

Table 7. Results of Classical Assumptions Tests

Test Type	**Test Statistic**	**P-value**	**Test Result**
Jarque-Bera Normality Test	1.842	0.398	Not rejected (residuals are normal)
White Heteroscedasticity Test	5.123	0.276	Not rejected (variance is homogeneous)
Durbin-Watson Autocorrelation Test	1.987	—	Around 2 (no autocorrelation)
Multicollinearity Test (VIF)	Maximum VIF: 2.21	—	No multicollinearity exists

Source: Research findings

According to the classical hypothesis's tests of the assumptions, it may be concluded that the estimated model has the necessary statistical validity. The Jarque-Bera normality test show that model residuals are normally distributed so the normality assumption has been achieved. The White test also indicated that no heteroscedasticity issue exists in the model. It is also around 2, hence we can establish that there is no serial autocorrelation among error terms as his value suggests there is no significant serial autocorrelation. Finally, note that the variance inflation factor (VIF) values for all variables were below 5, making multicollinearity not a problem among independent variables. 26 Overall, the configuration of the classical model assumptions has been achieved, and one might trust the estimates.

5. Conclusion and Recommendations

This study was conducted to examine the impact of digital infrastructure development and green innovation on energy productivity and economic growth in selected Middle Eastern countries. The statistical population comprised 18 regional countries over the period 2010-2023, with data collected in panel format. To analyze structural relationships among variables, a simultaneous equation system model was employed, which enables the examination of mutual and simultaneous effects among key variables.

The results of this research demonstrate that digital infrastructure development has a positive and significant effect on energy productivity. The expansion of digital infrastructure plays an effective role in enhancing energy productivity through energy consumption optimization and demand management improvement. These findings align with existing theories regarding the relationship between digitalization and energy productivity. Particularly, digital technologies such as the Internet of Things and artificial intelligence can intelligently manage energy consumption and contribute to reducing energy waste. In fact, leveraging digital technologies enables organizations to manage energy based on actual demand in an optimal manner. Previous studies such as Karimi and Rezaei (2023), Zhao and Shah (2024), and Zaki and Mansour (2022) have also demonstrated that digitalization can increase energy productivity by improving energy efficiency across various industries. These findings indicate that investment in digital infrastructure serves as one of the key strategies for achieving energy sustainability goals in developing and transitional countries. According to this evidence, various nascent digital infrastructures, such as high-speed internet, 5G technology and the Internet of Things, could be developed by Middle Eastern countries to improve energy productivity by promoting industry smartification and energy consumption optimization strategies.

Further findings demonstrate that green innovation exerts a positive significant effect on energy productivity. This is to say, investments in clean and smart technologies can result in stamped out energy intensity and increased energy productivity. The theories of green innovation are based on the argument that clean technologies are not only necessary for achieving improvement in environmental performance, but also for enhancing energy productivity by way of maximising resource efficiency. Thus green technologies can lead to a less expensive energy and resource efficient operation. It has also been found that countries that are adopting green innovations have achieved better in enhancing the environmental quality than in enhancing energy productivity (Zhao & Shah, 2024). For instance, energy applications can leverage new and breakthrough technologies to minimize energy utilization and decrease its cost. Thus, there is a need for governments to promote green innovations and to offer economic and legal incentives to create clean technologies. These are steps which can help to increase energy productivity and reach environmental goals.

Secondly, the model estimates reveal that the development of digital infrastructure exerts a positive, and significant effect on economic growth. The spread of digital infrastructure, especially Internet technology and communication technology, increases efficiency in all sectors and promotes the development of new jobs and innovations in companies. Endogenous growth theory suggests that digital infrastructure can increase economic growth in a country by boosting human capital and communication. This discovery is consistent with the results of Bahaeddini et al. (2024) and Li et al. (2024) indicating that countries with more advanced digital infrastructure tend to perform better in economic growth. Moreover, ICT infrastructure can be a catalyst for economic growth by improving innovation, efficiency and employment intensity. It is therefore recommended that countries in the region rapidly develop digital infrastructure, which in the process can help in enhancing the different economic sectors; as such, it is appropriate for the regional countries to invest in information and communication technology infrastructure and digitalize different economic sectors.

Lastly, results confirmed that green innovation positively and significantly affects economic growth. This is consistent with environmental economic theories which argue that green innovations can induce the birth of new industries and increase output and economic growth. Thus, investment in green technologies not only brings about a better environment but also ensures long-term economic prosperity. This result is in line with the findings of the studies by Patimar and Zamani (2024) and Zhao and Shah (2024). These studies have found that nations have managed to simultaneously grow their economy while reversing the environmental trend in countries with advanced green innovation. Especially in the developing world, green innovations can help to generate new jobs and reduce dependence on fossilized energy providers. In the end, it is suggested that countries should promote green ingenuities and stand by the environmental works. It resulted in sustainable economic growth to implement tax breaks for firms and industries that use green technologies.

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