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The Role of Productive Capacity Pillars in CO_2 Emissions: How does their Interaction Matter in the MENA Region?

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ABSTRACT

Analysis of productive capacity is essential for inclusive and sustainable growth and can influence environmental quality. This is particularly relevant for the MENA region, characterized by high fossil fuel dependence and climate vulnerability. This study fills a gap by analyzing the direct effects and interactions of the three productive capacity pillars on CO_2 emissions in MENA. It examines the impact of natural capital (NC), information and communication technology (ICT), and institutional quality (IQ) on CO_2 emissions (2000-2021) using the ARDL-PMG model and causality analysis. Control variables include GDP, renewable, and non-renewable energy consumption. Results show that ICT and IQ reduce emissions, but their interaction with NC increases them due to oil dependence. However, ICT-IQ interaction offers potential for emission reduction. GDP growth and non-renewable energy increase emissions, while underdeveloped renewable energy helps reduce them. Our findings provide insights for policymakers to enhance productive capacity while promoting sustainable development.

Keywords: Productive Capacities, CO_2 Emissions, ARDL-PMG, MENA
JEL Classifications: Q56, O131

1. INTRODUCTION

According to UNCTAD (2006), productive capacity is essential for the production of goods and services and for promoting inclusive and sustainable growth. Gnangnon (2022) and Giombini et al. (2023) highlight their key role in strengthening economic resilience and promoting balanced growth by reducing poverty, creating jobs and limiting dependence on natural resources. UNCTAD (2024) adds that their consolidation helps countries to escape the middle-income trap, increase their resilience to external shocks and reduce their structural vulnerabilities. These issues are critical for the MENA region, which is heavily dependent on fossil fuels: the oil sector accounts on average for 55% of real GDP in exporting countries and 31% in the GCC, while GDP per capita fluctuates with oil prices (World Bank, 2024). This highlights the urgent need to build productive capacity in order to diversify the economy and ensure lasting stability. The development of productive capacity in the MENA region must necessarily take into account environmental constraints, which pose a major challenge in the face of critical issues such as water scarcity and the depletion of arable land, exacerbated by rapid urbanisation and heavy dependence on fossil fuels (Abumoghli and Goncalves, 2020). The World Bank's MENA Climate Change Roadmap (2021-2025) highlights that the region is home to five of the world's ten largest emitters of CO_2 per capita, namely Qatar, Kuwait, the United Arab Emirates, Bahrain and Saudi Arabia. MENA is also the only region where growth in CO_2 emissions per capita has outpaced growth in average income. Under a business-as-usual scenario, greenhouse gas (GHG) emissions could triple by 2060 compared to 2000 levels (World Bank, 2022). COP27 in Egypt and COP28 in the United Arab Emirates, two countries in the region, have raised political awareness of the climate emergency. These issues are further complicated by the fact that the region faces persistent socio-economic crises such as poverty, unemployment and urban-rural inequalities, which make marginalized populations particularly vulnerable to climate impacts (Hallegatte, 2016). An integrated approach aimed at strengthening productive capacities to promote sustainable economic growth and reduce poverty must therefore take environmental challenges into account.

In order to measure productive capacities in the form of an index, UNCTAD (2020) rely on the three pillars defined by UNCTAD (2006) directly related to the quality of the environment. For example, natural capital (NC) represents the first pillar, i.e. productive resources. The impact of NC is ambivalent, as it is both an economic driver and a source of environmental pressure (Azam et al., 2023; Mahmood, 2023; Bergougui and Murshed, 2023; Raihan et al., 2024; Amer et al., 2024). In MENA, hydrocarbons play a central role: on average, fossil fuels account for 50% of exports from the GCC, Iraq, Libya and Iran. The region's share of global oil production is expected to rise from 35% to 44% by 2030, driven by population and economic growth (World Bank, 2022).

The second pillar, entrepreneurial capabilities, is embodied by information and communication technologies (ICT). ICTs' environmental impact is mixed. While they reduce CO_2 emissions through teleworking, smart cities and green technologies (Ben Jebli et al., 2024; Kahouli et al., 2025), they also stimulate economic growth, increasing energy consumption and e-waste (Chatti, 2021; Bildirici et al., 2022; Ebaidalla and Abusin, 2022; Awad, 2022). In July 2023, 66% of the population in North Africa used the internet, higher than the global average of 64.5%, while this rate reached 92% in the GCC countries (Mordor Intelligence, 2025). According to Cusolito et al. (2022), ICTs could increase GDP per capita by 40%, manufacturing productivity by 10% and tourism by 70% in the region, while reducing frictional unemployment and doubling female participation, provided that infrastructure, electronic payments and digital regulation are strengthened.

The third pillar, production linkages, is illustrated by the institutional quality (IQ). As Williamson (1989) and North (1990) have shown, the quality of institutions has a direct impact on economic growth. However, this growth can paradoxically increase CO_2 emissions by increasing energy demand (Abid, 2016; Nguyen et al., 2018; Ali et al., 2019; Arvin et al., 2022; Yang et al., 2022; Jahanger et al., 2023). Nevertheless, strong institutions and well-designed public policies remain essential to implement the stringent environmental regulations needed to reduce CO_2 emissions (Dridi et al., 2024). Thus, the institutional framework is both a lever for growth and a key tool for addressing challenges. According to the OECD (2024), improving the institutional framework in the MENA region is essential, especially in the face of declining oil reserves and the impacts of climate change.

A limited assessment of the direct environmental impacts of the factors reflecting the three pillars of productive capacity, namely NC, ICTs, and IQ, and a fragmented implementation of these factors risk leading to incoherent strategies, thereby hindering the development of productive capacity, which is essential for achieving integrated economic and environmental goals in the region. UNCTAD (2020) emphasises the interdependence of these pillars and their synergy, which is necessary for inclusive and sustainable growth. However, existing studies mainly focus either on the direct impact of the productive capacity index on environmental quality (Lin et al., 2024) or on the impact of variables reflecting the pillars of productive capacity on environmental quality (Lin et al., 2023), without considering their interactions. Thus, there is a major gap in the literature, particularly in the MENA context, regarding integrated approaches that take into account the interdependencies between the pillars of productive capacity and their influence on environmental quality.

This study fills this gap by examining the direct effects of the pillars (NC, ICT and institutional quality) and their interactions on CO_2 emissions in the MENA region between 2000 and 2021, using an ARDL-PMG model and causality analysis. To refine the estimates, control variables such as GDP (Grossman and Krueger, 1995), renewable and non-renewable energy (Dridi et al., 2024; Hamrouni et al., 2025) are included. This approach is particularly relevant as primary energy demand in the region is expected to double by 2030, while the region's share of global oil production is projected to increase from 35% to 44%, driven by population and economic growth (World Bank, 2022). To our knowledge, this study represents the first empirical analysis that simultaneously examines the direct and combined effects of variables representing the three pillars of productive capabilities with the aim of explaining CO_2 emissions.

The article is organized as follows: Section 2 provides a comprehensive literature review, while Section 3 details the data sources and methodology. Section 4 presents the empirical findings along with their critical analysis. Finally, Section 5 summarizes the key conclusions and discusses the policy implications.

2. LITERATURE REVIEW

In this literature review, we will examine the impact of three variables representing the three pillars of productive capacity on CO_2 emissions: NC and CO_2 emissions, ICT and CO_2 emissions, and IQ and CO_2 emissions.

2.1. Natural Capital and CO_2 Emissions

The impact of NC on CO_2 emissions remains a subject of debate, with empirical studies highlighting contrasting effects. On one hand, several studies emphasize the aggravating role of natural resource exploitation in environmental degradation. In the Asian context, Li et al. (2022) demonstrate that dependence on traditional resources, such as coal and forest rents, exacerbates CO_2. This trend is also observed in China by He et al. (2022), who quantify a 0.242% increase in emissions for every 1% rise in NC use. This positive relationship is also evident in Bangladesh, as reported by Raihan et al. (2024), who document a 0.04% increase in emissions for an equivalent rise in NC rents. Similarly, Tauseef Hassan et al. (2021) show that natural resource extraction in Pakistan leads to a significant increase in emissions, while Ling et al. (2021) find that negative shocks to these resources in China amplify CO_2 emissions. Beyond Asia, studies focusing on Europe and OECD countries underscore the detrimental impact of oil rents on the environment. Ahmadov et al. (2019) highlight that while resource abundance can sometimes support renewable energy adoption, oil rents hinder this transition, thereby exacerbating emissions and presenting governance challenges. Chen and Wang (2020) confirm this trend within the European Union, where dependence on natural resource rents is positively correlated with CO_2 emissions, without generating substantial income growth—thus underscoring the environmental costs of overexploitation. Quantitative analyses further reinforce these findings in the case of BRICS countries. Ullah et al. (2023) and Balcilar et al. (2023) establish a positive link between NC utilization and emissions, with an estimated 0.10% increase in CO_2 emissions in these countries and between 0.06% and 0.10% in sub-Saharan Africa for a 1% rise in resource exploitation. Similarly, Bergougui eand Murshed (2023) highlight the negative impact of NC on sustainable development, noting that a 1% increase in resource rents leads to a 0.113% decline in sustainable development in developing countries, particularly those reliant on fossil fuel exports. Similar observations emerge in Latin American economies. Raihan (2023) demonstrates that in Uruguay, natural resource rents, combined with economic growth and trade globalization, significantly contribute to rising CO_2 emissions. Likewise, Nathaniel et al. (2021), analyzing 18 Latin American and Caribbean countries, find that resource exploitation is a key driver of increasing emissions, although human capital can play a mitigating role. In GCC countries, Saqib et al. (2022) confirm the positive relationship between resource rents and CO_2 emissions, while Xiaoman et al. (2021) observe that a 1% increase in natural rents translates into higher emissions across the MENA region. Similar trends are noted in Morocco by Zhang et al. (2023), who measure a 0.242% rise in emissions for every 1% increase in natural rents. In Saudi Arabia, Mahmood (2023) further refines this analysis by emphasizing that oil and gas extraction increases carbon intensity, particularly through flaring, although a moderating effect is observed for emissions from the cement sector.

However, other studies indicate that under certain conditions, NC can contribute to reducing CO_2 emissions. Mehmood (2022) highlights a counterintuitive trend in Pakistan and India, where natural resource rents appear to decrease emissions—strongly contrasting with their aggravating effect in Bangladesh. This negative relationship is also reported in France by Azam et al. (2023), who stress that the increase in NC rents does not systematically lead to higher emissions, notably due to the growing role of alternative and nuclear energy. IQ emerges as a key factor in moderating this effect. Tufail et al. (2021) show that while natural resource rents and fiscal decentralization tend to independently increase emissions in OECD countries, strong institutions help temper this dynamic. A similar finding is established by Mahmood and Saqib (2022) in OPEC countries, where oil rents generally drive emissions higher, although technical and compositional effects can lead to specific reductions. From a broader perspective, Amer et al. (2024) emphasize that the effect of NC on emissions varies depending on governance and the institutional framework in place. Finally, Mehmood et al. (2022) identify an inverted U-shaped relationship in G-11 countries, suggesting that natural resource exploitation initially increases emissions but, at higher income levels, can contribute to their reduction—thus validating the environmental Kuznets curve hypothesis.

2.2. Institutional Quality and CO_2 Emissions

The imperative to mitigate climate change has driven extensive research into the determinants of CO_2 emissions, with IQ emerging as a pivotal factor. IQ influences environmental sustainability through governance mechanisms, regulatory frameworks, and economic interactions. However, empirical evidence on its impact remains inconclusive. While institutional improvements are generally linked to better environmental governance, some studies suggest that enhanced IQ may, under certain conditions, lead to higher emissions. For instance, Nguyen et al. (2018) and Ali et al. (2019) argue that stronger institutions can facilitate economic expansion, potentially increasing emissions in the short term. Similarly, Abid (2016) challenges the Environmental Kuznets Curve (EKC) hypothesis, indicating that rising GDP, often enabled by improved governance, can correlate with persistent emissions growth. Yang et al. (2022) further highlight how institutional frameworks addressing income inequality and resource management may inadvertently promote higher energy consumption. Beyond CO_2 emissions, Arvin et al. (2022) emphasize the broader sustainability impact of institutions, particularly in enhancing foreign aid effectiveness, reducing inequality, and improving resource governance.

Despite these complexities, a significant body of research underscores the mitigating role of IQ in emissions reduction. Empirical analyses across various regions consistently reveal a negative correlation between IQ and CO_2 emissions. For example, Bletsas et al. (2022) demonstrate that a 1% improvement in IQ leads to an estimated 0.05% decrease in emissions, highlighting the importance of robust governance. Stef et al. (2023) further emphasize the role of specific institutional attributes, such as the rule of law and control of corruption, in achieving emissions reductions across diverse countries. Similar conclusions are drawn by Amin et al. (2023), Cui et al. (2024) and Zhang et al. (2023), all of whom stress the critical role of effective governance in strengthening environmental regulations and promoting sustainable practices.

Moreover, IQ enhances the effectiveness of green policies and technologies. Kwakwa (2023) and Obobisa et al. (2022) show that robust IQ amplifies the impact of renewable energy adoption and green technological innovation on emissions reduction. Wang and Yang (2022) and Khan et al. (2022) confirm that the success of green technologies and renewable energy investments depends on strong institutional frameworks. The interaction between IQ and economic factors, such as financial development and foreign direct investment (FDI), also shapes environmental outcomes. Godil et al. (2020) find that the effect of IQ on emissions varies with financial development levels, while Adedoyin et al. (2022) suggest that improved governance mitigates emissions associated with FDI and economic growth. Bakhsh et al. (2021) explore the interplay between IQ, FDI, and technological innovation, reinforcing the idea that institutions serve as key mediators in determining environmental impact. Within the EKC framework, several studies provide insights into the evolving relationship between IQ and emissions. Mehmood et al. (2021) and Maduka et al. (2022) suggest that the impact of IQ follows a non-linear trajectory, initially contributing to emissions growth before facilitating reductions at higher development levels. Cui et al. (2024) further highlight the role of IQ in mitigating the environmental impacts of geopolitical risks and economic policy uncertainty, underscoring the importance of robust governance in addressing external shocks.

2.3. ICT and CO_2 Emissions

ICT have a dual impact on CO_2 emissions, capable of both increasing and reducing them depending on contextual factors such as economic structures, development levels, and policy frameworks, underscoring their complex role in environmental sustainability.

A significant body of research highlights ICT's potential to exacerbate emissions, particularly in developing economies. Gelenbe and Caseau (2015) demonstrated that ICT infrastructure increases energy consumption, despite its potential for emissions reduction in other areas. This finding is reinforced by Majeed (2018), who, in a study of 132 countries, found that ICT worsens environmental degradation in developing nations while promoting sustainability in developed ones. Similarly, Ebaidalla and Abusin (2022) identified a positive effect of ICT on emissions in Gulf Cooperation Council (GCC) countries, though globalization partially mitigates this impact. In Sub-Saharan Africa, Asongu (2018) reported that ICT reduces CO_2 emissions, while Awad (2022) found its environmental impact negligible. On a broader scale, Chatti (2021) emphasized that ICT increases emissions due to its reliance on electricity and its influence on the transportation sector. Raheem et al. (2020) and Bildirici et al. (2022) further confirmed that ICT investments in G7 countries drive economic growth but simultaneously elevate energy consumption and emissions.

Conversely, ICT also demonstrates significant potential to reduce emissions through efficiency improvements and sustainable innovations. Wang and Xu (2021) showed that internet use and human capital significantly lower emissions, particularly in high-income countries, a finding supported by Mirza et al. (2020), who highlighted ICT's role in fostering inclusive development. In GCC countries, Islam et al. (2023) reported a negative relationship between ICT and emissions, reinforcing its environmental benefits. Studies by Su et al. (2023) and Wang et al. (2023) in China found that ICT development reduces emissions but generates spatial spillover effects requiring careful management. Jahanger et al. (2023) emphasized ICT's role in improving environmental quality, particularly alongside nuclear energy, while Edquist and Bergmark (2024) observed that mobile broadband initially raises emissions but eventually leads to reductions, especially in high-income nations. Similarly, Shaaban-Nejad et al. (2022) confirmed ICT's statistically significant negative impact on global emissions, with stronger effects in OECD countries.

The relationship between ICT and emissions often follows a non-linear trajectory. Li et al. (2021) observed an inverted U-shaped relationship, where initial ICT expansion raises CO2 levels, but later stages contribute to efficiency gains. This aligns with findings by Atsu et al. (2021), who linked ICT and fossil fuel consumption to increased emissions in South Africa, and Arshad et al. (2020), who confirmed the Environmental Kuznets Curve (EKC) hypothesis in South and Southeast Asia. Faisal et al. (2020) and Anser et al. (2021) noted similar patterns in Asia and Europe, where ICT can both raise emissions and contribute to reductions through economic growth and policy interventions. Godil et al. (2020) found that ICT reduces emissions at lower quantiles but increases them at higher levels in Pakistan, while Zhou (2023) observed that ICT benefits nations facing ecological challenges but degrades environments in well-functioning ecosystems. Bieser et al. (2023) highlighted that the ICT sector contributes 1.5-4% of global emissions, primarily from end-user device production, and Tsimisaraka et al. (2023) emphasized the need for renewable energy to mitigate ICT's positive correlation with emissions in top emitter countries.

3. DATA, DESCRIPTIVE STATISTICS AND METHODOLOGY

3.1. Data

This research investigates the factors influencing CO_2 emissions across 14 MENA countries[1] from 2000 to 2021. It explores how CO_2 emissions are shaped by key economic and environmental variables, including GDP at constant prices, RE and NRE, NC, IQ, and ICT. Table 1 provides an overview of these variables, along with their abbreviations and data sources.

3.2. Descriptive Statistics

This section offers a descriptive analysis of the data to address the study's empirical objective. It outlines the maximum, minimum, and mean values of various indicators for the selected countries from 2000 to 2021. Table 2 displays the descriptive statistics for the analysis variables.

The descriptive statistics in Table 2 reveals significant variability in the data across the MENA region countries. CO_2 emissions (in million metric tons) have an average of 153.8, with a range from 12.09 (Lebanon) to 681.13 (Iran), showing substantial disparities in emissions between the countries. GDP (in constant 2015 USD) also varies widely, with an average of 205 billion USD, ranging from 16.2 to 1130 billion USD, highlighting significant economic inequalities. Regarding energy, renewable sources account for only 1.03% of the total energy on average, while non-renewable sources dominate at 2.60%, with values ranging from 0.17% in Saudi Arabia to 12.89% in Turkey. NC shows considerable dispersion, with an average of 46.37 and a standard deviation of 8.53, with the maximum observed in Morocco and the minimum in Jordan. The IQ index has an average of 51.26, with values ranging from 27.2 to 72.3, while the adoption of ICT ranges from 8.6 to 81.2, with an average of 40.49, highlighting disparities in access to this technology. In summary, these variables illustrate significant differences between the countries in the MENA region in terms of economic, environmental, and technological development. Figure 1 shows the evolution of the variables of interest introduced in our model. The overall trend of CO_2 emissions throughout the period reveals that Saudi Arabia (KSA) and Iran have the highest emissions. This can be attributed to their heavy reliance on fossil fuels, particularly oil, to support their economies. Turkey, Egypt,

1 Algeria, Bahrain, Egypt, Iran, Jordan, Kuwait, Lebanon, Morocco, Oman, Qatar, Saudi Arabia, Tunisia, Turkey, UAE.

and the United Arab Emirates (UAE) follow, with lower CO_2 emissions compared to the first two countries. These nations, while possessing significant economies, exhibit lower emission levels due to factors such as economic diversification, investments in renewable energy, and reduced fossil fuel consumption compared to Saudi Arabia and Iran.

The Natural Capital evolution of shows that Saudi Arabia has relatively high natural capital, with the highest curve among the countries studied. This is explained by the country's wealth of natural resources, particularly its vast oil reserves and other resources linked to the oil industry, as well as investments in infrastructure projects such as water desalination and the exploitation of agricultural lands. In contrast, Lebanon shows a much lower natural capital curve, reflecting its limited natural resources and the challenges related to their management. Due to its smaller geographical size and environmental issues such as deforestation and pollution, the country has fewer resources to exploit. This difference highlights not only the natural wealth of these two countries but also the economic and environmental challenges associated with managing and preserving natural capital.

The Institutional quality trend reveals that the United Arab Emirates (UAE) and Qatar have the highest curves, indicating strong institutional quality in these countries. This can be attributed to their stable governments, effective resource management, and policies that promote transparency, investment in infrastructure, and economic development. These countries

Table 1: Definitions of variables

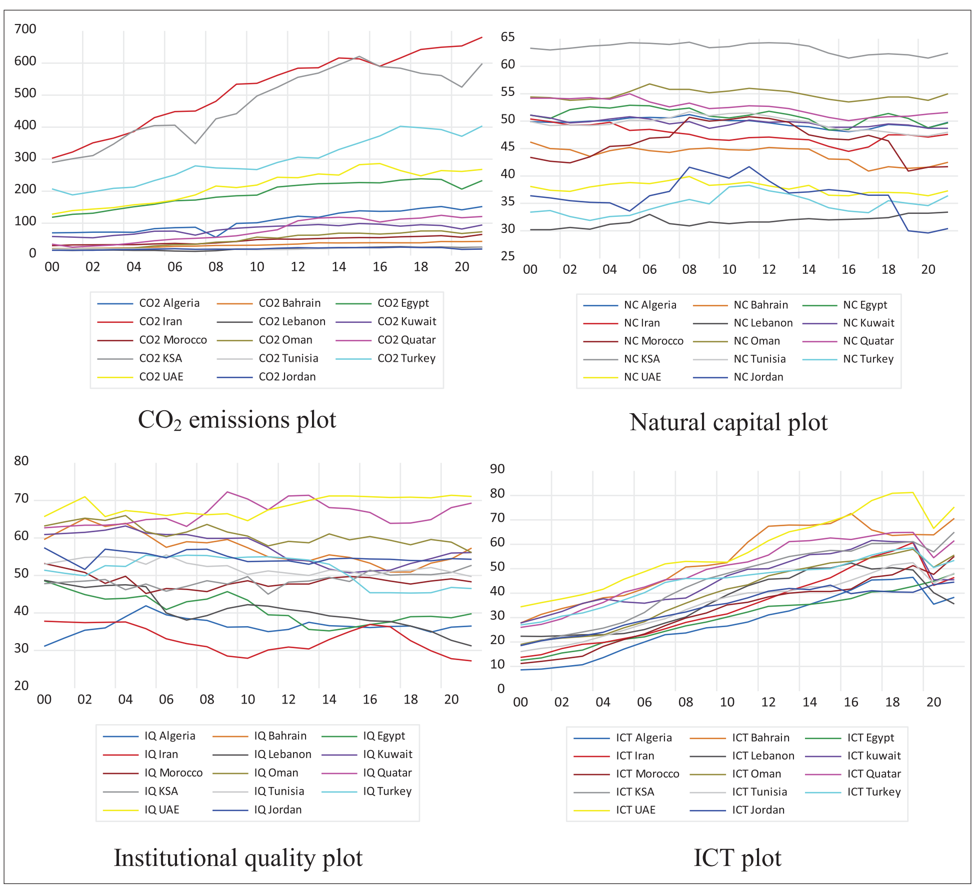
Variables	Description	Source
CO_2	CO_2 emission (MMt)	EIA, 2024
GDP	Gross domestic product (constant 2015 USD)	WDI, 2024
RE	Renewable energy	EIA, 2024
NRE	Non-renewable energy	EIA, 2024
NC	Natural capital	UNCTAD, 2024
IQ	Institutional quality	UNCTAD, 2024
ICT	Information and communication technology	UNCTAD, 2024

Table 2: Descriptive statistics

Statistics	CO_2	GDP	RE	NRE	NC	IQ	ICT
Mean	153.8000	2.05E+11	1.027041	2.596118	46.36526	51.26266	40.48864
Maximum	681.1340	1.13E+12	1.477394	12.89341	64.40000	72.30000	81.20000
Minimum	12.09081	1.62E+10	0.997703	0.166152	29.60000	27.20000	8.600000
Std. Dev.	169.8448	2.19E+11	0.069033	2.989079	8.529447	10.79091	15.15105

CO_2: Carbon dioxide emissions (MMT), GDP: Gross domestic product (constant 2015 USD), RE: Renewable energy, NRE: Non-renewable energy, NC: Natural capital, IQ: Institutional quality, ICT: Information and communication technologies

Figure 1: Evolution of key environmental and economic variables in the MENA region



have also implemented institutional reforms that enhance investor confidence and economic stability. In contrast, Iran shows the lowest curve in terms of institutional quality, reflecting political, economic, and social challenges that may hinder good governance. Issues such as corruption, political instability, and international sanctions negatively impact the effectiveness of its institutions and their ability to foster sustainable growth.

Finally, ICT evolution shows that all MENA countries are experiencing growth in the use of these technologies, although this growth occurs at varying levels. This trend is largely driven by increased internet access, the digitalization of government and commercial services, as well as innovations in telecommunications and mobile internet. Investments in digital infrastructure, public policies supporting digital transformation, and the adoption of new technologies have contributed to this expansion across the region. However, notable differences exist between countries, with some, such as the United Arab Emirates (UAE) and Qatar, showing particularly high levels of ICT adoption due to visionary initiatives in smart cities and technological innovation, while other countries in the region are also benefiting from this dynamic, but at a slower pace and with less intensity.

3.3. Methodology

This study analyzes the impact of NC, IQ, and ICT on CO_2 emissions in MENA countries from 2000 to 2021. To improve accuracy, GDP and energy consumption (renewable and non-renewable) are included as control variables. Panel cointegration techniques are applied to examine long-term relationships while accounting for non-stationarities in time series data. The methodology follows four steps: Assessing cross-sectional dependence, determining integration orders using panel unit root tests, and estimating relationships through the PMG-ARDL technique developed by Pesaran et al. (1999).

The empirical framework is represented by the following relationship:

$$CO_{2it} = f(GDP_{it}, RE_{it}, NRE_{it}, NC_{it}, IQ_{it}, ICT_{it}) \quad (1)$$

Where: CO_2: Carbon dioxide emission, GDP: Gross domestic product, RE: Renewable energy, NRE: Non-renewable energy, NC: Natural capital, IQ: Institutional quality, ICT: Information and communication technologies. Taking into account the specifications of the selected variables, we formulate the CO_2 emission function using the logarithmic transformation as follows:

$$LNCO_{2it} = \alpha_1 LNGDP_{it} + \alpha_2 LNRE_{it} + \alpha_3 LNNRE_{it} + \alpha_4 LNNC_{it} + \alpha_5 LNIQ_{it} + \alpha_6 LNICT_{it} + \varepsilon_{it} \quad (2)$$

Where $LN(.)$ indicates the natural logarithmic form; $i = 1, \ldots N$ and $t = 1, \ldots T$ indicate the country and period respectively. The coefficients α_i; $i = 1,\ldots,6$ represent the parameters associated with the independent variables; α_0 denotes the specific fixed effect and ε_{it} is the error term.

To study the interactions between certain variables, equation (2) is extended into three equations. Equations (3) and (4) respectively introduce the interactions between NC and institutional quality ($LNNC_{it} \times LNIQ_{it}$), as well as between NC and ICT ($LNNC_{it} \times LNICT_{it}$). Finally, the last equation (5) examines the interactions between IQ and ICT ($LNIQ_{it} \times LNICT_{it}$). These extensions allow for a better understanding of how these variables interact and influence CO_2 emissions in MENA countries, considering the potential effects of their mutual relationships on the model's results. In the following, we present the different equations introducing these interactions:

$$LNCO_{2it} = \alpha_0 + \alpha_1 LNGDP_{it} + \alpha_2 LNRE_{it} + \alpha_3 LNNRE_{it} + \alpha_4 LNIQ_{it} + \alpha_5 LNICT_{it} + \delta_1 (LNNC_{it} \times LNIQ_{it}) + v_{it} \quad (3)$$

$$LNCO_{2it} = \alpha_0 + \alpha_1 LNGDP_{it} + \alpha_2 LNRE_{it} + \alpha_3 LNNRE_{it} + \alpha_4 LNIQ_{it} + \alpha_5 LNICT_{it} + \delta_2 (LNNC_{it} \times LNIQ_{it}) + v_{it} \quad (4)$$

$$LNCO_{2it} = \alpha_0 + \alpha_1 LNGDP_{it} + \alpha_2 LNRE_{it} + \alpha_3 LNNRE_{it} + \alpha_4 LNNC_{it} + \alpha_5 LNIQ_{it} + \delta_3 (LNIQ_{it} \times LNICT_{it}) + v_{it} \quad (5)$$

δ_j; $j = 1, \ldots 3$, represent the parameters associated with the interaction terms ($LNNC_{it} \times LNIQ_{it}$), ($LNNC_{it} \times LNICT_{it}$) and ($LNIQ_{it} \times LNICT_{it}$) used in equations (3) to (5) and v_{it} is the error term.

These interactions make it possible to examine not only the direct effects of the independent variables on CO_2 emissions, but also their combined effects, which can provide a better understanding of the underlying mechanisms. Estimates of the coefficients associated with these interaction terms are interpreted to assess the impact of the complex relationships between the explanatory variables and CO_2 emissions.

The results of the cross-sectional dependence (CD) tests are presented in Table 3. These tests reject the null hypothesis of cross-sectional independence, except for the Breusch-Pagan chi-square test. Therefore, we opt for the first-generation panel unit root test (PURT). To assess the order of integration of each variable, two PURT methods are used: The Augmented Dickey-Fuller (Dickey and Fuller, 1979) test and the Phillips-Perron (Phillips and Perron, 1988) test.

4. RESULTS AND DISCUSSION

The results presented in Table 4 show that all the tests performed indicate that the selected variables exhibit non-stationarity at the level. However, when they are differentiated once, they show stationarity. Therefore, it is clear that the variables are integrated of

Table 3: Cross-sectional dependence test results

Test	Statistic (%)	d.f.	Prob.
Breusch-Pagan Chi-square	113.0654	91	0.0584
Pearson LM normal	0.597845		0.5499
Pearson CD normal	0.034169		0.9727
Friedman Chi-square	16.44156	21	0.7444
Frees Q	−0.022325		
Asymtotic critical values*	1	0.222533	
	5	0.153662	
	10	0.117399	

*Frees (1995) Q distribution

Table 4: Panel unit root test results

	PP						
At level	**LNCO$_2$**	**LNGDP**	**LNRE**	**LNNRE**	**LNNC**	**LNIQ**	**LNICT**
t-Stat	0.9964	1.0000	0.9932	0.9924	0.4958	0.2748	0.9999
Prob.	1.0000	0.9991	0.4123	1.0000	0.3564	0.2599	0.9935
	At 1st Diff						
	d (LNCO$_2$)	**d (LNGDP)**	**d (LNRE)**	**d (LNNRE)**	**d (LNNC)**	**d (LNIQ)**	**d (LNICT)**
t-Stat	0.0013	0.4385	0.0017	0.0059	0.0004	0.0005	0.2085
Prob.	0.0087***	0.0186**	0.0010***	0.0344**	0.0011***	0.0271**	0.0028***
ADF							
At level	LNCO$_2$	LNGDP	LNRE	LNNRE	LNNC	LNIQ	LNICT
t-Stat	0.9964	0.9788	0.9935	0.9978	0.4533	0.2642	0.9880
Prob.	0.8619	0.9995	0.3673	1.0000	0.3776	0.3720	0.9947
	At 1st Diff						
	d (LNCO$_2$)	**d (LNGDP)**	**d (LNRE)**	**d (LNNRE)**	**d (LNNC)**	**d (LNIQ)**	**d (LNICT)**
t-Stat	0.0012	0.4422	0.0019	0.0059	0.0004	0.0004	0.1309
Prob.	0.2038	0.0139**	0.0004***	0.4004	0.0009***	0.0292***	0.2010
Decision	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)	I (1)

"***" and "**" indicate statistical significance at the 1% and 5%, respectively

order one, denoted I(1), and that cointegration can be tested with. To examine cointegration, we can use the cointegration statistics proposed by Pedroni (1999; 2001).

The results of the cointegration tests are presented in Table 5. Of the seven statistics from the Pedroni tests, four suggest the presence of cointegration, supporting the alternative hypothesis. Similarly, both the Kao and Westerlund cointegration tests reject the null hypothesis of no cointegration. Therefore, based on these results, the existence of long-run cointegration can be confirmed. Given that cointegration has been established in the long run, we can estimate the model presented in our paper using the PMG-ARDL approach. The results of the estimations are presented in Table 6.

The results of the PMG-ARDL model estimation show significant relationships between the variables and CO_2 emissions, both in the long and short term. In the long run, GDP has a positive and significant effect on CO_2 emissions with a coefficient of 0.328, indicating that economic growth leads to an increase in emissions. Conversely, renewable energy consumption has a negative and significant effect on CO_2 emissions. In fact, a 1% increase in renewable energy leads to a 0.63% reduction in emissions. These results are in line with those found by Li et al. (2022), but contradict those found by Hasni et al. (2023) in the case of APEC countries, where renewable energy has not yet led to a significant reduction in CO_2 emissions. Non-renewable energy consumption has a positive and significant effect on CO_2 emissions. In fact, a 1% increase in non-renewable energy consumption leads to a 0.893% increase in CO_2 emissions, reflecting the higher emissions associated with the use of fossil fuels. These results are consistent with the findings of Ben Jebli et al. (2024). NC also has a positive and significant effect on CO_2 emissions. A 1% increase in NC leads to a 0.4% increase in CO_2 emissions.

These results are consistent with those obtained by Ahmadov et al. (2019), Chen and Wang (2020) and Tauseef Hassan et al. (2021), but contrast with those obtained by Mehmood (2022) and Bergougui and Murshed (2023). Both IQ and ICT diffusion

Table 5: Panel cointegration tests results

Pedroni cointegration tests				
Alternative hypothesis: Common AR coefs. (within-dimension)				
			Weighted	
Within-dimension	**Statistic**	**Prob.**	**Statistic**	**Prob.**
Panel v-statistic	−0.672758	0.7494	−1.764260	0.9612
Panel rho-statistic	1.666055	0.9521	2.400765	0.9918
Panel PP-statistic	−8.784120	0.0000***	−5.206885	0.0000***
Panel ADF-statistic	−4.576729	0.0000***	−3.340399	0.0000***
Alternative hypothesis: individual AR coefs. (between-dimension)				
	Statistic	**Prob.**		
Group rho-statistic	3.955071	1.0000		
Group PP-statistic	−9.587456	0.0000***		
Group ADF-statistic	−4.087017	0.0000***		
Westerlund cointegration test				
	Statistic	**P-value**		
Variance ratio	−1.3150	0.0943*		
Kao cointegration test				
	t-statistic	**Prob.**		
ADF	−9.41253	0.0000***		

"***" and "*" indicate statistical significance at the 1% and 10%, respectively

contribute to reducing emissions. A 1% increase in IQ leads to a 0.510% reduction in emissions, as confirmed by Anwar et al. (2021) and Bletsas et al. (2022). Meanwhile, a 1% increase in ICT adoption results in a 0.221% reduction in emissions, as found by Majeed (2018) and Shaaban-Nejad et al. (2022).This shows that better institutions and more advanced technologies can play an important role in reducing emissions (Wang and Yang, 2022; Khan et al., 2022).

In the short run, the error correction term is significant, indicating a rapid adjustment toward long-run equilibrium, with about 39% of the short-term deviation being corrected each period. However, the short-term effects are more mixed. Non-renewable

Table 6: The PMG-ARDL estimates

Long run	Model 1		Model 2		Model 3		Model 4	
Variable	**Coefficient**		**Prob.***		**Coefficient**		**Prob.***	
LNGDP	0.328671	0.0000***	0.335495	0.0000***	Coefficient	Prob.*	Coefficient	Prob.*
LNRE	−0.631954	0.0000***	−0.676951	0.0000***	0.219855	0.0000***	0.485535	0.0000***
LNNRE	0.893780	0.0000***	0.890976	0.0000***	−0.146063	0.0004***	−0.847220	0.0009***
LNNC	0.467008	0.0005***			0.693415	0.0000***	0.886922	0.0000***
LNIQ	−0.510504	0.0000***	−1.024113	0.0000***			1.300316	0.0000***
LNICT	−0.221092	0.0000***	−0.223657	0.0004***	−0.437477	0.0000***	−0.240584	0.0000***
LNNC×LNIQ			0.130986	0.0000***	−0.277023	0.0000***		0.0000***
LNNC×LNICT								
LNIQ×LNICT					0.062257	0.0000***		
							−0.030242	0.0000***
Short run	**Model 1**		**Model 2**		**Model 3**		**Model 4**	
	Coefficient	**Prob.***	**Coefficient**	**Prob.***	**Coefficient**	**Prob.***	**Coefficient**	**Prob.***
COINTEQ01	−0.394651	0.0000***	−0.387938	0.0000***	−0.704061	0.0002***	−0.689845	0.0324**
D (LNGDP)	−0.120342	0.4642	−0.121020	0.4638	0.157428	0.2933	−0.142877	0.5599
D (LNRE)	3.748480	0.1929	3.925679	0.1587	14.15555	0.3860	72.55232	0.2900
D (LNNRE)	0.543964	0.0000***	0.550825	0.0000***	0.333030	0.0481**	0.455845	0.0071***
D (LNNC)	−0.322149	0.5751					−0.465566	0.5179
D (LNIQ)	0.171365	0.0414**	0.560863	0.3568	0.115294	0.4567	0.027256	0.8868
D (LNICT)	0.067982	0.3824	0.069369	0.3706	0.158112	0.8511		
D (LNNC×LNIQ)			−0.097371	0.5415				
D (LNNC×LNICT)					−0.061149	0.7706		
D (LNIQ×LNICT)							−0.003239	0.9006
C	−1.291837	0.0000***	−0.624226	0.0001***	0.332157	0.0004***	−8.174145	0.0334**

"***" and "**" indicate statistical significance at the 1%, and 5%, respectively

energy consumption has a significant positive effect on emissions, while GDP and renewable energy do not have a significant short-term impact. IQ has a positive but significant short-term effect, indicating that improvements in IQ may initially lead to higher emissions, possibly due to the time needed for institutional reforms to have an impact on environmental policies. Overall, these results emphasize that while economic and energy factors have a direct impact on emissions, IQ and ICT adoption can contribute to reducing emissions over time, especially in the long run.

The introduction of the interaction term in model 3 does not change the signs of the coefficients compared to model 2 without interaction, confirming that the inclusion of the interaction does not affect the direction of the impact of the variables on CO_2 emissions, but rather helps to better understand the combined impact of NC and IQ. Indeed, the estimation results show several significant relationships between the variables and CO_2 emissions, both in the long run and in the short run. In the long run, GDP has a positive and significant coefficient of 0.335, indicating that an increase in GDP is associated with an increase in CO_2 emissions. On the other hand, the use of renewable energy (RE) reduces CO_2 emissions, highlighting the positive impact of adopting renewable energy sources. Non-renewable energy (NRE), with a coefficient of 0.890, means that an increase in the use of non-renewable energy leads to higher CO_2 emissions. IQ, with a negative and significant coefficient, confirms that better institutions are associated with a reduction in CO_2 emissions. The use of ICT has a negative but relatively weak effect on CO_2 emissions, with a coefficient of −0.223. Finally, the interaction between NC and IQ (LNNC×LNIQ), represented by a significant coefficient of 0.130, suggests that better institutions enhance the impact of NC in reducing CO_2 emissions.

The introduction of interaction terms in models 4 and 5 allows for the analysis of the combined impact of certain variables, particularly the interaction between NC and ICT in model 4, as well as the interaction between IQ and ICT in model 5. In model 4 the interaction term between NC and ICT (LNNC × LNICT) has a positive and significant coefficient of 0.062. This suggests that the impact of NC on CO_2 emissions is enhanced by the adoption of ICT. In other words, when countries increase their NC while also investing in digital technology, they can potentially maximize the environmental benefits of NC, leading to a reduction in CO_2 emissions. This highlights the importance of the synergy between these two variables: NC and digital technology can interact in a beneficial way to reduce emissions. In model 5, the interaction term between IQ and ICT (LNIQ × LNICT) shows a negative coefficient and significant of −0.030242. This result indicates that better institutional quality, combined with the adoption of ICT, is associated with a greater reduction in CO_2 emissions. In other words, when IQ is high and countries also invest in ICT, they are better equipped to implement effective policies for managing natural resources, which leads to reduced emissions. This suggests that the impact of ICT on CO_2 emissions is more significant in strong institutional contexts. The introduction of these interaction terms in the models helps to better understand the combined effects of these key variables, revealing complex relationships between NC, IQ, and ICT. The inclusion of these interactions shows that the impact of individual variables on CO_2 emissions can be amplified or attenuated when they interact with each other. For example, model 3 highlights that NC alone may not be sufficient to reduce CO_2 emissions without the support of digital technology, while model 4 emphasizes that strong institutions and ICT together can play a crucial role in mitigating CO_2 emissions. These results underscore the importance of integrated policies that account for these interactions to maximize environmental benefits.

Table 7: Granger causality test

Variables	Short-run							Long-run
	Δ(LNCO_2)	Δ(LNGDP)	Δ(LNRE)	Δ(LNNRE)	Δ(NC)	Δ(IQ)	Δ(ICT)	
Δ(LNCO_2)		2.730682	0.242092	14.78095	3.977454	0.046559	1.238254	−0.002253
		(0.0984)*	(0.6227)	(0.0001)***	(0.0461)***	(0.8292)	0.2658	(0.00136)***
Δ(LNGDP)	0.005627		0.640774	0.044383	0.057808	0.066908	1.606865	−0.002897
	(0.9402)		(0.4234)	(0.8331)	(0.8100)	(0.7959)	(0.2049)	(0.00067)***
Δ(LNRE)	0.284954	1.586327		0.079463	0.882777	0.034804	0.320681	7.39.10-5
	(0.5935)	(0.2079)		(0.7780)	(0.3474)	(0.8520)	(0.5712)	(0.00019)***
Δ(LNNRE)	0.292283	11.87326	0.797853		0.973194	0.160868	0.153251	−0.002281
	(0.5888)	(0.0006)***	(0.3717)		(0.3239)	(0.6884)	(0.6954)	(0.00112)***
Δ(LNNC)	1.559454	0.259972	0.267124	0.551338		0.399450	0.006389	−0.000749
	(0.2117)	(0.6106)	(0.6053)	(00.4578)		(0.5247)	(0.9365)	(0.00043)***
Δ(LNIQ)	0.667282	2.761408	0.325490	1.572021	1.177894		0.019588	0.000246
	(0.4140)	(0.0966)*	(0.5683)	(0.2099)	(02778)		(0.8887)	(0.00061)***
Δ(ICT)	0.150817	2.970846	7.143822	0.000394	0.456623	0.603583		−0.008191
	(0.6978)	(0.0848)*	(0.0075)**	(0.9842)	(0.4992)	(0.4372)		(0.00100)***

'***', '**' and '*'indicate statistical significance at 1%, 5% and 10%respectively

4.1. Granger Causality Test

We examined causality using the Engle and Granger (1987) method. Short-term causality was tested with the Fisher statistic, while long-term causality was assessed through the lagged error correction term (ECT) using the t-statistic. Results are presented in Table 7.

All coefficients of the error correction term (ECT) are statistically significant, suggesting that the long-run results indicate bidirectional causality among all variables. The results of the Granger causality test highlight significant short and long-term relationships between the studied variables, providing valuable insights into the interactions between CO_2 emissions, ICT, non-renewable energy, GDP, and institutional quality. In the short term, notable relationships exist between CO_2 emissions and the use of non-renewable energy, ICT, and GDP, suggesting an interconnection between these factors. Granger causality suggests a unidirectional causality between CO_2 emissions and GDP in the short run, while Mahmoodi (2017), Elfaki et al. (2022), Zhang and Zhang (2021) and Hasni et al. (2023) confirm the existence of a bidirectional causality between GDP and CO_2. However, this is not consistent with the results of Qudrat-Ullah and Nevo (2022), who find no causality between economic growth and CO_2 emissions. The result implies that any change in the trend of economic growth will lead to an increase in CO_2 emissions. Similarly, a unidirectional short-term causality from non-renewable energy and NC to CO_2 emissions was found.

The causality between CO_2 emissions and ICT is also significant, reflecting the growing impact of digitization in emission management. In the long term, these relationships remain robust, with a notable impact of ICT and IQ on emissions, reinforcing the importance of effective institutions in mitigating emissions. Additionally, the results show the expected positive relationship between the use of non-renewable energy and the increase in CO_2 emissions, while ICT could be linked to technological strategies aimed at reducing these emissions. These results are satisfactory as they highlight significant causal relationships that can guide public policies aimed at reducing CO_2 emissions, considering the importance of ICT and strong institutions.

5. CONCLUSION AND POLICY IMPLICATIONS

UNCTAD (2006; 2024) stresses that building productive capacity is a fundamental lever for sustainable and resilient growth. These recommendations are particularly relevant for the MENA region, where the dependence on hydrocarbons weakens the economy. However, the development of productive capacity in this region must necessarily integrate environmental constraints, which are all the more pressing in the face of rapid urbanisation, heavy reliance on fossil fuels, and growth in CO_2 emissions outpacing average income growth, with the risk of tripling emissions by 2060 in the absence of appropriate policies. Productive capacity rests on three essential pillars: productive resources (NC), entrepreneurial capabilities (ICT) and productive linkages (IQ). However, beyond their individual impact, it is their interdependence and synergy that determine their effectiveness (UNCTAD, 2020). Analysis of these interactions is therefore essential to better understand their combined impact on CO_2 emissions and to guide public policies that reconcile economic growth and environmental sustainability. This study therefore examines the direct effects of NC, ICT and IQ, as well as their interactions, on CO_2 emissions in the MENA region between 2000 and 2021. It uses an ARDL-PMG model and causality analysis, including control variables such as GDP and renewable and non-renewable energy consumption. The results suggest that ICT and IQ contribute directly to reducing emissions. However, their interaction with NC tends to increase emissions due to the high dependence of oil-producing countries on natural resources. On the other hand, the interaction between ICT and IQ has significant potential to reduce emissions, highlighting the need for an integrated approach for an effective environmental transition in the MENA region.

In the light of our findings and the orientations of the MENA Climate Roadmap (2021-2025), we make recommendations to address the region's economic and environmental challenges, focusing on the interactions between the pillars of productive capacity: ICT, IQ and NC. A transition to a resilient, low-carbon economy requires structural reforms aimed at diversifying the economy while supporting sustainable growth. It is crucial to promote economic diversification to reduce dependence on hydrocarbons, while supporting green industries, sustainable agriculture and digital services. The introduction of green taxation, including carbon taxes and incentives to invest in sustainable sectors, is also a key lever for achieving climate goals. Although the MENA region remains heavily dependent on hydrocarbons, it has considerable renewable energy potential. Appropriate management of the energy transition is therefore essential. The deployment of renewable energies, particularly solar and wind needs to be accelerated by facilitating private investment and adopting favourable regulations. In addition, reforming fossil fuel subsidies and redirecting them towards low-carbon infrastructures will provide sustainable funding for energy projects.

In terms of developing productive capacity, it is necessary to fully exploit the assets of ICTs, IQ and NC. ICTs must be used to optimise energy consumption and foster innovation in resource management, for example through smart grids, artificial intelligence for sustainable agriculture and emissions monitoring using intelligent sensors. IQ must be strengthened through more transparent and inclusive environmental governance, with greater involvement of the private sector in green finance. Sustainable management of NC, particularly in the water and agriculture sectors, is also essential to ensure food security and preserve biodiversity.

The interaction between these three pillars requires a coordinated approach. Although ICT and IQ have a positive impact on environmental quality, their effect remains insufficient in the face of the challenges posed by NC. It is therefore essential for MENA countries to strengthen the sustainable management of natural resources and maximise the synergies between ICT and IQ to support the energy transition and improve resource management. A harmonious dynamic between these dimensions is essential to optimise the management of resources and industrial processes, while strengthening the transparency and regulation needed to implement climate and economic reforms. In short, an integrated approach, taking advantage of the synergies between technology, governance and resource management, is essential to ensure sustainable development and an effective energy transition in the MENA region, thereby contributing to its long-term competitiveness and sustainability.

Finally, it is worth highlighting some of the limitations of our research. On the one hand, the heterogeneity of the countries in the MENA region is an important factor to take into account in the analysis. Some countries are heavily dependent on hydrocarbons, while others, albeit in the same region, have embarked on more advanced economic diversification. This diversity means that the recommendations made need to be tailored to the specific characteristics of each country, taking into account its economic, political and environmental context. In addition, future research could include other elements of productive capacity, such as human capital, structural change and the involvement of the private sector in the estimates. A more in-depth analysis of these factors would provide a better understanding of the impact of all components of productive capacity on environmental dynamics in the region.

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