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Reducing Carbon Footprint through E-government: Towards a Synergy with Renewable Energy and Governance in MENA Countries

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ABSTRACT

This study examines how digital government development can reduce CO_2 emissions while considering the effects of interaction with renewable energy use and governance quality. Using the Generalised Method of Moments (GMM) in a dynamic panel applied to 13 countries in the MENA region, the results of Westerlund's cointegration tests reveal no stable long-term relationship between CO_2 emissions and the explanatory variables, justifying the adoption of a dynamic difference approach. E-government, as measured by the EGDI index, has an overall positive and significant impact on CO_2 emissions, suggesting that digitalisation, in its current state, is responsible for higher energy usage. However, when e-government is incorporated into a strong institutional framework and a green energy strategy, interactions with environmental governance and the deployment of renewable energies overcome this effect. GDP per capita and financial development also contribute to the reduction of CO_2. These findings highlight the key role of digital government, which should not be seen as simply technical support activity but rather as a strategic element in the process of pollution control and environmental governance in MENA countries.

Keywords: Digital Government, Carbon Dioxide Emissions, MENA, Green Energy, Climate Governance.
JEL Classifications: H83, O38, Q42, Q58

1. INTRODUCTION

Since combating climate change has emerged as a major planetary concern, governments have taken creative measures to mitigate greenhouse gas emissions, including carbon dioxide (CO_2). Ecological development is one of the most pressing issues facing state and non-governmental organisations in developing nations, along with socioeconomic justice and democracy. In developing countries, a few studies reveal a negative link between environmental contamination and economic progress, despite evidence of environmental degradation linked to international trade and economic development. The technology's socio-environmental complexity makes it impossible to categorise as either impact-positive or -negative. Therefore, there may be ramifications for both environmental preservation and economic prosperity as e-government grows (Khalid et al., 2021; Veidemane, 2022; Orhan and Guajardo, 2022). By rethinking the way public services are delivered, countries can not only meet today's environmental demands, but also prepare a sustainable future for generations to come (Alvarez-Herranz et al., 2017; Chen and Lei. 2018; Mirza et al., 2020; Yong et al., 2023).

The development of electronic government institutions plays a pivotal role in enhancing both environmental sustainability and governance efficiency. By leveraging digital government tools, which utilise new technologies to streamline government

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operations and improve public access to information, these institutions can significantly reduce carbon dioxide emissions. In this regard, implementing online services and biometric voting not only facilitates accelerated government processes, but it also reduces the need for physical interactions and transit, ultimately leading to fewer greenhouse gases (Zhu et al., 2022; Wang et al., 2024; Li and Lu, 2024; Feng et al., 2024).

Additionally, by providing citizens with timely access to information about their rights and governmental measures, electronic government fosters a more informed and engaged public, further enhancing the efficiency and accountability of governance. Thus, the integration of digital technologies in government functions serves as a crucial mechanism for achieving both environmental and governance objectives (Bannister and Connolly, 2012).

Communications and information technologies (TIC) play an important part in e-government institutions by enabling the electronic transmission, processing, and implementation of political decisions inside public sectors. Achieving the climate targets set by the Paris Agreement is still a challenge for many nations as carbon dioxide releases expand at alarming rates. These changes have social repercussions on governance and, in particular, on the general structure and organization of society. Governments often find that their competences and functions need to be redefined. Some tasks can be performed more efficiently by others, and it is often necessary to reorganize existing activities and eliminate certain administrative tasks. Furthermore, there is a dynamic disequilibrium in the social context of government actions. A market economy requires government to adapt to the changing standards, needs, and demands of society. One of the most important factors in deciding the role and function of government is the growing effect of environmental preservation and resource concerns (Li et al., 2025; Zioło et al., 2022).

In the Eastern Mediterranean and North Africa (MENA) region, pollution represents the primary environmental risk (Dhaoui. 2021). Particularly in the Gulf nations, urban air pollution poses significant threats to public health and welfare. The principal sources of air pollutants include the densely populated transportation sector, power generation, industrial activities, desalination plants, and flaring operations. Exposure to this air pollution has direct effects on public health, bringing respiratory conditions like asthma and bronchitis. Furthermore, about 70% of the water in the MENA region—one of the most affected by hydric stress—is used for agriculture and food production, increasing reliance on nonrenewable energy sources. The toxic contamination of surface waters, aquifers, rivers, and lakes endangers not only ecosystems but also economic progress. In countries like Iran, Iraq, Syria, Lebanon, Jordan, and Egypt, the development of the petroleum and gas industry has also been negatively impacted by water scarcity (Heger et al., 2022).

The effectiveness of governance and e-government's capacity to reduce CO_2 emissions for MENA nations have not, as far as the authors know, been the subject of previous research. According to recent studies, comprehensive approaches are required to comprehend how effective governance affects environmental quality globally. Furthermore, the relationship between pollution and successful governance exhibits complex behaviour and differs based on the size of the country's economy. As a consequence, it becomes essential to investigate the influence of e-government institutions on environmental issues. Further, the modern age of e-government seems to be stimulating proposals aimed at lowering CO_2 emissions.

This study aims to investigate the effect e-government on CO_2 emissions in 13 MENA countries from 2010 to 2021. It considers economic factors (GDP per capita), institutional factors (quality of governance), as well as financial and energy factors (renewable energy sources).

The structure of this paper is as follows. An overview of the literature is presented in Section 2. The method and model are explained in Section 3. The empirical findings are discussed in Section 4, and conclusions and suggestions are included in Section 5.

2. LITERATURE REVIEW

Recent research has examined the effect of e-governance, a novel kind of economic development, on CO_2 emissions (Wang et al., 2022). Digital governance aids the authorities in identifying energy market patterns and adjustments to prices by regulating the energy supply through costing, cross-subsidies, and taxes (Höpner, 2006). Additionally, technology facilitates government coordination of energy supply and consumption. In fact, market processes and administrative interventions can be adjusted to better regulate the overall amount of energy consumed and, in turn, the overall amount of carbon emissions through the use of digital operations (Zhang and Deng, 2022).

The World Bank (2001, p. 6) states that digital government is characterised by "government-owned or operated information and communications technology (ICT) systems that transform relationships with citizens, the private sector, and other government agencies in ways that promote citizen empowerment, improve service delivery, enhance accountability, increase transparency, or improve government effectiveness"

This transition is critical because it focuses on effectively providing services while improving administration via better accessibility for citizens, businesses, and other public bodies (Khalid and Sarker, 2019). Furthermore, e-government projects have the potential to improve the government's participation in decreasing carbon emissions and supporting environmental efforts by combining and enhancing the existing public reporting system.

E-government has advanced significantly from the early days of online tax filing, voter registration, driver's licence renewal, electronic government grant applications, and the advent of technology-assisted electronic voting systems.

While the focus continues on improving service delivery via these platforms, there is a strong emphasis on finding solutions that can demonstrably reduce carbon emissions. This move demonstrates how e-government services are currently provided and clear evidence of their impacts on CO_2 emissions (Von Haldenwang, 2004; Grigalashvili, 2022).

Digital government has both direct and indirect implications on carbon emission levels. The direct effects primarily stem from the reduction in paper consumption and paper-based logistics. In theory, the shift to virtual payments should reduce greenhouse gases associated with the production and distribution of paper.

However, e-government requires extensive use of technologies and servers. These infrastructures consume electrical energy, which, given the typical energy mix, generates greenhouse gases. Additionally, the development of electronic traffic data exchanged between clients and servers to meet service requests spontaneously increases energy consumption.

Thus, certain applications of e-government services and policies, whether implemented by the public or private sector, lead to tangible reductions in CO_2 emission levels. It is essential to understand these processes well to determine whether governments can leverage e-government initiatives. Although e-government's direct effects on greenhouse gas emissions are a crucial aspect of the overall effect, its indirect impacts need to be taken seriously because they are equally important regardless of how direct emissions from ICT infrastructure are taken into account.

The indirect impact analysis can be broken down into various components, each of which has the potential to have either good or negative indirect effects. Following the setting in place of an electronic government structure, there may be an increase in direct emissions, but this may be more than offset by the reductions in pollution from additional sources, leading to a net reduction in the release of CO_2.

An analysis of the global emission database for atmospheric research, which covers twenty-eight countries from 2010 to 2020, is used to examine the effect of electronic governance on carbon dioxide emissions. Three distinct stages are identified by a segmented regression analysis: an initial period of emissions growth from 2010 to 2013, followed by a period of decline until 2017, then a period from 2017 to 2020 during which greenhouse gases remain relatively stable. The data indicates that the rate of emission reduction varies depending on the level of development of electronic governance throughout the decline phase: The industrialised nations are experiencing larger declines than their developing counterparts, which is consistent with the framework of the previously described electronic and environmental governance index (You et al., 2024; Li et al., 2025; Dehdar et al., 2022).

Baroi and Alam (2021) argue that e-governance generates two levels of interaction: internal and external. Internally, it facilitates the optimisation of internal issues related to government work. As for the external level, it proposes electronic communication systems whose aim is fluid interaction, connecting government and citizens.

Innovation and good governance, according to Hooda and Singla (2020) and Umbach and Tkalec (2022), include things like enabling the user process through ICT, having an effective and transparent data system in the administration process, and being efficient and able to predict corrupt actions.

Mahmood et al. (2023), using spatial econometrics methodologies via the Environmental Kuznets Curve (EKC) for 17 MENA economies, intended to study the impacts of economic success, financial expansion, and urbanisation on the generation of carbon. Their results suggest that the effect of urbanisation and patents on emissions is insignificant.

A study by Krishnan and Teo (2012) looked at 105 nations from different areas to investigate the connections between e-government, corruption, economic growth, and pollution. The SEM model's econometric findings demonstrate a substantial and positive correlation between e-government and economic development via the reduction of corruption.

To examine the implications of e-government development on the sustainability of tiny island nations (SIDS), Lee (2017) has done a quantitative analysis. The findings reveal that the rise of e-government has both immediate and subsequent implications on ecological sustainability, resulting from increased government effectiveness.

Hassan (2017) examined the interplay between environmental damage, economic prosperity, corruption prevention, and e-government in Asia. His findings indicate that education and effective law enforcement minimize pollution. Additionally, the implementation of Pigovian fees on polluting enterprises and adherence to recommended fertiliser levels are crucial for significantly reducing pollution.

Wang et al. (2023) investigated how digital governance affected the performance of carbon emissions. The results suggest that digital governance optimises environmental performance across industrial structure and renewable energy consumption. This conclusion is based on panel data from 40 Chinese cities collected between 2011 and 2019.

According to the majority of studies that have examined the role of various factors in explaining emissions, it is accepted that economic growth, urbanisation, trade openness, natural resource rents, energy intensity, government environmental regulations and green credit policies are responsible for emissions (Ang, 1999; Sun, 2006; Zhang et al., 2014; Castro and Lopes, 2022; Lin and Zhang, 2023; Jammali et al., 2025).

3. MODEL AND METHODOLOGY

3.1. Variables and Sample

To analyze the effect of e-government on CO_2 emissions, we mobilize a series of relevant variables covering environmental, economic, financial, energy, and institutional dimensions. The dependent variable is carbon dioxide emissions per capita, measured in metric tons and excluding the land use, land-use change, and forestry (LULUCF) sector, sourced from the World Bank's World Development Indicators (WDI) database. The primary explanatory variable is the e-government development index (EGDI), derived from the United Nations e-Government Survey, which assesses the level of digitalization of public services. Additional explanatory variables are introduced to control for economic effects (GDP in constant 2015 dollars), financial effects (domestic credit to the private sector as a percentage of GDP), energy effects (the share of renewable energy consumption), and institutional effects (the government effectiveness index).

EGDI × REC and EGDI × GE are two interaction variables that are taken into consideration in order to examine the combined effect of e-government with renewable energy consumption and government efficiency. These interactions allow possible to investigate whether institutional efficacy or energy performance enhance or mitigate the impact of e-government on CO_2 emissions. In order to capture both temporal dynamics and structural variety within the region, the research is carried out on a panel of 14 MENA nations (including Algeria, Egypt, Iran, Morocco, and Tunisia, among others) throughout the period from 2003 to 2023. Table 1 lists the primary variables that were kept along with their sources.

3.2. Model

Estimated Model Specification: The estimated baseline model can be expressed as follows:

The aim of the empirical model is to assess how e-government affects CO_2 emissions, simultaneously accounting for the diversity of the panel's countries. The baseline specification relies on a dynamic model in which CO_2 emissions per capita depend on their lagged values (to capture the persistence of the phenomenon) as well as the previously mentioned explanatory variables. The model also includes interaction effects to identify potential synergies between digital development and other dimensions of sustainable development. To achieve this, the econometric approach employed is the system GMM method, which is suitable for correcting potential endogeneity issues and biases related to fixed effects and the dynamics of the panel. The estimated baseline model can be expressed as follows:

Model 1:

$$CO2_{i,t} = \alpha_i + \beta_1 CO2_{it-1} + \beta_2 GDP_{it} + \beta_3 GE_{it} + \beta_4 FD_{it} + \beta_5 REC_{it} + \beta_6 EGDI_{it} + \varepsilon_{i,t} \quad (1)$$

Table 1: Variable definitions

Variable	Description	Source
CO_2	Carbon dioxide (CO_2) emissions excluding LULUCF per capita (t CO_2e/capita	WDI
GDP	GDP (constant 2015 US$)	WDI
REC	Renewable energy consumption (% of total final energy consumption)	WDI
GE	Government Effectiveness	WDI
EGDI	E-goverment	The UN e-governance survey
FD	Domestic credit to private sector by banks (% of GDP)	WDI

To test the combined effect of e-government with renewable energy consumption and government efficiency, two interaction variables are integrated into the first model: EGDI × REC in the second model and EGDI × GE in the third model. These interactions allow us to examine whether the effect of e-government on CO_2 emissions is amplified or moderated by energy performance or institutional efficiency.

Model 2: Interactive variable EGDI × REC

$$CO2_{i,t} = \alpha_i + \beta_1 CO2_{it-1} + \beta_2 GDP_{it} + \beta_3 GE_{it} + \beta_4 FD_{it} + \beta_5 REC_{it} + \beta_6 EGDI_{it} + \beta_7 EGDI \times REC_{it} + \varepsilon_{i,t} \quad (2)$$

Model 3: Interactive variable EGDI × GE

$$CO2_{i,t} = \alpha_i + \beta_1 CO2_{it-1} + \beta_2 GDP_{it} + \beta_3 GE_{it} + \beta_4 FD_{it} + \beta_5 REC_{it} + \beta_6 EGDI_{it} + \beta_7 EGDI \times GE_{it} + \varepsilon_{i,t} \quad (3)$$

Avec, i=1…N et t=1….T

α_i fixed country effect, β Estimation coefficients, et $\varepsilon_{i,t}$ error terms.

i and *t* index countries and years respectively

3.3. Methodology

The study's methodology is founded on a robust econometric approach that enables a thorough assessment of how the growth of e-government affects CO_2 emissions across a sample of MENA nations. Given the dynamic nature of the phenomenon under investigation, potential endogeneity effects, and the panel structure of our data, we opt for estimation using the system generalised method of moments (System GMM) developed by Blundell and Bond (1998).

3.3.1. Preliminary econometric tests

Several preliminary econometric tests are conducted to verify the statistical properties of the data.

- Cross-sectional dependence test
  Initially, we apply the cross-sectional dependence (CD test) of Pesaran (2004), which allows us to detect the presence of correlation among the panel units (in this case, the countries). This test is crucial, as cross-sectional dependence can bias the results of standard unit root and cointegration tests.
- Stationarity tests
  Next, we check the order of integration of the variables using stationarity tests: First-generation tests: Levin, Lin & Chu (LLC), Im, Pesaran & Shin (IPS), and second-generation tests: Pesaran CADF (Cross-sectionally Augmented Dickey-Fuller), which is better suited in the presence of cross-sectional dependence.
- Westerlund cointegration test
  In order to assess if CO_2 emissions and the explanatory variables namely, e-government, economic, financial, and institutional indicators have a long-term connection, we employ the Westerlund (2007) cointegration test. The main advantage of the assessment is its resilience to cross-sectional reliance and variation among nations. The existence (or lack thereof) of a long-term equilibrium can be determined using the four statistics (Gt, Ga, Pt, and Pa). The results show that

there was no cointegration during the period under study, which supports the use of a differencing approach and dynamic estimation using GMM.

3.3.2. GMM estimator's rationale

Several technical limitations are addressed when the GMM model is applied to dynamic panel data:

Among the explanatory variables, the existence of a lagged dependent term (dynamic endogenous variable),

the possibility of endogeneity between some variables (e.g., e-government and governance or emissions levels), as well as the presence of different individual impacts that are not detected.

The GMM (Generalised Method of Moments) addresses these issues through the use of internal instruments by constructing equations in differences and levels. Two main forms are distinguished:

- The first-difference GMM (Arellano and Bond, 1991)
- The system GMM (Blundell and Bond, 1998), which combines equations in levels and differences and is more efficient when the explanatory variables are persistent.
- The GMM estimator is typically applied in two steps:
- First step: assumption of homoscedasticity, unweighted instruments.
- Second step: the residuals from the first step are used to estimate a more efficient variance-covariance matrix, which enhances the statistical robustness of the results.

The GMM estimator's efficacy in systems is especially evident in panels with relatively modest T (periods) and moderate N (number of units), which explains how our study was set up (13 countries over 21 years).

3.3.3. Validity tests of the GMM model

The suitable application of the GMM technique requires the econometric diagnostic testing of instruments and model assumptions, particularly:

- The Sargan/Hansen test (over-identification test)
  This test assesses the validity of the instruments used in the model. The null hypothesis is that the instruments are valid, meaning they are not correlated with the error terms. A $P > 0.05$ indicates that the hypothesis of instrument validity cannot be rejected.
- The Arellano and Bond autocorrelation tests (AR(1) and AR(2)) check for the presence of autocorrelation in the model's errors. The null hypothesis is the absence of autocorrelation. The AR(1) test is typically rejected (as the differencing transformation introduces mechanical autocorrelation), but the AR(2) test should not be significant to ensure the validity of the instruments.

4. RESULTS

4.1. Descriptive Statistics and Preliminary Tests

Table 2 provides an overview of the characteristics of the panel data used (273 observations).

Table 2: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
EGDI	273	0.516	0.1565397	0	0.9602
GDP	273	25.396	0.9557681	23.62686	27.38514
GE	273	−0.147	0.5644768	−1.749675	1.197413
FD	273	51.078	26.44456	1.266035	138.4197
REC	273	3.492	4.897386	0	22.4
CO_2	273	12.58891	13.52366	1.288041	53.59839

The analysis of descriptive statistics provides an overview of the main characteristics of the variables in a sample of 273 observations. This sample covers the MENA region countries from 2003 to 2023.

The dependent variable, CO_2 emissions per capita (CO_2), shows a relatively high average of 12.59 tonnes per capita, with a significant standard deviation of 13.52. This indicates a large heterogeneity among the countries in the sample. Some economies, like Qatar and Saudi Arabia, have very high emission levels, while others, such as Tunisia and Morocco, have much lower levels.

The study's key variable, e-government (EGDI), has an average value of 0.516, indicating that the region's public services are moderately digitalized.

In terms of digital services, the most developed nations (such as Bahrain and the United Arab Emirates) and those that are falling behind have noteworthy differences, as evidenced by the variable's range of 0 to 0.96 and its notable dispersion ($\sigma = 0.157$).

The GDP per capita (logarithm of GDP in constant 2015 dollars) has an average of 25.40, with moderate variations (min = 23.63; max = 27.39), reflecting the disparities in wealth between high-income oil-producing countries and middle-income countries. In parallel, government effectiveness (GE) shows a slightly negative average (−0.147), indicating generally weak governance in the region, although some countries achieve positive scores (up to 1.19), contrasting with countries experiencing governance failures (min = −1.75).

Financial development (FD), measured by credit to the private sector as a percentage of GDP, shows an average of 51.08%, but with a high dispersion ($\sigma = 26.44$). This result indicates significant heterogeneity in access to bank financing across MENA countries. Finally, the consumption of renewable energy (REC) is relatively low, with an average of 3.49% and a strong asymmetry (values ranging from 0% to 22.4%), highlighting the region's persistent dependence on fossil fuels.

Descriptive statistics reveal significant structural disparities within MENA countries, economically, institutionally, and environmentally. These differences justify the use of a dynamic and flexible econometric model such as system GMM, capable of capturing specificities.

4.2. Correlation Matrix

The correlations between the different variables in the model can be examined using the correlation matrix shown in Table 3.

Table 3: Correlation matrix

	EGDI	GDP	GE	FD	REC	CO_2
EGDI	1.0000					
GDP_	−0.0039	1.0000				
GE	0.5009	−0.2744	1.0000			
FD	0.4915	−0.3696	0.4170	1.0000		
REC	−0.2308	−0.2806	−0.0635	0.1783	1.0000	
CO_2	0.4587	0.0019	0.6419	0.1741	−0.5302	1.0000

Overall, the correlation coefficients are below 0.8, indicating an absence of severe multicollinearity among the explanatory variables.

The EGDI (e-Government Development Index) exhibits a moderately positive correlation with CO_2 emissions per capita (ρ = 0.4587), which may indicate that countries more advanced in digitalisation also tend to have higher levels of emissions, likely due to a greater degree of economic or industrial development. Additionally, there is a good correlation between the EGDI and financial development (FD) (ρ = 0.4915) and government effectiveness (GE) (ρ = 0.5009), suggesting that institutional quality, financial depth, and public service modernisation are all consistent.

The correlation between CO_2 emissions (CO_2) and government effectiveness (GE) is particularly strong (ρ = 0.6419), suggesting that countries with more effective governments paradoxically tend to emit higher levels of CO_2. This may be attributed to their level of industrialisation or the presence of energy-intensive economic activities. Conversely, renewable energy consumption (REC) is negatively correlated with CO_2 emissions (ρ = −0.5302), which aligns with expectations: a greater share of renewable energy in total consumption tends to reduce pollutant emissions.

The variable "rec" has a weak and negative correlation with both GDP (ρ = −0.2806) and e-government (ρ = −0.2308), which may indicate that the more technical or economically developed nations (often hydrocarbon producers in the MENA region) still use renewable energy resources to a limited degree.

4.3. The VIF Multicollinearity Test (Variance Inflation Factor)

The Variance Inflation Factor (VIF) test aims to assess the presence of multicollinearity issues among the explanatory variables in a regression model. A high VIF value (greater than 10) indicates that the variable is strongly correlated with other independent variables, which can distort the model's estimates.

Table 4 shows that the average VIF is 1.53, which is extremely low, and that no variable has a VIF greater than 2. This implies the explanatory variables do not exhibit significant multicollinearity. The reliability of the econometric model's estimates is enhanced by these findings, which indicate minimal multicollinearity among the explanatory variables. Consequently, the variables can be retained in their current form in the regression without the risk of bias from redundant data.

4.4. Pesaran's Transversal Dependence Test (2004)

The results of the Pesaran (2004) cross-sectional dependence test show significant interdependence among the cross-sectional units, as indicated by a CD statistic of 4.76 (P < 0.01). The presence of dependence among the residuals indicates that shocks can spread from one country to another within the sample. Therefore, first-generation stationarity tests, which rely on the assumption of independence among units, are no longer appropriate. It is essential to use second-generation stationarity tests that consider cross-sectional dependence, such as Pesaran's CIPS or CADF.

Table 4: VIF test

Variable	VIF	1/VIF
EGDI	1.83	0.546
FD	1.74	0.574
GE	1.51	0.664
GDP	1.34	0.746
REC	1.24	0.807
Average VIF	1.53	

4.5. Stationarity

The stationarity of the variables is evaluated using the Pesaran CADF test. The findings show whether the variables need differencing or are stagnant at their values. The test checks the panel data for the existence of unit roots.

Table 5 shows the results of the stationarity tests. Static variables at levels do not require differencing, although non-stationary variables at levels may become stationary following initial differencing. The results help to understand the long-term relationships between the panel's factors.

4.6. Results of Westerlund's Cointegration Test

The results of the CADF test by Pesaran (2007), which is appropriate for panels with cross-sectional dependence, indicate that all variables except for egdi_ are non-stationary at level but become stationary after taking the first difference. This means they are integrated of order one, I(1). The variable egdi_ is already stationary at level, so it is integrated of order zero, I(0). These findings support the use of cointegration methods in our model.

The Westerlund test (2007) is used to assess the existence of a cointegration relationship in an Error Correction Model (ECM) for panel data. For both specifications (with 0 and 1 lag), none of the statistics (Gt, Ga, Pt, Pa) are significant, as indicated by high P-values (all > 0.05) and as detailed in Table 6. Therefore, we do not reject the null hypothesis of no cointegration for this panel. There is no stable long-term relationship between CO_2 emissions and the selected explanatory variables in this sample of 13 countries over the studied period, according to the Westerlund test.

The results indicate that there is no cointegration during the studied period. This supports the application of dynamic estimates through GMM and the differencing model. The system GMM estimator is efficient for panels with a small T (time period) and moderate N (number of countries), which corresponds to our study involving 13 countries over 12 years.

4.6.1. GMM estimation

The GMM estimation results (Table 7) reveal several significant relationships between the explanatory variables and CO_2 emissions.

Table 5: Second-generation stationarity test (Pesaran CADF)

Variable	Level or Difference.	t-bar	CV (5%)	Z[t-bar]	P-value	Stationarity
CO_2	Level	−1.776	−2.250	−0.024	0.490	Non stationary
ΔCO_2	First difference	−3.080	−2.260	−4.701	0.000	stationary
GDP_	Level	−1.411	−2.250	1.333	0.909	Non stationary
ΔGDP_	First difference	−2.766	−2.260	−3.591	0.000	Stationary
GE	Level	−1.408	−2.250	1.347	0.911	Non stationary
ΔGE	First difference	−2.578	−2.260	−2.926	0.002	Stationary
FD	Level	−1.997	−2.250	−0.845	0.199	Non stationary
ΔFD	First difference	−3.271	−2.260	−5.377	0.000	Stationary
REC	Level	−1.841	−2.250	−0.263	0.396	Non stationary
ΔREC	First difference	−3.365	−2.260	−5.707	0.000	Stationary
EGDI_	Level	−2.814	−2.250	−3.879	0.000	Stationary
ΔEGDI_	First difference	−2.847	−2.260	−3.877	0.000	Stationary

Table 6: The Westerlund Cointegration Test (H_0: No cointegration)

Lags	Statistics	Value	Z-value	P-value	Interpreters
0	Gt	−1.765	1.536	0.938	Insignificant (H_0 not rejected)
	Ga	−5.760	2.800	0.997	Insignificant (H_0 not rejected)
	Pt	−7.883	−0.900	0.184	Insignificant (H_0 not rejected)
	Pa	−7.160	0.395	0.654	Insignificant (H_0 not rejected)
1	Gt	−0.902	4.595	1.000	Insignificant (H_0 not rejected)
	Ga	−0.791	5.134	1.000	Insignificant (H_0 not rejected)
	Pt	−2.259	3.703	1.000	Insignificant (H_0 not rejected)
	Pa	−1.366	3.022	0.999	Insignificant (H_0 not rejected)

Hypothesis (H_0): There is no cointegration relationship between the dependent variable (CO_2) and the explanatory variables (GDP, GE, FD, REC, and EGDI)

Table 7: The dynamic panel estimate results (GMM method)

Variables	Model 1	Model 2	Model 3
GDP_	−12.815 (***) (−3.96)	−14.278 (***) (−4.01)	−2.301 (−1.56)
GE	6.478 (***) (4.14)	6.049 (**) (2.60)	56.49(***) (3.27)
FD	−0.134 (*) (−2.04)	−0.142 (*) (−1.83)	−0.228(*) (−1.91)
REC	−1.797 (**) (−2.93)	−0.335 (−0.49)	−1.289*** (−9.88)
EGDI_	19.663 (**) (2.23)	28.066 (*) (1.99)	69.50(*) (1.90)
EGDI_REC	—	−3.502 (**) (−2.49)	
EGDI_GE	—	—	−101.1(**) (−2.38)
Constant	3.422 (***) (4.06)	3.763(***) (4.09)	56.35* (2.13)
Diagnostic statistics			
AR (1)	z = −0.69 P=0.488	z = −0.75 P=0.453	z = −1.93 P=0.054
AR (2)	z=0.38 P=0.705	z=0.89 P=0.374	z=1.38 P=0.167
Sargan	$\chi^2(3) = 7.63$ P=0.054	$\chi^2(3) = 3.93$ P=0.269	$\chi^2(3) = 4.77$ P=0.573

Significant at 1% (***), 5% (**), and 10% (*) levels

These relationships are consistent across all three estimated models and provide important insights into the economic, institutional, and energy factors influencing environmental performance in MENA countries.

The validity tests for the instruments (Sargan and Hansen) are generally satisfactory across the three models ($P > 0.05$, except for the Sargan test in model 3), which enhances the credibility of the results. Additionally, the Arellano-Bond autocorrelation tests (AR(1) and AR(2)) confirm the absence of second-order autocorrelation, a crucial condition for the validity of the GMM model.

The results presented in the GMM estimation table generally indicate a significant relationship between the various explanatory variables and CO_2 emissions (the dependent variable). Across the three models, GDP per capita consistently shows a negative and significant effect on CO_2 emissions. This result, counterintuitive at first glance, may reflect a trend towards more carbon-efficient economies as income increases, in line with the Environmental Kuznets Curve hypothesis.

The effectiveness of governance (EG) has a positive and significant effect across all models, suggesting that governance efforts, while present, may not yet have reached a sufficient level of effectiveness to reverse the trend of emissions.

The financial development (FD) exhibits a negative effect in all cases, with significance at the 10% level in the first model and further reinforced in the third. This indicates that the expansion of the financial sector may promote more environmentally friendly investments or enhance energy efficiency.

The use of renewable energy sources (REC) has a strong negative effect in models 1 and 3, indicating that a higher share of renewable energy in production helps reduce CO_2 emissions. However, in model 2, this effect is not significant, suggesting that other factors may lessen its impact when interactions are considered.

Regarding the e-Government Development Index (EGDI), its effect is positively significant across all models. This may indicate an increase in digital economic activities that require more energy consumption, especially if this digitalisation relies on less environmentally friendly infrastructures. However, the interaction effects provide a more nuanced understanding of this relationship.

In model 2, the association between digital transformation and renewable energy consumption (EGDI_REC) has a negative and significant impact, indicating that digitalisation becomes more environmentally friendly when combined with a green energy plan.

The model 3 includes an expanded estimate of the impact of e-government by taking into account a variety of economic, financial, energy, and institutional factors. The coefficient is negative and highly significant in relation to the PIB per capita. This supports Kuznets' theory of the environmental curve. In the MENA countries, rising incomes appear to favour lower-carbon growth. This is due to investments in proprietary technologies and long-term development policies.

The effect is positive and highly significant for government efficiency. This shows that although there have been institutional improvements, governance mechanisms are still insufficiently effective to cut emissions. This implies that governance is more declarative than operational. Alternatively, improved institutions may accompany more sustained economic activity, which generates higher emissions in the short term. These findings are consistent with those of Dossou et al. (2025), Traoré and Asongu (2024), and Liu et al. (2020), who show that effective governance improves the economic effect of environmental policies and spending, enabling public investments in decreasing emission levels to be more profitable.

In terms of financial development, the coefficient is both negative and significant. This demonstrates how expanding the financial sector helps to reduce emissions. This is most likely due to better resource allocation and funding for greener energy projects. The results suggest that bank loans are environmentally responsible, demonstrating a genuine commitment to environmental management. New tools and structures are emerging nowadays, prompting traditional companies to adjust their plan of action so as to incorporate the local community in the development of energy infrastructure. These findings support those of Batool et al. (2022), who found a correlation between a decrease in carbon and financial development. This synergy between finance and ecology accentuates the importance of incorporating ethical procedures into the banking sector to promote an inclusive and friendly energy transition.

The use of renewable energy has a significant and negative impact as well. This reinforces the importance of the energy transition. As the proportion of renewable energy increases, emissions decrease. This result emphasises the significance of energy diversification policies. The coefficient for e-government is positive and significant. This implies that digitisation is currently increasing CO_2 emissions. This increase is attributable to the use of energy by digital infrastructures, which are frequently powered by fossil fuels.

Finally, there is a positive and significant impact from the relationship between e-government and governance. This suggests that the ability of e-government to lower emissions depends on the standard of governance. Effective governance might make digitisation a tool for the ecological transition. This effect can be achieved by increasing the transparency, traceability, and efficacy of public policies. These results are similar to those of Chen et al. (2023) and Xu (2022).

The empirical findings support the significant contribution of e-government and governance to the decrease of carbon emissions in the MENA region. The e-government's negative and statistically significant impact supports the findings of several studies (Elbahnasawy, 2014; Neves et al., 2020), which highlight the potential of digital tools and the digitisation of public services to increase transparency, decrease inefficiencies, and promote more sustainable practices. Given the MENA region's persistent reliance on fossil fuels, this finding emphasises the significance of digital reforms as a means of achieving an ecological transition. Furthermore, the role of governance appears as vital. The significance of governance indicators complements the work of Traoré et al. (2024), Kaufmann et al. (2010) and Méon and Sekkat (2005), who demonstrate that institutional quality determines the effectiveness of environmental policies. The results demonstrate that more accountable and transparent systems increase the impact of green initiatives in MENA countries, whose institutions are still weak and frequently characterised by centralised governance. In addition, the relevance of renewable energies, which might vary depending on the country, confirms the conclusions of Manoharan et al. (2023), Bhattacharya et al. (2016) and Saidi and Hammami (2015), who point out that investment in green energy is a significant aspect in long-term decarbonisation. These findings highlight the need for tailored policies that encourage the adoption of green practices. By understanding regional differences, governments can better promote effective renewable energy solutions that meet local needs. However, the scope of this effect is limited by the current low contribution of renewables to the MENA region's energy mix, which stresses the urgency to speed up the energy transition. These findings are especially relevant in the MENA region, where structural issues such as a strong reliance on hydrocarbons, a lack of economic diversification, and demographic pressures coexist with a high exposure to climate risks. As a result, public policies must balance energy transition with economic growth and social stability. This multidimensional strategy reiterates the need for an integrated approach that involves governance, digitisation, and expenditure on renewable energy.

5. CONCLUSION

This study analyses the relationships between the environmental performance of MENA countries and the number of public services provided between 2003 and 2021. The findings show that the relationship between the environment and digitisation is complicated and dependent on a number of factors. E-government's environmental benefits are not always guaranteed. Its success is contingent upon robust institutional support and a concurrent shift in energy practices. While the development of e-government may initially increase CO_2 emissions due to intensified digital infrastructure and higher energy demand, its effects become more nuanced when combined with effective environmental governance and a transition to renewable energy sources.

According to theory, this study adds to the body of knowledge on digital transformation and durability. It demonstrates how the effects of e-government rely on the institutional and energy settings. These findings allow for the formulation of recommendations for the MENA countries.

First and foremost, a green energy transition needs to proceed hand in hand with digitisation. This includes creating digital infrastructures powered by renewable energy sources, such as solar or eolian data centres. It's also critical to promote energy efficiency in public computer systems. econd, environmental governance needs to be strengthened. This means putting in place monitoring mechanisms and translating climate strategies into contraindicated regulations. Enhancing the transparency and integrity of institutions is essential if e-government is to effectively control and lessen environmental externalities.

Thirdly, with the goal of supporting the ecological transition, the financial sector must be mobilised. This can be achieved by encouraging green finance, for instance, by offering green obligations or preferentially priced credits for long-term projects. Additionally, the establishment of public-private partnerships may contribute to funding ecological digital infrastructure.

Finally, it's critical to examine regional cooperation. The MENA region's countries can pool their resources in the areas of technological and energy innovation and exchange digitalisation experiences

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