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Exploring the Relationship Between ICT and Carbon Dioxide Emissions in MENA Countries: A Panel ARDL-PMG Analysis

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ABSTRACT

The Middle East and North Africa (MENA) region faces significant challenges in sustainable development, digital technological advancements, and environmental protection, especially as pollution sources continue to increase and diversify. As MENA countries aim for economic progress, it is essential to understand how digital technological advancements impact the environment. Information and Communication Technologies (ICT) are vital for improving productivity and achieving development goals; however, they can also lead to pollution and increased CO_2 emissions due to their energy consumption and creation of electronic waste. Therefore, this study examined the short and long-term effects of ICT, economic growth, institutions, population, non-renewable energy and financial development on CO_2 emissions in MENA countries from 2003 to 2021. In addition, this study investigates how ICT interacts with institutions and populations and explores how these interactions affect CO_2 emissions. We used the panel autoregressive distributed lag (ARDL-PMG) model because it tests both short-term and long-term effects. Additionally, it is effective with small sample sizes, making it ideal for our study, which includes only eleven countries. Our findings show that CO_2 emissions are significantly affected, in the short and long term, by ICT, economic growth, population size, and non-renewable energy. In contrast, effective institutions contribute to reducing these emissions. Based on these findings, we offer economic recommendations to support sustainable development in the MENA region, aiming to balance technological advancements with the urgent need to address climate change and reduce CO_2 emissions. Policymakers should integrate ICT with renewable energy, invest in sustainable sources, and enhance regulations for green technologies. Strengthening

education on sustainable ICT practices and implementing energy efficiency policies will also help reduce CO_2 emissions in the MENA region.

INTRODUCTION

Information and Communication Technologies (ICT) are important in all countries. As digitalization accelerates, ICT is increasingly utilized across various sectors, including education, health, finance, and transportation, driving innovation and improving efficiency. The growing reliance on digital tools has revolutionized business operations, enhanced connectivity, and facilitated the rapid dissemination of information. In the MENA region[1] the adoption of ICT is seen as a key driver for economic growth, enabling countries to diversify their economies and improve public services. According to Mordor Intelligence report (2023), "The MENA ICT Market size is estimated at USD 183.48 billion in 2024, and is expected to reach USD 250.29 billion by 2029, growing at a Compound Annual Growth Rate (CAGR) of 6.41% during the forecast period (2024-2029))". The rise of ICT not only fosters job creation and skill development but also supports sustainable practices by optimizing resource use. However, this rapid growth also presents challenges, particularly concerning its environmental impact, specifically in terms of CARBON DIOXIDE emissions (Raheem et al. 2020; Lee et al. 2024). Understanding the relationship between ICT and carbon dioxide emissions is essential for MENA countries as they navigate the dual goals of economic development and environmental sustainability. On the one hand, these countries increasingly recognize the need for ICT to drive economic growth, diversify their economies, and improve public services. With a young and rapidly growing population, these nations are looking to ICT to create jobs and enhance public services. On the other hand, MENA countries rely heavily on fossil fuels for energy production, which complicates their environmental impact. In this context, ICT can significantly influence emissions in both beneficial and detrimental ways. On the positive side, ICT can enhance energy efficiency by employing non-polluting technologies that optimize energy and reduce pollution. (Wen et al. 2022; Onyeneke et al. 2024; Linghu et al.2024). Moreover, ICT facilitates the integration of renewable energy sources, like solar and wind, in different sectors of the economy (Zeeshan et al.,2023). However, the rapid expansion of ICT infrastructure, including data centers and telecommunications networks, can create an upsurge in energy demand. In MENA countries, where much of the energy still comes from fossil fuels, this increased demand can result in higher carbon dioxide emissions if renewable energy sources are not adequately integrated. Additionally, the production and disposal of electronic devices contribute to environmental challenges, with energy-intensive manufacturing processes and significant electronic waste posing risks if not managed properly. Thus, while ICT holds considerable potential to support sustainable development and reduce emissions, its impact will depend on how effectively these technologies are integrated with renewable energy initiatives, robust environmental policies, and efforts to bridge the digital divide. This study aims to investigate the short-run and long-run effects of ICT, GDP, non-renewable energy, institutional, financial development, and population on carbon dioxide emissions in MENA countries during the period 2003- 2021.

The key questions guiding our study are:

- What is the impact of ICT on carbon dioxide emissions in the MENA region during 2003-2021?

[1] The sample of this study includes eleven countries from the MENA region, namely: Algeria, Egypt, Jordan, Kuwait, Morocco, Oman, Qatar, Saudi Arabia, Tunisia, Turkey, and the United Arab Emirates.

- Does institutional quality moderate the relationship between ICT and carbon dioxide emissions in the MENA region?
- How does population growth influence the effect of ICT on carbon dioxide emissions in the MENA region?
- What policy recommendations can be developed to mitigate the impact of ICT on carbon dioxide emissions in the MENA region?

Study Hypotheses

Considering the economic realities of the MENA region and drawing from existing literature, this study deliberates the following hypotheses:

- ICT is expected to increase carbon dioxide emissions.
- The economic growth (GDP) in the MENA region, heavily reliant on the oil and manufacturing sectors, is expected to be a significant source of carbon dioxide emissions.
- Population growth is likely to have a positive effect on carbon dioxide emissions in the MENA region, as the arid and hot climate increases energy consumption for air conditioning and transportation.
- Non-renewable energy is anticipated to positively influence carbon dioxide emissions due to the MENA's strong dependence on fossil fuels, particularly oil and natural gas, which are widely used in production, transportation, and industry. The region's abundant reserves of these resources make them easily accessible and economically viable.
- Institution quality and Financial Development are expected to reduce carbon dioxide emissions.

The remainder of this paper is structured as follows. Section 2 provides a comprehensive literature review, summarizing key studies on the impact of ICT on carbon dioxide emissions across various regions and countries. Section 3 outlines the data sources, describes the empirical model used, and explains the analytical methods employed in the research. Section 4 presents and discusses the results, drawing comparisons with existing literature to highlight significant insights. Finally, Section 5 summarizes the main findings and offers practical policy recommendations to address the identified challenges effectively.

1. Literature review

The economic literature presents divergent results on the relationship between ICT and carbon dioxide emissions. Some studies suggest that ICT can have a positive impact by enhancing energy efficiency, promoting cleaner technologies and enabling more sustainable practices, which collectively contribute to reducing emissions. Conversely, other studies indicate that the widespread adoption and use of ICT may contribute to increased energy consumption and higher carbon dioxide emissions, especially due to the energy demands of the ICT sector and the production of electronic devices. This divergence among study findings shows how complex the relationship between ICT and emissions is and highlights the need for more research on how ICT can promote economic growth and reduce its environmental impact. Ebaidalla et al. (2022) show a positive and significant relationship between ICT use and increased emissions in GCC countries, thereby indicating that greater ICT adoption exacerbates environmental degradation in this region. Similarly, using the PMG model, Raheem et al. (2020) explored the relationships between ICT, financial development (FD), carbon dioxide emissions, and economic growth in the G7 countries from 1990 to 2014. Their findings indicate a long-run positive effect of ICT on carbon dioxide emissions. The results of this study also show that the interaction between ICT and FD produces negative coefficients, suggesting that although ICT contributes to increased emissions, its interaction with FD may help mitigate this effect. Adebayo et al. (2022) used advanced non-parametric methods to study the effects of ICT on carbon dioxide emissions in the top 10 ICT nations from 1986 to 2019. Their results show a positive effect on carbon dioxide emissions in the Netherlands, South Korea, and Iceland. Furthermore, Lee et al. (2024) studied the effects of ICT on carbon dioxide emissions in G20 countries from 2000 to 2019. Results show a strong positive effect of ICT on emissions in lower-quantile countries. However, this effect weakens in higher quantile countries. This means that ICT does not always increase emissions as countries develop. Additionally, Si and Rahman (2024) examine the effects of ICT on carbon dioxide emissions in the Persian Gulf economies from 1990 to 2021, finding that while fixed telephone and internet subscriptions correlate with increased carbon dioxide emissions, mobile cellular subscriptions surprisingly contribute to a reduction in emissions, highlighting the complexity of the relationship between ICT and environmental outcomes. Akwasi et al. (2022) used the AMG and CCEMG methods to study how ICT, globalisation, renewable energy and the quality of institutions affected carbon dioxide emissions in seven emerging economies from 1995 to 2016. They found that economic globalization and renewable energy reduce carbon dioxide emissions. However, ICT, along with poor institutional quality and fossil fuel use, harmed the environment. Timchenko et al (2024) studied the global impact of the ICT sector. They found that this sector is responsible for about 4% of the world's greenhouse gas emissions. This is mainly due to high ICT consumption and growing e-waste. Zeeshan et al. (2023) used the Cross-CS-ARDL model to study the effect of ICT on environmental sustainability in BRICS nations from 1990 to 2019. Their results show that ICT can help improve sustainability by encouraging eco-friendly practices, especially in tourism and trade. Kim (2022) examines the long- and short-term effects of ICT, economic growth, trade openness, and renewable energy on carbon dioxide emissions in OECD countries between 1990 and 2018. Findings reveal that while ICT may contribute to increased carbon dioxide emissions in the long term, its overall effect is minimal compared to the significant elevation of emissions due to economic growth. Tahsin (2022) investigated the effect of ICT and technological innovation on environmental quality in 34 Asian developing nations from 1990 to 2018. Results show an inverted U-shaped relationship where pollution decreases after a certain level of ICT development, with innovation promoting energy efficiency. Onyeneke et al. (2024) used the ARDL approach to explore the long- and short-term effects of ICT, renewable energy consumption, and economic growth on per capita carbon dioxide emissions in 29 African countries from 2001 to 2020. Findings show that ICT and economic growth increase emissions, while renewable energy consumption reduces them. Briglauer et al. (2023) evaluated the impact of core elements of ICT on carbon dioxide emissions across 34 OECD countries from 2002 to 2019. The results reveal that the positive indirect effects of basic and fiber-optic broadband connections often outweigh the negative impacts of mobile broadband networks. This suggests the need for tailored climate policies that effectively leverage the benefits of different ICT components while mitigating their negative effects. These findings highlight the complex interaction between ICT and carbon dioxide emissions, where net effects are influenced by various factors, including economic conditions, energy practices, and the specific contexts of each country. Wen et al. (2022) investigated the asymmetric impacts of ICT, renewable energy consumption, economic growth, and population on carbon dioxide emissions in Mexico, Indonesia, Nigeria, and Turkey from 1990 to 2018. Findings show that ICT and renewable energy significantly reduce emissions, while economic growth and financial development increase them. Linghu et al. (2024) studied how ICT affected carbon dioxide emission efficiency in 30 Chinese provinces from 2008 to 2019. They found that a 10% increase in the ICT development index leads to a 0.11% increase in energy efficiency, which helps lower emissions.

While the impact of ICT on carbon dioxide emissions has been extensively studied, a significant research gap remains concerning the MENA region. Existing literature often examines ICT's effect in isolation, overlooking its interplay with critical regional factors such as institutional quality (e.g., governance effectiveness, regulatory frameworks) and population dynamics (e.g., urbanization, demographic shifts). These factors are particularly relevant in the MENA context, where varying levels of institutional stability and rapid population growth present challenges and opportunities. This study addresses this gap by adopting a comprehensive approach, investigating not only the direct effects of ICT on carbon dioxide emissions but also its indirect effects through interactions with institutional and demographic variables. Furthermore, the period from 2003 to 2021 was marked by profound transformations in the MENA region, including rapid digital adoption, fluctuating economic conditions, and significant socio-political shifts. These dynamics are likely to have influenced the relationship between ICT and environmental outcomes. However, prior research has largely overlooked these evolving interactions, leaving a critical gap in understanding how ICT's role in emissions has evolved in response to regional changes.

3. Data and Methods

3.1. Data source and Descriptive statistics

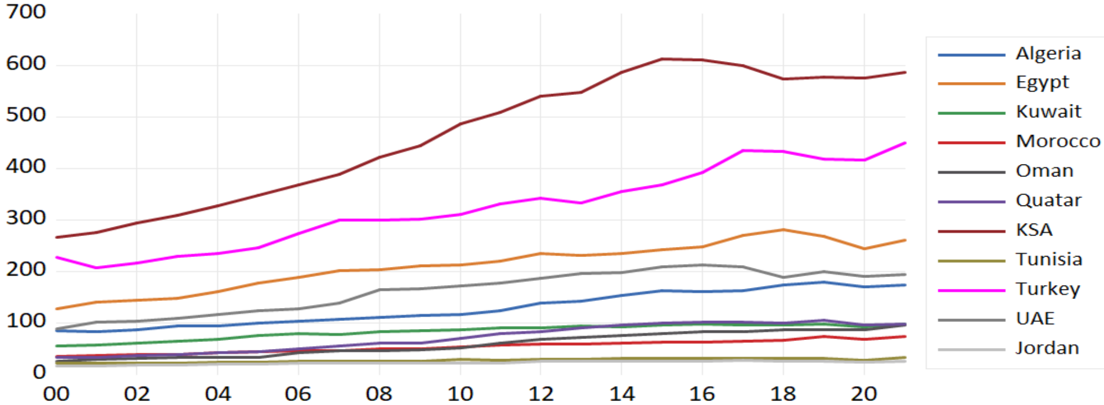
carbon dioxide emissions serve as an indicator of pollution, mainly resulting from the combustion of coal, natural gas, oil, and other fossil fuels. Non-renewable energy sources include oil, natural gas, and coal. Economic growth is measured by GDP, expressed in trillions of dollars, adjusted for purchasing power parity (PPP). The variable population is used because it represents an important source of energy consumption. Financial development (FD) is crucial for evaluating a country's financial sector as it promotes investment in cleaner technologies and sustainable practices. By enhancing access to capital, FD encourages innovation and eco-friendly solutions, thereby impacting carbon dioxide emissions through improved resource efficiency and reduced carbon footprints.

Institutional quality affects carbon dioxide emissions by enabling effective environmental policies, enforcing emission standards and promoting cleaner technologies. It fosters public engagement and attracts investment in renewable energy, ultimately supporting sustainable development and reducing emissions. According to UNCTAD, “Institutions aim at measuring political stability and efficiency through regulatory quality, effectiveness, success in fighting criminality, corruption and terrorism, and safeguard of citizens’ freedom of expression and association”.

The ICT Index is a composite index created by the International Telecommunication Union (ITU) to measure the level of information and communication technology (ICT) development in each country. It combines 14 indicators organized into three sub-indices: Access, Use, and Skills.

According to UNCTAD, the ICT index evaluates the accessibility and integration of communication systems, including fixed-line and mobile phone users, internet access, and server security. The ICT Index measures ICT spread across countries in three dimensions: Connectivity, Access, and Policy, which includes the presence of Internet exchanges and competition in telecommunications and Internet service providers.

Shape 1: CO2 Emission Trends in MENA Countries in Million Metric Tons (2003-2021)



Shape 2: ICT index Trends in MENA Countries (2003-2021)

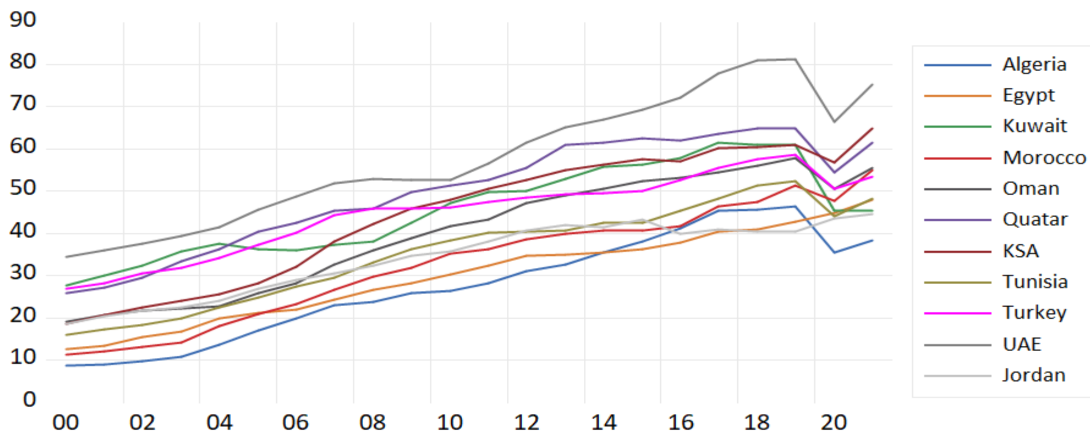


Table 1 below summarizes the sources of the various variables, including their symbols and units of measurement.

Table 1. Variables definition

Variables	Symbol	Unit of measurement	Sources
Carbon dioxide emissions	carbon dioxide	MMt*	The U.S. Energy Information Administration EIA (2023)
Non-renewable energy	NRE	QBTU**	
Gross Domestic Product	GDP	Constant 2015 USD	

Population	Pop	Total number of inhabitants	WDI(2023)
Financial Development	FD	index	IMF (2021)
ICT	ICT	Index	UNCTAD (2024)
Institutions	INST		
* MMt: Million Metric Tons. ** QBTU:. Quadrillion British Thermal Units			

Descriptive statistics reveal significant disparities among MENA countries. As shown in Table 2, the average carbon dioxide emissions across these countries are 154.27 MMt, with a standard deviation of 147.22 MMt, indicating substantial variation. Emissions range from a low of 17.67 MMt to a high of 611.42 MMt. There are also notable differences in GDP within the region, with the average GDP surpassing the median and a standard deviation of 2.38×10^{11}. Furthermore, we observe considerable disparities in population. This variation influences energy consumption, as countries with larger populations generally have higher energy demands, increasing carbon dioxide emissions. In the same way, the mean value of non-renewable energy consumption (2.65 Q Btu) is higher than the median (1.62 Q Btu), and the maximum value is substantially greater than the minimum.

Table 2. Descriptive statistics.

Variables	carbon dioxide	GDP	NRE	ICT	INST	POP	FD
Mean	154.2742	2.33E+11	2.648269	43.13206	53.18565	27653449	36.73416
Median	95.21092	1.24E+11	1.621334	42.60000	53.00000	11174383	39.09832
Maxim	611.4230	1.13E+12	12.26998	81.20000	72.30000	1.09E+08	52.63228
Minim	17.67124	2.13E+10	0.248990	10.70000	34.90000	748525.0	20.23260
Std.Dev.	147.2228	2.38E+11	2.701427	13.56789	9.805634	29648622	7.551774

Similarly, these descriptive statistics reveal significant disparities in ICT, institutional quality, and financial development across MENA countries. These disparities are due to several key factors, such as economic resources, regulatory effectiveness, access to finance, etc.

3.2. Methods

3.2.1. Cross-sectional dependence (C-SD) test

In the following, we analyzed cross-sectional dependence (C-SD) to identify correlations between variables and ensure reliable results. We use the Breusch-Pagan Chi-square and Pearson's normal CD tests. The null hypothesis of these tests assumes that there is no significant correlation among the panel units. The results of the C-SD test, conducted using the Pearson test, yield a t-statistic of -0.0465 and a probability of 0.9629. This confirms that the application of first-generation panel unit root tests (PURTs) is appropriate and justified.

3.2.2 Panel unit root tests (PURT)

Before testing the effects of the different explanatory variables on CO2 emissions and to avoid unbiased results, we used the Augmented Dickey-Fuller (ADF, 1979) and Phillips-Perron (PP, 1988) unit root tests to check the stationarity of the variables. These tests help determine whether the variables are stable in the long term or show non-stationary trends. The results in Table 3 reveal that all variables are not stationary at the level, but all become stationary at the first difference. With these findings, we can investigate the presence of long-term cointegration among the variables.

Table 3. Panel Unit Root Tests (PURT).

ADF	At level	lnCO2	lnGDP	lnNRE	lnPOP	lnINST	lnICT	lnFD
	t-Statistic	30.382	50.785	1.587	3.800	15.168	1.371	4.213
	Prob.	0.109	0.000	1.000	1.000	0.855	1.000	1.000
	First dif	d(lnCO2)	d(lnGDP)	d(lnEC)	d(lnPOP)	d(lINST)	d(lICT)	d(lnFD)
	t-Statistic	120.934	37.208	107.130	23.188	152.219	55.810	172.363
	Prob.	0.000	0.022	0.000	0.036	0.000	0.000	0.000
PP	At level	lnCO2	lnGDP	lnNRE	lnPOP	lnINST	lnICT	lnFD
	t-Statistic	63.738	87.214	1.417	0.036	26.277	0.412	3.191
	Prob.	0.000	0.000	1.000	1.000	0.240	1.000	1.000
	First dif	d(lnCO2)	d(lnGDP)	d(lnNRE)	d(lnPOP)	d(lnINST)	d(lnICT)	d(lnFD)
	t-Statistic	119.107	70.7064	145.484	26.2566	213.313	86.6716	207.855
	Prob.	0.000	0.000	0.000	0.024	0.000	0.000	0.000

3.2.3. Pedroni cointegration test results

In the following section, we use the seven cointegration tests developed by Pedroni (2001) to evaluate the long-run cointegration between variables. These tests are divided into two categories: the intra-dimension panel, which consists of four tests (Panel v, Panel rho, Panel PP, and Panel ADF), and the inter-dimension group, which includes three tests (Panel rho, Panel PP, and Panel ADF). The results, presented in Table 4, indicate that in the intra-dimension panel, the Panel v and rho tests did not show evidence of cointegration. Conversely, the PP and ADF tests indicated a significant level of cointegration. In the inter-dimension group, the Panel rho test failed to reject the null hypothesis of no cointegration, while the Panel PP and ADF tests confirmed the existence of cointegration. In conclusion, four out of the seven tests provided evidence of long-term cointegration between the variables, allowing us to affirm its existence and proceed with long-term estimations.

Table 4. Pedroni cointegration test results.

	Panel (within-dimension)				Group (between-dimension)		
Test	Panel v	Panel rho	Panel PP	Panel ADF	Group rho	Group PP	Group ADF
Statistic	-1.43065	2.28398	-1.77628	-3.63871	3.56027	-3.81058	-4.90388
Prob	0.9237	0.9888	0.0378	0.0001	0.9998	0.0001	0.0000

3.3. Model

As our main objective is to test the effects of ICT along with other variables on carbon dioxide emissions, we have adopted the following model:

$$CO2_{it} = \mathrm{f}\,(GDP_{it}, ICT_{it}, NRE_{it}, INST_{it}, POP_{it}, FD_{it}) \qquad (1)$$

carbon dioxide, GDP, ICT, NRE, INST, POP and FD represent carbon dioxide emissions, GDP, information and communication technology, non renewable energy consumption, institutions, population and financial development, respectively.

Empirically, we used the panel ARDL *(p, q)* model proposed by Pesaran et al. (1999).

$$lnCO2_{it} = +\alpha_i + \sum_{j=1}^{p-1} \beta_{1ij}\, lnCO2_{it-j} + \sum_{j=0}^{q-1} \beta_{2ij}\, lnGDP_{it-j} + \sum_{j=0}^{q-1} \beta_{3ij}\, lnICT_{it-j} + \sum_{j=0}^{q-1} \beta_{4ij}\, lnNRE_{it-j} + \sum_{j=0}^{q-1} \beta_{5ij}\, lnINST_{it-j} + \sum_{j=0}^{q-1} \beta_{6ij}\, lnPOP_{it-j} + \sum_{j=0}^{q-1} \beta_{7ij}\, lnFD_{it-j} + \varepsilon_{it} \qquad (2)$$

All variables are transformed to logarithmic form to interpret the estimated coefficients as elasticities. According to the work of Pesaran et al. (1996, 2001), the equation (2) can be expressed in the following alternative form:

$$\Delta lnCO2_{it} = +\alpha_i + \theta_{1i} lnCO2_{it-1} + \theta_{2i} lnGDP_{it-1} + \theta_{3i} lnICT_{it-1} + \theta_{4i} lnNRE_{it-1} + \theta_{5i} lnINST_{it-1} + \theta_{6i} lnPOP_{it-1} + \theta_{7i} lnFD_{it-1} + \sum_{j=1}^{p-1} \delta_{1ij}\, \Delta lnCO2_{it-j} + \sum_{j=0}^{q-1} \delta_{2ij}\, \Delta lnGDP_{it-j} + \sum_{j=0}^{q-1} \delta_{3ij}\, \Delta lnICT_{it-j} + \sum_{j=0}^{q-1} \delta_{4ij}\, \Delta lnNRE_{it-j} + \sum_{j=0}^{q-1} \delta_{5ij}\, \Delta lnINST_{it-j} + \sum_{j=0}^{q-1} \delta_{6ij}\, \Delta lnPOP_{it-j} + \sum_{j=0}^{q-1} \delta_{7ij}\, \Delta lnFD_{it-j} + v_{it} \qquad (3)$$

The long-term effects are represented by the terms in levels, while short-term effects are represented by the terms in first differences. We choose the lagged variables (p, q) based on the Schwarz information criterion (SIC). We chose the ARDL model for three reasons. First, this model does not require all variables to be stationary at the same level, which is confirmed by our Panel Unit Root tests showing that all variables are stationary at either I(0) or I(1). Second, the model allows us to analyze both short-term and long-term effects. Third, it works well even with small sample sizes, making it suitable for our study, which includes only eleven countries.

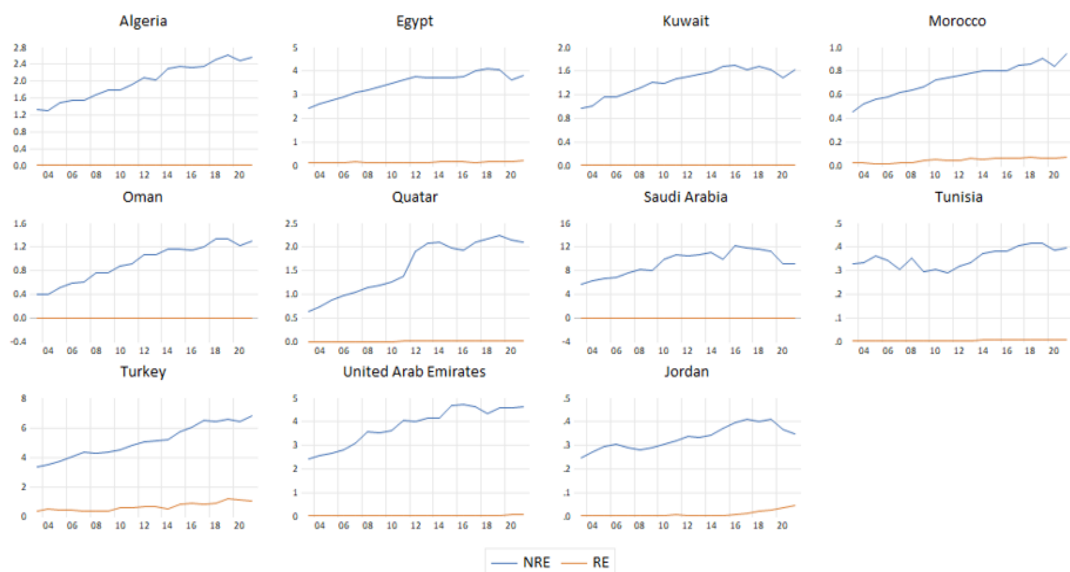
4. Results and Discussion

To achieve the objective of this paper, we utilize the ARDL-PMG approach. The optimal lag length for the panel ARDL model has been determined to be ARDL(1, 1, 1, 1, 1,1,1). The findings are presented in Table 5. ECT-1 describes the long-run equilibrium adjustment term. In all three specifications, it is negative and significant, indicating a rapid adjustment toward the long-run equilibrium. These findings reveal a positive and significant effect of ICT on carbon dioxide emissions, both in the short and long term, suggesting that

ICT contributes to environmental degradation. Specifically, according to specification **1**, a 1% increase in the ICT is associated with a rise in carbon dioxide emissions of 0.094% in the short term and 0.112% in the long term. Considering the average value of carbon dioxide emissions (154.2742) in the MENA region between 2003 and 2021 (Table 2), a 1% increase in the ICT index results in an average rise in carbon dioxide emissions of 14.5 MMT in the long term (calculated by multiplying 154.2742 by 0.094).

The increased carbon dioxide emissions linked to ICT in the MENA region are primarily driven by the region's heavy reliance on non-renewable energy sources, such as fossil fuels, to power its digital infrastructure, rather than utilizing renewable alternatives. Shape 3, depicting energy consumption trends from 2003 to 2021, visually reinforces this dependence, demonstrating the overwhelming prevalence of non-renewable energy use and highlighting the direct correlation between this energy choice and rising carbon dioxide emissions. Furthermore, as illustrated by Figure 2, the MENA region is characterized by significant ICT development during this period.

Shape 3: Trends in Renewable and Non-Renewable Energy consumption (in QBTU) in MENA Countries (2003-2021).



Despite the positive effect of ICT on carbon dioxide emissions, the results from specification **2** indicate that, in the long term, the quality of institutions and their interaction with ICT, measured by the variable **LICTINST,** can mitigate this effect. Specifically, the interaction between institutional quality and ICT is negatively significant, suggesting that stronger institutions can reduce the detrimental impact of ICT on the environment by effectively implementing and enforcing environmental policies, incentivizing sustainable practices, promoting public awareness and participation and establishing robust regulatory frameworks. These mechanisms ensure that ICT development aligns with ecological goals, steering technological advancements toward sustainability rather than contributing to degradation.

Our findings regarding the positive effect of ICT on carbon dioxide emissions align with those of previous studies that report similar results (Ebaidalla et al. 2022; Adebayo et al. 2022; Onyeneke et al. 2024; Lee et al. 2024).

Concerning GDP, the findings indicate a positive effect on carbon dioxide emissions, both in the short and long term. This effect arises from the fact that economic growth drives energy consumption, particularly within the industrial sector. Our results align with numerous studies that have similarly shown a positive relationship between GDP and carbon dioxide emissions.

Estimations across all three specifications also reveal a significant and positive impact of non-renewable energy and population growth on carbon dioxide emissions both in the short and long term. This can be attributed to the vast reserves of oil and natural gas found in MENA countries, which are major contributors to carbon dioxide emissions. The reliance on fossil fuels not only meets high energy demand but also drives industrial growth and rapid urbanization, addressing cooling needs in the region. As the population increases, the demand for non-renewable energy sources rises to satisfy consumption, transportation, and housing needs, particularly as lifestyles change due to technological advancements. In addition, over the past two decades, MENA countries have experienced rapid urbanization, contributing to higher carbon dioxide emissions through increased energy consumption.

Table 5. PMG-ARDL estimates.

Dependent variable: LCO_2			
Long Run			
	Specification 1	Specification 2	Specification 3
LGDP	0.203222***	0.165805**	0.204408***
	(2.757)	(2.008)	(2.683)
NRE	0.251256***	0.261431***	0.254897***
	(5.829)	(6.792)	(5.701)
LPOP	0.300516***	0.287178***	0.209046**
	(3.088)	(2.663)	(2.253)
LFD	-0.092170	0.031127	-0.072165
	(-0.833)	(0.249)	(-0.639)
LICT	0.112689**	1.587275***	
	(2.398)	(8.062)	
LINST	-1.704598***		-1.711333***
	(-11.963)		(-11.840)
LICTINST		-1.505461***	
		(-7.492)	
LICTP			0.091966**
			(2.177)
Short Run			
	Specification 1	Specification 2	Specification 3
ECT_{-1}	-0.186053*	-0.167700*	-0.185903*
	(-1.860)	(-1.722)	(-1.886)
D(LGDP)	0.363388**	0.302285**	0.356118**
	(2.143)	(1.989)	(2.123)
D(NRE)	0.294048**	0.299680**	0.292587**
	(2.138)	(1.856)	(2.071)
D(LPOP)	0.528629**	0.966377***	0.711057*
	(2.232)	(2.883)	1.765782
D(LFD)	-0.042621	-0.100949	-0.043955

	(-0.424)	(-0.870)	(-0.424)
D(LICT)	0.094176*	-0.061633	
	(1.676)	(-0.318)	
D(LINST)	0.106273		0.105871*
	(0.803)		(0.802)
D(LICTINST)		0.161366	
		(0.951)	
D(LICTP)			0.100366**
			(1.816)

*, ** and *** indicates statistical significance at the 10% , 5% and 1 % level respectively. The values in brackets are t-statistics.

The positive and significant effects observed in both the short and long term from the interaction between ICT and (**LICTP** variable) indicate that population growth can enhance the positive impact of ICT on carbon dioxide emissions. This suggests that the rising use of ICT, when coupled with population growth, amplifies the negative effects of ICT on the environment.

This result can be attributed to several key factors. As more people use ICT, the demand for energy-intensive data centers rises, which typically depend on fossil fuels like coal and oil for power. Additionally, population growth is fueling urbanization, resulting in higher ICT consumption in cities. Furthermore, the surge in online shopping promotes increased consumerism, leading to greater production and electronic waste and both contribute significantly to carbon dioxide emissions. The findings regarding the effects of population and non-renewable energy align with existing literature, which also identifies a positive correlation between non-renewable energy, population, and carbon dioxide emissions (Adebayo et al. 2022).

Across all specifications, financial development consistently exhibits a negative, yet statistically insignificant, relationship with carbon dioxide emissions in the MENA region, both in the short and long term. This lack of significance makes it difficult to determine the true impact of financial development on emissions. The observed insignificance likely arises from the moderate and heterogeneous nature of financial market development within the MENA region. While a relatively well-established financial infrastructure exists, particularly in the GCC countries, further enhancements are crucial, especially in non-GCC nations, to effectively reduce emissions. Consequently, the current level of financial development across the broader MENA region appears insufficient to exert a statistically significant influence on carbon dioxide emissions, highlighting the need for continued improvements to unlock its potential environmental benefits.

5. Conclusion and policy recommendations

In this study, we examined the effects of ICT (key variable), GDP, financial development, institutions, population and renewable energy on carbon dioxide emissions in MENA countries. The results indicate that, mutually in the short and long term, carbon dioxide emissions are positively and significantly influenced by ICT, economic growth population, and non-renewable energy consumption. In contrast, institutions contribute to reducing these emissions. Based on these findings, a set of policy recommendations can be formulated to mitigate emissions and promote sustainable development in this region. First, it is important to combine the use of ICT with plans that support renewable energy. They need to invest more in renewable sources like solar, wind, and geothermal energy. This will help decrease reliance on fossil fuels and lower carbon dioxide emissions. Second, as the world shifts toward a green economy, MENA countries should strengthen the role of ICT and green technologies in both the public and private sectors by implementing stricter environmental regulations and using fiscal measures like environmental taxes and financial incentives. These actions will encourage the adoption of green technologies and help create a balance between economic growth and protecting the environment. Third, MENA countries should strengthen education and training programs to reduce pollution from ICT. These programs should focus on minimizing waste and reliance on non-renewable energy sources and promoting sustainable practices and cleaner technologies in the ICT sector. Fourth, since economic growth contributes to emissions, MENA countries need to implement energy efficiency policies by adopting advanced energy-saving technologies and promoting the use of energy-efficient ICT equipment. These actions will help reduce emissions while supporting sustainable growth. Finally, given the positive impact of institutions and their helpful interaction with ICT in reducing emissions, MENA countries need to strengthen the role of institutions in enforcing environmental regulations. Improving these institutions will help implement regulations more effectively, leading to lower pollution.

Finally, this study does not completely analyze how ICT affects carbon dioxide emissions in the MENA region, so future research can explore more areas. First, it would be important to examine specific sectors impacted by ICT, such as energy, transportation, and manufacturing. Second, comparing how ICT affects carbon dioxide emissions in different MENA countries could provide useful insights. Third, it's important to study user behavior, including how people adopt and use ICT and how it influences emissions. Furthermore, examining new technologies like artificial intelligence could provide valuable information about future trends.

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