



Exploring the Relationship Between ICT and Carbon Dioxide Emissions in Middle East and North African (MENA) Countries: A Panel ARDL-PMG Analysis

Kahouli Zohra

Imam Mohammad Ibn Saud Islamic University (IMSIU), Saudi Arabia

†Corresponding author: Kahouli Zohra; kahouli_zohra@yahoo.fr

Abbreviation: Nat. Env. & Poll. Technol.

Website: www.neptjournal.com

Received: 25-01-2025

Revised: 28-02-2025

Accepted: 10-03-2025

Key Words:

ICT and CO₂ emissions

MENA countries

Panel data

ARDL-PMG model

Citation for the Paper:

Zohra, K., 2025. Exploring the relationship between ICT and carbon dioxide emissions in Middle East and North African (MENA) countries: A panel ARDL-PMG analysis. *Nature Environment and Pollution Technology*, 24(4), D1764. <https://doi.org/10.46488/NEPT.2025.v24i04.D1764>

Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.



Copyright: © 2025 by the authors

Licensee: Technoscience Publications

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

ABSTRACT

The Middle East and North Africa (MENA) region faces significant challenges in sustainable development, digital technological advancement, 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 their environment. Information and Communication Technologies (ICT) are vital for improving productivity and achieving development goals; however, they can also lead to pollution and increased CO₂ emissions owing 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 CO₂ emissions in MENA countries from 2003 to 2021. This study investigates how ICT interacts with institutions and populations and explores how these interactions affect CO₂ emissions. We used the panel autoregressive distributed lag (ARDL-PMG) model because it tests both short- and long-term effects. Additionally, it is effective with small sample sizes, making it ideal for our study, which includes only 11 countries. Our findings show that CO₂ emissions are significantly affected, in the short and long terms, by ICT, economic growth, population size, and non-renewable energy. In contrast, effective institutions contribute to reducing emissions. Based on these findings, we offer economic recommendations to support sustainable development in the MENA region, aiming to balance technological advancement with the urgent need to address climate change and reduce CO₂ emissions. Policymakers should integrate ICT with renewable energy, invest in sustainable sources, and enhance green technology regulations. Strengthening education on sustainable ICT practices and implementing energy efficiency policies will help reduce CO₂ 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, thereby driving innovation and improving efficiency. The growing reliance on digital tools has revolutionized business operations, enhanced connectivity, and facilitated rapid information dissemination. In the MENA region, 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 the 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 fosters job creation and skill development and 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 their public services. However, 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 use and reduce pollution (Wen et al. 2022, Onyeneke et al. 2024, Linghu et al. 2024). Moreover, ICT facilitates the integration of renewable energy sources, such as solar and wind, into 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 properly managed (Kahouli et al. 2025). 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- and long-run effects of ICT, GDP, non-renewable energy, institutional and financial development, and population on carbon dioxide emissions in MENA countries during the period 2003–2021.

The key questions guiding our study were as follows:

- What is the impact of ICT on carbon dioxide emissions in the MENA region during 2003-2021?
- 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 the existing literature, this study deliberates the following hypotheses:

- ICT is expected to increase carbon dioxide emissions.
- Economic growth (GDP) in the MENA region, which is 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 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.
- Institutional quality and Financial Development are expected to reduce carbon dioxide emissions.

The remainder of this paper is organized 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 this study. Section 4 presents and discusses the results, drawing comparisons with the existing literature to highlight significant insights. Finally, Section 5 summarizes the main findings and offers practical policy recommendations to effectively address the identified challenges.

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 while reducing its environmental impact. Ebaidalla & Abusin (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 to 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 showed 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. The results show a strong positive effect of ICT on emissions in lower-quantile countries. However, this effect weakens in higher quantile countries. This implies that ICT does not always increase emissions as countries develop.

Additionally, Si & Rahman (2024) examined 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, globalization, renewable energy, and the quality of institutions affect 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, harms the environment. Timchenko et al. (2024) studied the global impact of the ICT sector. They found that this sector is responsible for approximately 4% of the world's greenhouse gas emissions. This is mainly due to high ICT consumption and the 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 the tourism and trade sectors. 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. The 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 effects of ICT and technological innovation on environmental quality in 34 Asian developing nations from 1990 to 2018. The 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. The findings show that ICT and economic growth increase emissions, whereas 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 the net effects are influenced by various factors, including economic conditions, energy practices, and the specific contexts of each country Hamrouni et al. (2025). 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. The findings show that ICT and renewable energy significantly reduce emissions, whereas economic growth and financial development increase them. Linghu et al. (2024) studied how ICT affects carbon dioxide emission efficiency in 30 Chinese provinces from 2008 to 2019. They found that a 10% increase in the ICT development index led to a 0.11% increase in energy efficiency, which helped lower emissions.

While the impact of ICT on carbon dioxide emissions has been extensively studied, a significant research gap remains in the MENA region. Existing literature often examines ICT's effect of ICT in isolation, overlooking its interplay with critical regional factors such as institutional quality (e.g., governance effectiveness and regulatory frameworks) and population dynamics (e.g., urbanization and demographic shifts). These factors are particularly relevant in the MENA context, where varying levels of institutional stability and rapid population growth present both challenges and

opportunities. This study addresses this gap by adopting a comprehensive approach that investigates 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, including rapid digital adoption, fluctuating economic conditions, and significant sociopolitical shifts.

These dynamics are likely to influence the relationship between ICT and environmental outcomes. However, prior research has largely overlooked these evolving interactions, leaving a critical gap in understanding how the role of ICT in emissions has evolved in response to regional changes.

MATERIALS AND METHODS

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.

GDP measures economic growth, expressed in trillions of dollars and adjusted for purchasing power parity (PPP). The variable population was 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 the UNCTAD (2024), the ICT index evaluates the accessibility and integration of communication systems, including fixed-line and mobile phone users, Internet access, and server security. As illustrated in Fig. 1, ICT index shows strong digital adoption and use in the MENA region.

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.

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

The descriptive statistics reveal significant disparities among the 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 ranged 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 observed considerable disparities in the population. This variation influences energy consumption, as countries with larger populations generally have higher energy demands, which increases carbon dioxide emissions. Similarly, 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 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	WDI (2023)
Population	Pop	Total number of inhabitants	
Financial Development	FD	index	IMF2021))
ICT	ICT	Index	ITU (2024)
Institutions	INST		UNCTAD (2024)

* MMt: Million Metric Tons. ** QBTU:.. Quadrillion British Thermal Units

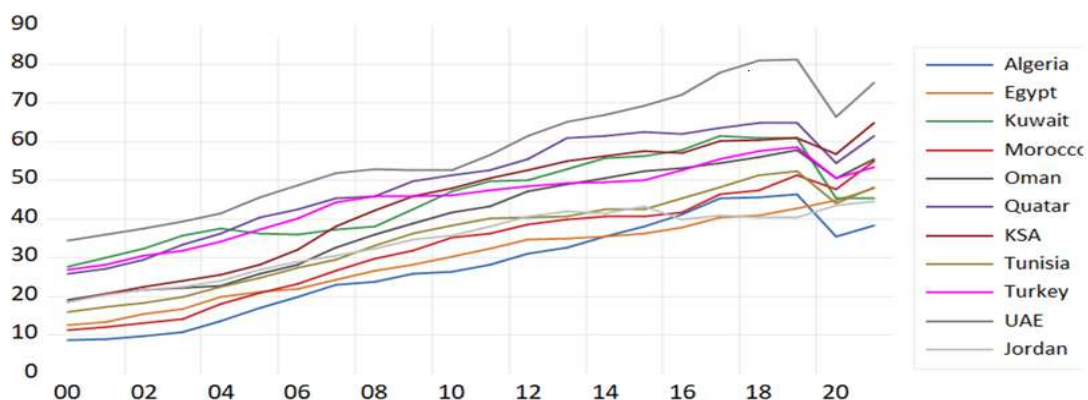


Fig. 1: ICT index Trends in MENA Countries (2003-2021).

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, and access to finance.

Methods

Cross-sectional dependence (C-SD) test: We analyzed cross-sectional dependence (C-SD) to identify correlations between variables and ensure reliable results. We used 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 panel units. The results of the C-SD test, conducted using the Pearson test, yielded a t-statistic of -0.0465 and a probability of 0.9629. This confirms that the application of first-generation panel unit root tests (PURT) is appropriate and is thus justified.

Panel unit root tests (PURT): Before testing the effects of the different explanatory variables on CO₂ emissions and to avoid biased results, we used the Augmented Dickey-Fuller

Table 3: Panel Unit Root Tests (PURT).

ADF	At level	lnCO ₂	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(lnCO ₂)	d(lnGDP)	d(lnEC)	d(lnPOP)	d(lnINST)	d(lnICT)	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	lnCO ₂	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(lnCO ₂)	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

(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 not all variables are 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 variables.

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 the variables. These tests are divided into two categories: the intra-dimension panel, which consists of four tests (Panels v, rho, PP, and ADF), and the inter-dimension group, which includes three tests (Panels rho, PP, and 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 indicate a significant level of cointegration. In the interdimension 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 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.

Model

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

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

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).

$$\ln CO2_{it} = +\alpha_i$$

Table 4: Pedroni cointegration test results.

Test	Panel (within-dimension)				Group (between-dimension)		
	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

$$+ \sum_{j=1}^{p-1} \beta_{1ij} \ln CO2_{it-j} + \sum_{j=0}^{q-1} \beta_{2ij} \ln GDP_{it-j} + \sum_{j=0}^{q-1} \beta_{3ij} \ln ICT_{it-j} + \sum_{j=0}^{q-1} \beta_{4ij} \ln NRE_{it-j} + \sum_{j=0}^{q-1} \beta_{5ij} \ln INST_{it-j} + \sum_{j=0}^{q-1} \beta_{6ij} \ln POP_{it-j} + \sum_{j=0}^{q-1} \beta_{7ij} \ln FD_{it-j} + \epsilon_{it} \dots(2)$$

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

$$\Delta \ln CO2_{it} = +\alpha_i + \theta_{1i} \ln CO2_{it-1} + \theta_{2i} \ln GDP_{it-1} + \theta_{3i} \ln ICT_{it-1} + \theta_{4i} \ln NRE_{it-1} + \theta_{5i} \ln INST_{it-1} + \theta_{6i} \ln POP_{it-1} + \theta_{7i} \ln FD_{it-1} + \sum_{j=1}^{p-1} \delta_{1ij} \Delta \ln CO2_{it-j} + \sum_{j=0}^{q-1} \delta_{2ij} \Delta \ln GDP_{it-j} + \sum_{j=0}^{q-1} \delta_{3ij} \Delta \ln ICT_{it-j} + \sum_{j=0}^{q-1} \delta_{4ij} \Delta \ln NRE_{it-j} + \sum_{j=0}^{q-1} \delta_{5ij} \Delta \ln INST_{it-j} + \sum_{j=0}^{q-1} \delta_{6ij} \Delta \ln POP_{it-j} + \sum_{j=0}^{q-1} \delta_{7ij} \Delta \ln FD_{it-j} + v_{it} \dots(3)$$

The terms in levels represent the long-term effects, while the 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 the short- and long-term effects. Third, it works well even with small sample sizes, making it suitable for our study, which includes only 11 countries.

RESULTS AND DISCUSSION

To achieve the objective of this study, we utilized 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 results 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 ICT is associated with a 0.094% increase in carbon dioxide emissions in the short term and a 0.112% increase 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. As shown in Fig. 2, the period 2003-2021 is marked by a high-pitched increase in CO₂ emissions in the MENA region.

Particularly, 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 the rising carbon dioxide emissions. Additionally, Fig. 3 attests that the MENA region is characterized by significant ICT development during this period.

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 negative and 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 the degradation of the environment.

Our findings regarding the positive effect of ICT on carbon dioxide emissions align with those of previous studies that report similar results (Ebaidalla & Abusin 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, in both the short and long terms. This effect arises because economic growth drives energy consumption, particularly in the industrial sector. Our results align with those of numerous studies that have similarly shown a positive relationship between GDP and carbon dioxide emissions.

Estimates 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 terms. 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. 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

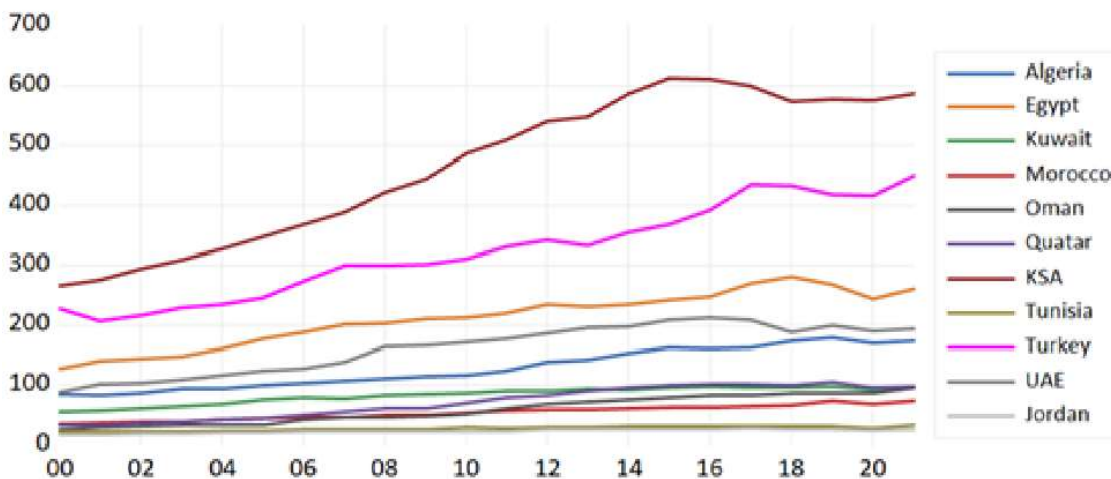


Fig. 2: CO₂ Emission Trends in MENA Countries in Million Metric Tons (2003-2021).

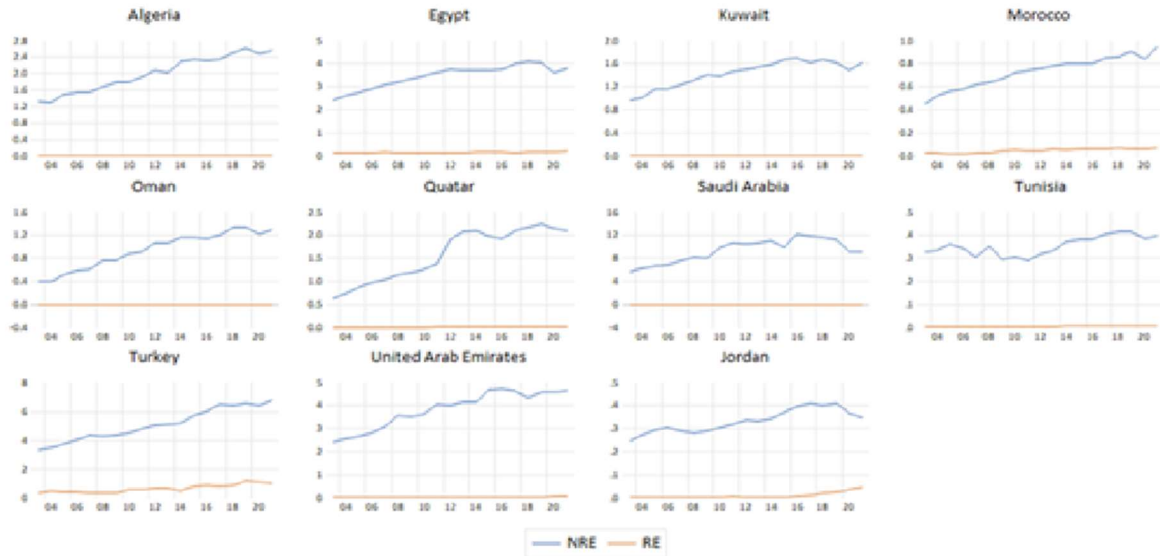


Fig. 3: Trends in Renewable and Non-Renewable Energy consumption (in QBTU) in MENA Countries (2003-2021).

to satisfy consumption, transportation, and housing needs, particularly as lifestyles change owing 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.

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 ICT's positive impact on carbon dioxide emissions. This suggests that the increasing use of ICT, when coupled with population growth, amplifies its negative effects on the environment.

This result can be attributed to several factors. As more people use ICT, the demand for energy-intensive data centers increases, which typically depend on fossil fuels such as coal and oil for power. Additionally, population growth fuels urbanization, resulting in higher ICT consumption in cities. Furthermore, the surge in online shopping promotes increased consumerism, leading to greater production and electronic waste, both of which contribute significantly to carbon dioxide emissions. The findings regarding the effects of population and non-renewable energy align with the 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 but statistically insignificant relationship with carbon dioxide emissions in the MENA region, both in the short and long terms. 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 in the MENA region. Although 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.

CONCLUSIONS

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, 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 the reduction of these emissions. Based on these findings, a set of policy recommendations can be formulated to mitigate emissions and promote sustainable development in the region. First, it is important to combine ICT with plans that support renewable energy. They need to invest more in renewable sources, such as solar, wind, and geothermal energy. This will help decrease the reliance on fossil fuels and lower carbon dioxide emissions. Second, as

Table 5: PMG-ARDL estimates.

Dependent variable: LCO ₂			
Long Run			
	Specification 1	Specification 2	Specification 3
LGDP	0.203222*** (2.757)	0.165805** (2.008)	0.204408*** (2.683)
NRE	0.251256*** (5.829)	0.261431*** (6.792)	0.254897*** (5.701)
LPOP	0.300516*** (3.088)	0.287178*** (2.663)	0.209046** (2.253)
LFD	-0.092170 (-0.833)	0.031127 (0.249)	-0.072165 (-0.639)
LICT	0.112689** (2.398)	1.587275*** (8.062)	
LINST	-1.704598*** (-11.963)		-1.711333*** (-11.840)
LICTINST		-1.505461*** (-7.492)	
LICTP			0.091966** (2.177)
Short Run			
	Specification 1	Specification 2	Specification 3
ECT ₋₁	-0.186053* (-1.860)	-0.167700* (-1.722)	-0.185903* (-1.886)
D(LGDP)	0.363388** (2.143)	0.302285** (1.989)	0.356118** (2.123)
D(NRE)	0.294048** (2.138)	0.299680** (1.856)	0.292587** (2.071)
D(LPOP)	0.528629** (2.232)	0.966377*** (2.883)	0.711057* 1.765782
D(LFD)	-0.042621 (-0.424)	-0.100949 (-0.870)	-0.043955 (-0.424)
D(LICT)	0.094176* (1.676)	-0.061633 (-0.318)	
D(LINST)	0.106273 (0.803)		0.105871* (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 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, such as environmental taxes and financial incentives. These actions will encourage the adoption of green technologies and help create a balance between economic growth and environmental protection. Third, MENA countries should strengthen education and training programs to reduce ICT pollution. These programs should focus on minimizing waste,

reducing reliance on non-renewable energy sources, and promoting sustainable practices and cleaner technologies in the ICT sector. Fourth, because economic growth contributes to emissions, MENA countries must 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 and support sustainable growth. Finally, given the positive impact of institutions and their helpful interaction with ICT in reducing emissions, MENA countries must strengthen the

role of institutions in enforcing environmental regulations. Improving these institutions will help implement regulations more effectively, leading to lower pollution levels.

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

ACKNOWLEDGEMENT

This work was supported and funded by the Deanship of Scientific Research at Imam Mohammad Ibn Saud Islamic University (IMSIU) (grant number IMSIU-DDRSP2502).

REFERENCES

- Adebayo, T.S., Agyekum, E.B., Altuntaş, M., Khudoyqulov, S., Zawbaa, H.M. and Kamel, S., 2022. Does information and communication technology impede environmental degradation? Fresh insights from non-parametric approaches. *Heliyon*, 8(3), p.e09108. DOI
- Akwasi, G.B., Benjamin, A., Bekun, F. and Asongu, S., 2022. Can information and communication technology and institutional quality help mitigate climate change in E7 economies? An environmental Kuznets curve extension. *Journal of Economic Structures*, 11(3), pp.200-220. DOI
- Briglauer, W., Köppl-Turyňa, M., Schwarzbauer, W. and Bittó, V., 2023. Evaluating the effects of ICT core elements on CO₂ emissions: Recent evidence from OECD countries. *Telecommunications Policy*, 47(8), p.102581.
- Ebaidalla, E.M. and Abusin, S., 2022. The effect of ICT on CO₂ emissions in the GCC countries: Does globalization matter? *International Journal of Energy Economics and Policy*, 12(6), pp.56-66.
- Hamrouni, D., Hasni, R. and Ben Jebli, M., 2025. The impact of economic complexity in trade, technology, and research on CO₂ emissions: evidence from OECD countries. *Environmental Modeling & Assessment*, pp.1-18.
- IMF 2021. International Monetary Fund Annual Report. Retrieved from <https://www.imf.org/external/pubs/ft/ar/2021/eng/downloads/>
- ITU 2024. Measuring digital development. ICT Development Index. Retrieved from https://www.itu.int/hub/publication/d-ind-ict_mdd-2024-3/
- Kahouli, Z., Hasni, R. and Jebli, M.B., 2025. Analyzing the influence of structural changes on CO₂ emissions in OECD countries: Employing panel cointegration techniques. *International Journal of Renewable Energy Development*, 14(1), pp.168-179. DOI
- Kim, S., 2022. The effects of information and communication technology, economic growth, trade openness, and renewable energy on CO₂ emissions in OECD countries. *Energies*, 15(7), p.2517. DOI
- Lee, H.S., Yap, L.T., Lee, S.Y. and Har, W.M., 2024. The impacts of ICT and innovation on carbon dioxide emissions in G20 countries. *IOP Conference Series: Earth and Environmental Science*, 1303(1), p.012011. DOI
- Linghu, J., Wojewodzki, M. and Cheong, T.S., 2024. Effects of information and communication technology on total-factor carbon emission efficiency and the health co-benefits. *Frontiers in Public Health*, 11, p.1301627.
- Onyeneke, R.U., Chidiebere-Mark, N.M. and Ayerakwa, H.M., 2024. Impact of information and communication technologies and renewable energy consumption on carbon emissions in Africa. *Carbon Research*, 3(1), p.53. DOI
- Pesaran, M.H., Shin, Y. and Smith, R.J., 1996. Testing for the existence of a long-run relationship. *Cambridge Working Papers in Economics*, 22(4), pp.1-35. Faculty of Economics, University of Cambridge.
- Pesaran, M.H., Shin, Y. and Smith, R.J., 2001. Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics*, 16(3), pp.289-326. DOI
- Raheem, I.D., Tiwari, A.K. and Balsalobre-Lorente, D., 2020. The role of ICT and financial development in CO₂ emissions and economic growth. *Environmental Science and Pollution Research*, 27(2), pp.1912-1922. DOI
- Si, H. and Rahman, Z.U., 2024. Embracing the digital revolution: Examining the relationship between ICT adoption and carbon emissions in the Persian Gulf. *PLOS ONE*, 19(6), p.e0304088. DOI
- Su, J., Wang, W. and Tang, S., 2023. The spatial spillover effect of ICT development level on regional CO₂ emissions. *Scientific Reports*, 13(1), p.7690. DOI
- Tahsin, J., 2022. The effects of ICT and technological innovation on environmental quality: Evidence from Asian developing countries. *International Journal of Management, Accounting & Economics*, 9(1), pp.1-20. DOI
- Timchenko, A., Kucheva, I. and Silakova, L., 2024. Assessing the negative impact of the IT sector on the environment: A call for sustainable solutions. *E3S Web of Conferences*, 474, p.03026. DOI
- UNCTAD 2024. Digital Economy Report 2024. Retrieved from <https://unctad.org/publication/digital-economy-report-2024>
- Wen, Y., Shabbir, M.S., Haseeb, M., Kamal, M., Anwar, A., Khan, M.F. and Malik, S., 2022. The dynamic effect of information and communication technology and renewable energy on CO₂ emission: Fresh evidence from panel quantile regression. *Frontiers in Environmental Science*, 10, p.953035. DOI
- WDI 2023. World Development Indicators. Retrieved from <https://databank.worldbank.org/source/world-development-indicators>
- Zeeshan, Z.S., Zhilin, Q., Mabrouk, F., Ramirez-Asis, E., M Alzoubi, H., Hishan, S.S. and Michel, M., 2023. Empirical linkages between ICT, tourism, and trade towards sustainable environment: Evidence from BRICS countries. *Economic Research—Ekonomika Istraživanja (Economic Research)*, 36(2), pp.1-20. DOI