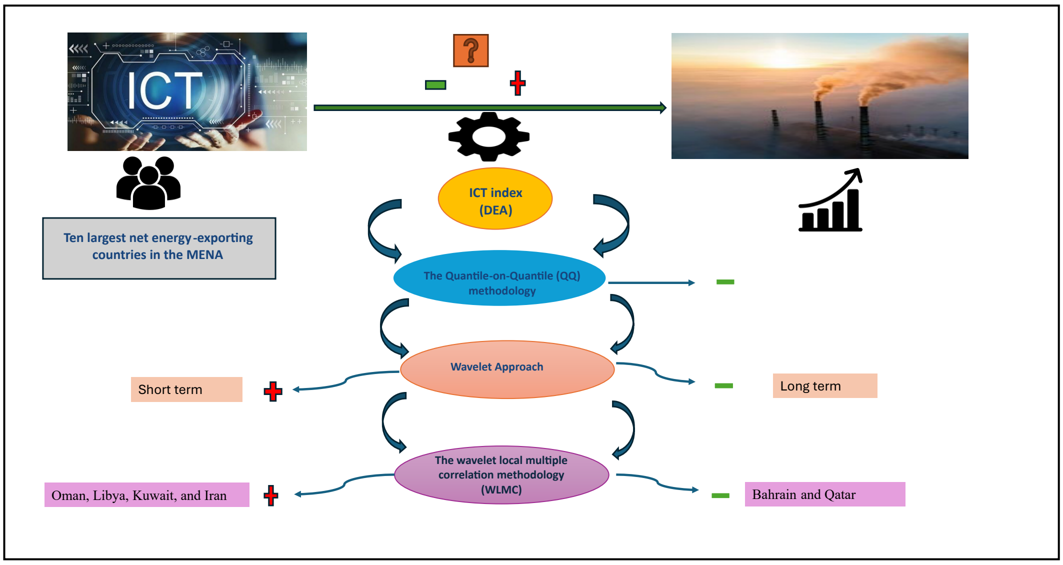
The Impact of ICT on CO_2 Emissions in MENA Energy-Exporting Countries: A Quantile and Wavelet Approach

Béchir Ben Lahouel
De Vinci Higher Education, De Vinci Research Center, Paris, France
bechir.ben_lahouel@devinci.fr

Lotfi Taleb
École supérieure des sciences économiques et commerciales de Tunis
University of Tunis – Tunisia
Univ. Manouba, ESCT, LARIMRAF LR21ES29, Campus universitaire Manouba, 2010, Tunisie
loootfi63@yahoo.fr

Graphical abstract



Abstract

This study examines the impact of Information and Communication Technology (ICT) on carbon dioxide (CO_2) emissions in ten net energy-exporting MENA countries from 1994 to 2019. A composite ICT index, developed using the Data Envelopment Analysis (DEA) method, is applied alongside advanced econometric techniques such as Quantile-on-Quantile (QQ) regression, wavelet coherence analysis, and Wavelet Local Multiple Correlation (WLMC). Results reveal that ICT has a significant positive effect on reducing emissions at both low and high quantiles, although the impact varies across countries. While ICT adoption initially correlates with increased emissions due to infrastructure demands, its long-term effect, particularly when integrated with renewable energy practices, is more beneficial for emissions reduction. The findings emphasize the potential of ICT in promoting environmental sustainability in the MENA region and the need for tailored ICT policies.

Keywords

ICT, CO_2 emissions, energy consumption, Quantile-on-Quantile, Wavelet, Net energy exporting MENA countries.

1. Introduction

The United Nations (UN) has established 17 Sustainable Development Goals (SDGs) in its 2030 Agenda, calling for urgent global action. Among these, reducing greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), is critical to combating climate change. A significant contributor to these emissions is the heavy reliance on fossil fuels across various sectors. As noted by Asongu et al. (2018), rapid and substantial cuts in CO_2 emissions are essential to mitigate the worsening effects of climate change. Many nations, particularly those with energy-intensive economies, have started implementing policies promoting environmentally sustainable growth, aiming to decouple economic growth from environmental degradation (Zhang & Liu, 2015).

A key driver in modern economic transformation is Information and Communications Technology (ICT). ICT encompasses hardware, communication devices, and software, facilitating knowledge dissemination, information flow, and economic productivity (Kallal et al., 2021). While ICT's positive economic impacts are well-documented (Niebel, 2018; Dedrick et al., 2013; Ben Lahouel et al., 2021; Magazzino et al., 2021; Sadorski, 2012; Ali et al., 2023; Kartal et al., 2024), its environmental impact remains debated. Some argue that ICT exacerbates environmental degradation through its energy consumption (Moyer & Hughes, 2012), while others highlight its potential to enhance environmental sustainability by promoting green technologies and efficient infrastructures (Higón et al., 2017).

This study contributes to this debate by exploring the relationship between ICT adoption and environmental sustainability, specifically in the context of CO_2 emissions. It focuses on the ten largest net energy-exporting countries in the MENA region, Algeria, Bahrain, Iran, Iraq, Kuwait, Libya, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE). These nations are major players in the global energy market and significant contributors to global CO_2 emissions (World Bank, 2018).

The MENA region, especially its energy exporters, have some of the highest per capita CO_2 emissions, as seen in Fig.1, which is indicative of their reliance on fossil fuels. MENA produced 4.33% of the world's CO_2 emissions in 2017 but only made up 4% of the world's GDP. Because of the differences in ICT development between these countries, between 20% and 60% of people in 2010 had internet penetration, there is a rare chance to look at how different ICT integration levels affect CO_2 emissions in countries that export energy..

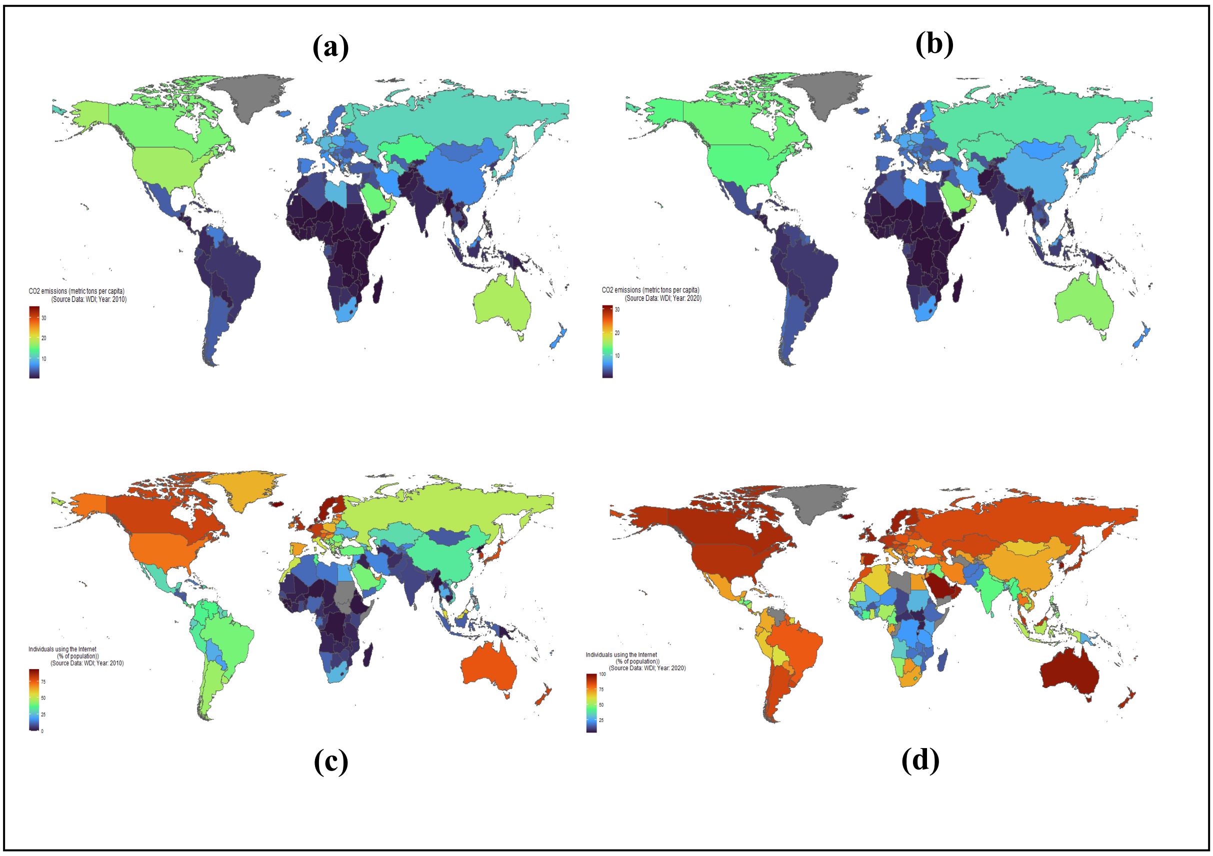


Fig.1 : **Global CO_2 emission and Internet use between 2010 and 2020**

Notes: (a) and **(b)** give the Global CO_2 emissions per capita in 2010 and 2020, respectively; **(c)** and **(d)** give the Global individuals using the Internet (% of population) in 2010 and 2020, respectively. (**Created by authors based on WDI data and WDI R package**)

Using a Super Efficiency Slacks Based (SE-SBM) DEA model (Tone, 2011), this study first creates a novel ICT index by including measures like internet penetration, cell phone usage, and landline telephone usage. Subsequently, the impact of ICT on CO_2 emissions is assessed at different quantiles using the Quantile-on-Quantile (QQ) regression technique (Sim & Zhou, 2015). Furthermore, to investigate temporal dynamics in the relationship between ICT and CO_2 emissions and account for non-stationary time-series data, wavelet coherence (WC) and wavelet local multiple correlation (WLMC) analyses are applied. Compared to standard models, the QQ and Wavelet techniques provides a more detailed picture by accounting for the diversity in ICT's effects over the whole emissions distribution

The novelty of this study lies in its application of the QQ approach to assess the effect of ICT on CO_2 emissions in the MENA region, where such analyses are rare. By focusing on country-specific data across different quantiles, this study provides a more detailed understanding of how ICT contributes to environmental sustainability, emphasizing the importance of tailored policy responses to various levels of ICT development and emissions intensity.

Fig. 2 summarises the conceptual framework and illustrates the intricate connections between CO_2 emissions, ICT adoption, and environmental sustainability. A crucial part of this strategy is the ICT index, which uses variables like internet penetration and telecommunications infrastructure to show how complicated ICT adoption is. The idea also highlights the mediating functions that economic expansion and regulatory regulations play, illustrating how broader socioeconomic conditions impact how well ICT supports sustainability.

The remainder of the paper is structured as follows: **Section 2** reviews the literature on ICT, CO_2 emissions, and environmental sustainability. **Section 3** explains the data and methodology. **Section 4** presents the results, and **Section 5** concludes with policy recommendations

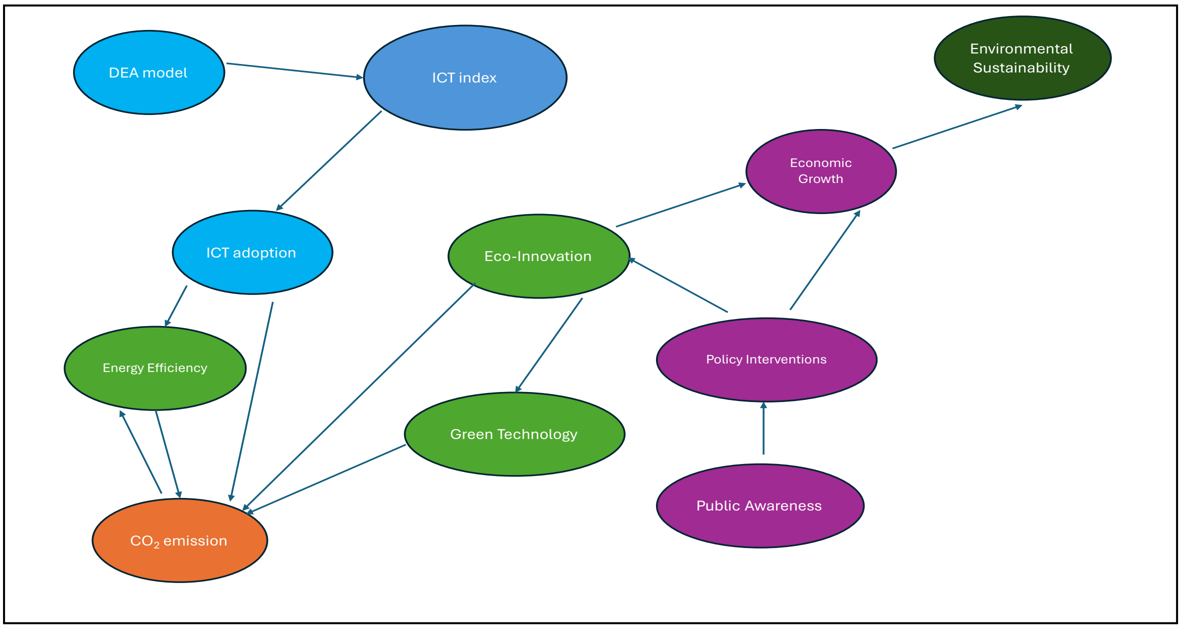


Fig. 2: ICT adoption; CO_2 emission and Environmental sustainability: A conceptual framework

2. Literature Review

The European Commission (2013) has made noteworthy contributions illustrating the relationship between technological advancements in ICT and eco-innovations. Many sustainable applications, like smart buildings, renewable energy networks, and sustainable transportation, depend on ICT. By promoting environmental sustainability, it also aids in the more effective and sustainable operation of the technology sector (Kemp and Pearson, 2008).

Even while ICT infrastructure has attracted major global investment and studies on its environmental consequences have only just begun, ICT played a vital role in the low-carbon economy at the start of the twenty-first century (Klimova et al., 2016). By reducing global CO2 emissions by 20% by 2030, ICT may be possible to separate economic growth from emissions

(GeSI SMARTer 2030 report, 2015; Ropke, 2012). Through ICT-enabled sustainability solutions, this potential is visible in a number of industries, including energy, transportation, manufacturing, services, agriculture, and buildings.

The role of economic growth and its environmental consequences depends on technological advancements, including ICT (Dinda, 2004). Although ICT is often seen as a driver for sustainable economic growth, some researchers suggest that globalization and trade expansion, facilitated by ICT, may increase carbon emissions (Danish, 2019; Magazzino et al., 2021; Shabani et al., 2019). Empirical evidence supporting ICT's role in promoting a sustainable economy is critical (Gouvea et al., 2018). Despite expectations, ICT’s contribution to carbon productivity growth has yet to fully materialize.

The literature identifies three effects of ICT on CO2 emissions. The utilization effect refers to the ICT production cycle, which significantly increases energy consumption and emissions (Park et al., 2018; Shabani & Shahnazi, 2019). The substitution effect suggests ICT reduces energy use by replacing physical goods and services with virtual alternatives, such as telecommuting and e-commerce (Jorgenson, 2001; Ozcan & Apergis, 2017). The cost effect, however, posits that price reductions enabled by ICT lead to increased demand and emissions (Shabani & Shahnazi, 2019).

A three-tier framework categorizes ICT’s environmental impact into first-order effects (production and recycling), second-order effects (improving energy efficiency), and third-order effects (systemic changes in consumption) (Berkhout & Hertin, 2001; Hilty et al., 2006). Empirical studies are divided on whether ICT mitigates or exacerbates environmental degradation. While some argue that ICT reduces energy consumption (Gouvea et al., 2018; Zhang & Liu, 2015; Kartal et al., 2024; Magazzino et al., 2021), others contend that ICT increases emissions due to higher energy demand (Avom et al., 2020; Moyer & Hugues, 2012).

Numerous studies have investigated the relationship between ICT and CO_2 emissions. In the same way that ICT has a long-term positive impact on emissions, its rapid proliferation may eventually pose environmental risks (Salahuddin et al., 2016). In addition to stimulating economic growth, ICT also increases electricity consumption and emissions in EU countries (Magazzino et al., 2021). Furthermore, others contend that internet use exclusively reduces emissions in developed countries (Al-Mulali et al., 2015; Avom et al., 2020, and Lee & Brahmasrene, 2014). Studies conducted more recently have looked at geographic variations, ICT raises emissions in low-income countries while moderating them in high- and middle-income ones (Danish et al., 2019). In contrast, studies like Mingay (2007) argue that ICT accounts for about 2% of global CO_2 emissions, with limited impact on reducing emissions.

The MENA region remains underexplored regarding ICT’s environmental impact, despite being a significant contributor to global CO_2 emissions. As one of the world’s most energy-intensive areas, its role in climate change is critical. This study aims to address this gap by examining the longitudinal relationship between ICT development and CO_2 emissions in the region’s ten largest energy-exporting countries. By doing so, it provides insights into ICT’s potential to promote environmental sustainability in a context where high levels of fossil fuel consumption drive substantial CO_2 emissions. The findings highlight the capacity of ICT to act as a tool for mitigating emissions and supporting sustainable development in energy-reliant economies.

3. Data and methodology

3.1 Data description and descriptive statistics

The current study examines the top ten net energy-exporting nations in the Middle East and North Africa (MENA) region, including Algeria, Bahrain, Iran, Iraq, Kuwait, Libya, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE), using data from the World Development Indicators (WDI). As demonstrated in other research (e.g., Shahzad et al., 2017; Shahbaz et al., 2016, 2018; Sinha et al., 2020), we concentrate on quarterly data and convert annual series into quarterly data points using the quadratic match-sum approach. The dataset contains 104 quarterly observations for each country, covering the period from Q1 1994 to Q4 2019. The handling of missing data is done via linear interpolation.

The dataset consists of two main variables: a unique composite ICT index that includes landline, mobile, and internet penetration rates (subscriptions per 100 inhabitants) and CO2 emissions per capita (metric tons), which measures environmental sustainability.

Table 1 presents the descriptive statistics for the ICT index and CO_2 emissions across the ten MENA countries. Qatar has the highest average CO_2 emissions per capita at 51.144 tons, followed by Kuwait (28.448 tons), the UAE (25.209 tons), and Bahrain (19.640 tons). To assess stationarity, we applied the Augmented Dickey-Fuller (ADF) unit root test and, the unit root test of Zivot-Andrews (1992) to examine the presence of structural breaks . Results revealing that all variables are nonstationary at levels but become stationary after first differencing.

The correlation coefficients displayed in **Table 2** indicate that, apart from Bahrain and Qatar, which show negative correlations of -0.893 and -0.812 between CO_2 emissions and ICT, respectively, the two variables exhibit a strong positive correlation in all other countries. At the 1% significance level, Oman and Algeria have the highest positive and negative correlations, respectively, while Libya shows a minimal correlation of 0.066 between ICT and CO_2 emissions.

Figs. 3 and 4 illustrate the evolution of the ICT use and penetration index (derived using a DEA model) and CO_2 emissions per capita. The trends show significant heterogeneity across countries, with Qatar and Saudi Arabia showing positive trends in both ICT adoption and CO_2 emissions, while others like Oman exhibit more volatility and stagnation.

Table 1: Descriptive statistics

	Mean	Min	Max	Std. dev.	ADF(Level)	ADF (Δ)	Z.A.(level)	Break year	Z.A. (Δ)	Break year
Panel A : ICT										
Algeria	.249	.152	.448	.094	2.231	-4.366***	-3.481	2014Q2	-5.595***	2004Q2
Iran	.427	.037	1.111	.305	-0.785	-5.541***	-5.266**	2012Q2	-7.338***	1998Q4
UAE	1.080	1.007	1.185	.047	-2.236	-5.240***	-5.690***	2007Q1	-6.659***	2006Q2
Qatar	.542	.192	1.099	.312	-1.016	-1.016***	-3.389	2012Q4	-7.757***	2010Q1
S. Arabia	.680	.366	1.035	.185	-1.356	-5.920***	-4.745*	1998Q3	-8.262***	2016Q1
Libya	.195	.051	.569	.178	-0.857	-4.179***	-4.107	2007Q2	-5.480***	2010Q2
Oman	.343	.075	.574	.169	-0.633	-6.138***	-3.942	2008Q2	-10.277***	2010Q4
Kuwait	.665	.068	1.134	.279	-1.364	-5.828***	-3.317	2015Q4	-9.776***	2015Q2
Iraq	.239	.037	1.111	.246	-1.485	-5.582***	-5.092**	2015Q1	-7.491***	1998Q4
Bahrain	.685	.311	1.328	.267	1.750	-4.839***	-4.475	2011Q2	-6.020***	1998Q4

Panel B :	**CO_2**									
Algeria	3.554	2.653	5.451	.723	-1.128	-5.032***	-4.524	2005Q2	-7.953***	2008Q2
Iran	6.814	4.214	8.600	1.450	-1.441	-5.697***	-3.718	1998Q3	-8.071***	1998Q4
UAE	25.209	18.268	36.642	4.144	-2.065	-5.986***	-5.171**	2005Q1	-8.426***	2001Q4
Qatar	51.144	35.921	70.844	11.012	-0.416	-5.641***	-5.445***	2007Q1	-7.560***	2010Q2
S. Arabia	16.008	10.450	20.666	2.640	-1.633	-6.091***	-5.020**	2015Q4	-9.926***	1999Q2
Libya	8.622	6.076	10.447	.772	-1.999	-6.302***	-5.751***	2015Q4	-10.274***	2010Q2
Oman	12.620	6.668	17.095	3.578	-1.560	-5.048***	-3.589	2015Q2	-6.061***	2007Q4
Kuwait	28.448	23.547	34.352	2.715	-1.142	-6.092***	-4.197	2004Q2	-8.570***	2009Q3
Iraq	3.997	2.131	5.36	.836	-0.287	-5.285***	-4.494**	2010Q2	-7.026***	2007Q3
Bahrain	19.640	7.398	30.119	7.610	-0.225	-5.244***	-5.591***	2010Q1	-6.966***	2009Q2

Note: This table gives descriptive statistics for the ICT use and penetration index and the CO_2 emissions in metric tonnes per capita for the top ten net energy-exporting nations in the MENA region. ***, ** and * indicate that the value is significant at the 1%. 5% and 10% levels of significance, respectively.

Table 2; **Person' correlation between CO_2 emissions**

Countries	Correlation
Algeria	0.5253***
	(0.000)
Iran	0.4165***
	(0.000)
UAE	0.4419***
	(0.000)
Qatar	-0.8127***
	(0.000)
S. Arabia	0.6655***
	(0.000)
Libya	0.0665
	(0.5026)
Oman	0.8930***
	(0.000)
Kuwait	0.0453
	(0.648)
Iraq	0.2740***
	(0.004)
Bahrain	-0.8473***
	(0.000)

Note: * indicates that the value is statistically significant at the 1% level of significance

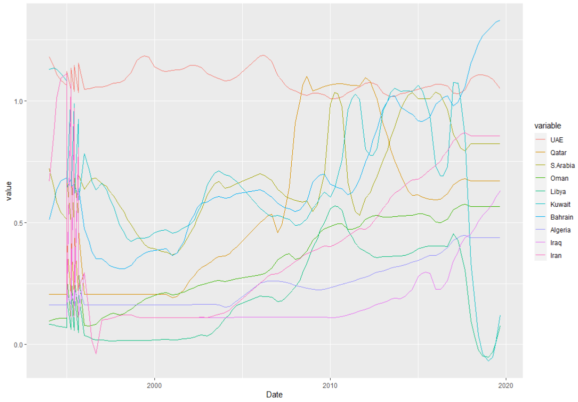


Fig.3 ICT use and penetration index for the top ten net energy-exporting nations in the MENA region derived by a super-efficiency Slacks-Based Measure (SE-SBM) DEA model.

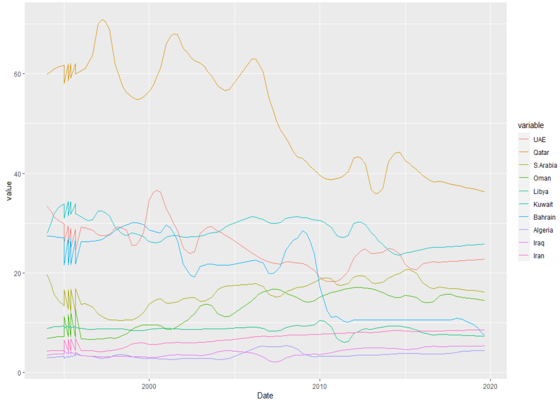


Fig.4. CO_2 emissions series in metric tons per capita, for the top ten net energy-exporting nations in the MENA region (Source WDI database) .

3.2 Methodology

This study aims to assess the impact of ICT usage and penetration on CO_2 emissions in the ten net energy-exporting MENA countries. In the first step, we construct an ICT index using an Data Envelopment Analysis (DEA). This index integrates key ICT components such as landline telephones, mobile subscriptions, and internet penetration. Next, we apply the quantile-on-quantile (QQ) regression methodology introduced by Sim and Zhou (2015), which allows for a more detailed analysis compared to traditional quantile regression (Shahzad et al., 2017). The QQ method captures the full quantile distribution of the relationship between ICT and CO_2 emissions, offering insights into how this relationship varies across different quantiles of the CO_2 distribution.

In addition to QQ regression, we employ a wavelet-based methodology to analyze the co-movement and lead-lag relationships between ICT and CO_2 emissions across different time and frequency scales. This method uses the Continuous Wavelet Transform (CWT) and Wavelet Coherence (WC) to examine the dynamic correlation between variables. Wavelet Coherence provides a more effective assessment of co-movement than traditional correlation or dynamic conditional correlation techniques (Liow, 2012; Zhou, 2010). This approach enables the identification of cyclical patterns, trends, and non-stationarity in the time series across various time horizons.

Finally, we adopt the Wavelet Local Multiple Correlation (WLMC) methodology, as proposed by Macho (2018) and Polanco-Martínez et al. (2020), to further refine our analysis. This technique allows us to examine localized correlations between ICT and CO_2 emissions over short, medium, and long-term timeframes. WLMC enhances traditional wavelet analysis by offering a deeper understanding of how these correlations evolve over time.

Fig. 5 provides a comprehensive visual summary of the empirical methodology design employed in this study. It illustrates the step-by-step approach used to assess the relationship between ICT development and CO_2 emissions across the ten largest net energy-exporting countries in the MENA region. This visual framework highlights how each of these methods complements the others in capturing both the time-varying dynamics and the non-linear relationships between ICT and environmental outcomes, providing a nuanced understanding of how ICT influences emissions across different quantiles, timeframes, and frequency scales.

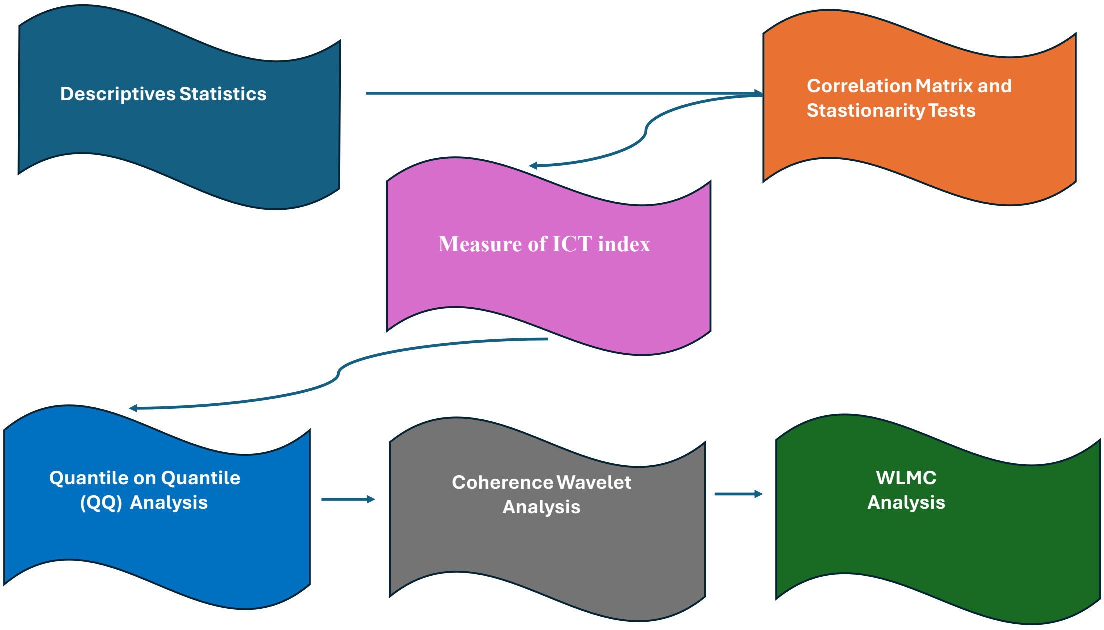


Fig. 5 Empirical methodology design

4. Empirical results

4.1 Measure of ICT index

Measuring ICT levels has received considerable attention in recent academic literature (Amri et al., 2019; Asongu et al., 2018, Avom et al., 2020; Danish, 2019; Salahuddin et al., 2016, and Tchamyou et al., 2019). In these studies ICT levels. ICT is often represented by single performance indicators that measure either ICT readiness or penetration. However, relying solely on these performance indicators provides an incomplete view of a country's overall ICT competency, as they only capture one aspect of ICT progress. To provide more precision regarding the ICT measure and following Tone (2011), we constrcut an ICT index by using Super Efficiency Slacks Based DEA model (SE-SBM). All the details concerning the construction of the ICT index used in this study are provided in **Appendix C**.

4.2 Estimates from the Quantile-on-Quantile Approach

This study examines the relationship between ICT usage and CO_2 emissions in the ten largest net energy-exporting countries of the MENA region using the Quantile-on-Quantile (QQ) methodology. The results are displayed in **Fig. 6**, which presents ten graphs showing the slope coefficient estimates for the impact of the τ^{th} quantile of ICT on the θ^{th} quantile of CO_2 emissions.

Overall, the QQ regression results indicate that ICT generally has a positive role in reducing CO_2 emissions in many MENA countries. However, the relationship is non-linear and varies significantly across countries and quantile levels, reflecting differing degrees of ICT penetration and varying stages of economic development.

For instance, Algeria and Iraq display the weakest link between ICT and CO_2 emissions, likely due to their relatively low levels of ICT development (ICT index values of 0.249 for Algeria and 0.239 for Iraq). Inadequate digital infrastructure and weak institutional support for environmental policies limit the potential of ICT to mitigate emissions in these countries.

The non-linear nature of the relationship is particularly evident in Bahrain and Iran, where the impact of ICT on CO_2 emissions is not uniform. In Bahrain, ICT adoption has a predominantly negative impact on emissions in lower and middle quantiles, suggesting that once ICT adoption reaches a critical threshold, it becomes more effective in reducing emissions. In contrast, the relationship is weaker in Iran, implying that ICT alone is insufficient without supportive environmental policies.

The non-linear results add a new dimension to the literature, revealing that ICT's effectiveness varies based on CO_2 emission levels, especially in highly polluted countries where the marginal benefits of ICT investment may decline. Unlike traditional econometric models, such as those used by Shahbaz et al. (2018) and Sinha et al. (2020), the QQ methodology captures the full distribution of ICT's impact across different quantiles.

In countries like Bahrain and the UAE, where ICT has substantial potential to curb emissions, policymakers should focus on further digital technology investments and promote ICT-driven green innovations. Conversely, countries like Algeria and Iraq should prioritize strengthening their digital infrastructures and aligning ICT investments with sustainable development goals**.**

These findings align with the observations of Sinha et al. (2020)**,** which identified the positive impact of technological innovations on sustainability. However, this study highlights more pronounced country-specific variations, particularly in nations with lower ICT penetration. This suggests that the role of ICT in environmental sustainability is context-dependent and requires tailored policy approaches.

For instance, the strong link between ICT and reduced emissions in Bahrain and Oman supports the conclusions of Alnaser (2015) and Alalouch et al. (2019), which emphasized the importance of proactive energy policies and sustainable technology investments in promoting environmental gains. Conversely, the weak correlation observed in Algeria and Iraq contrasts with the findings of Moghadam and Dehbashi (2018), who noted ICT's greater potential in reducing environmental harm under different circumstances.

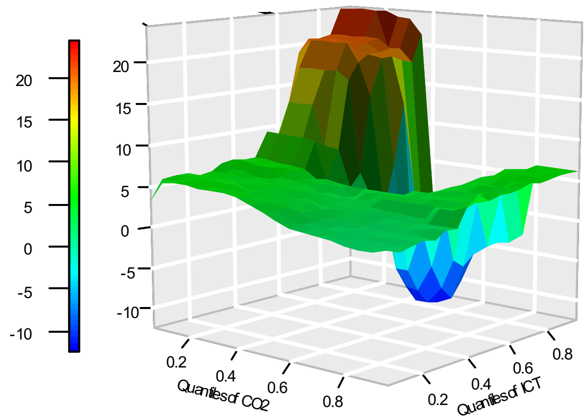
The relatively weak impact of ICT in Kuwait, particularly in higher emission quantiles, could be due to the country's reliance on fossil fuel subsidies, which hinder the adoption of cleaner technologies and undermine the environmental benefits ICT could offer.

In Saudi Arabia, despite initial evidence of ICT's positive impact in lower quantiles, the overall effect is limited by the country's dependence on fossil fuels and the slow transition to renewable energy. Similarly, while Qatar has high ICT penetration, its impact on emissions diminishes in higher quantiles, supporting Sinha et al.'s (2020) conclusion that ICT's benefits taper off in highly polluted contexts.

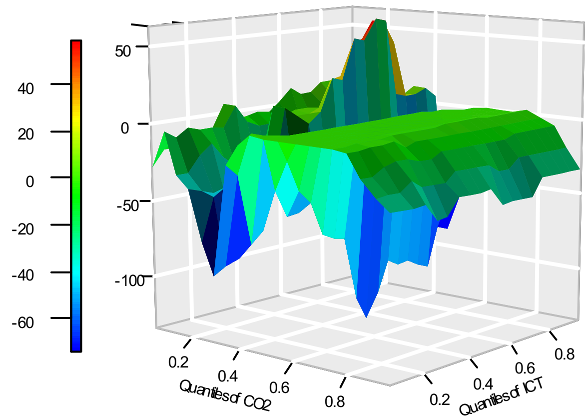
These variations reflect global findings from the OECD and World Bank, which indicate that ICT can drive environmental improvements when supported by strong institutional frameworks and complementary policies. For example, results from the UAE demonstrate the importance of policies promoting green technology adoption, whereas countries like Algeria and Iraq highlight the need for institutional reforms and investment in digital infrastructure.

In general, the findings support the hypothesis that ICT dramatically lowers CO_2 emissions over a range of quantiles, bringing fresh insights to the body of research on emissions in the Middle East and North Africa. ICT is identified in this study as a critical component impacting emissions, whereas prior research, like that of Magazzino and Cerulli (2019), focused on factors like GDP, energy consumption, and urbanization. Furthermore, the results imply that the impact of ICT changes with the CO_2 emissions, supporting the notion that focused investments on ICT and environmental regulations could result in notable advantages, particularly in nations with higher emission levels.

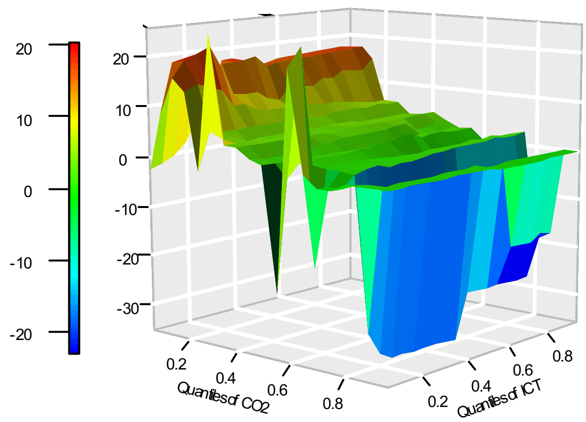
i). Algeria



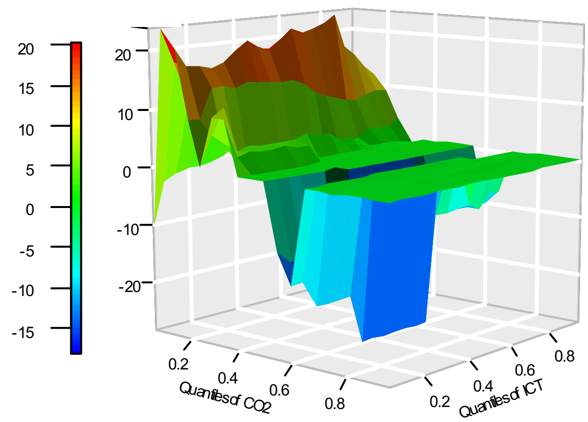
ii). Bahrain



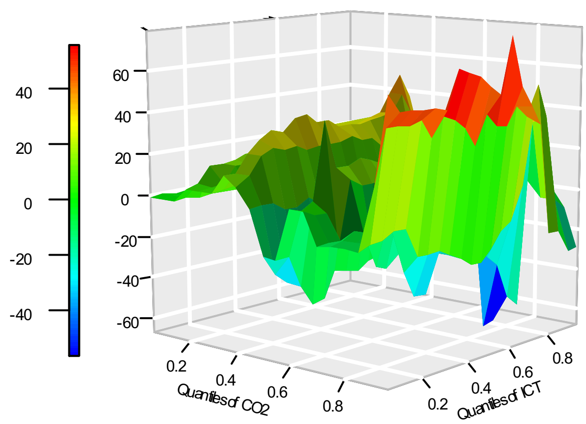
iii). Iran



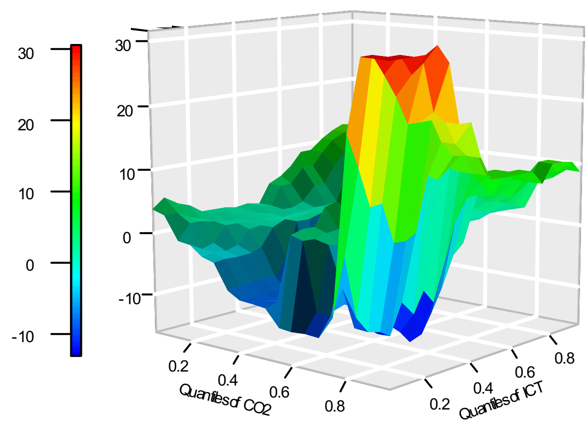
iv). Iraq



v). Kuwait



vi). Libya



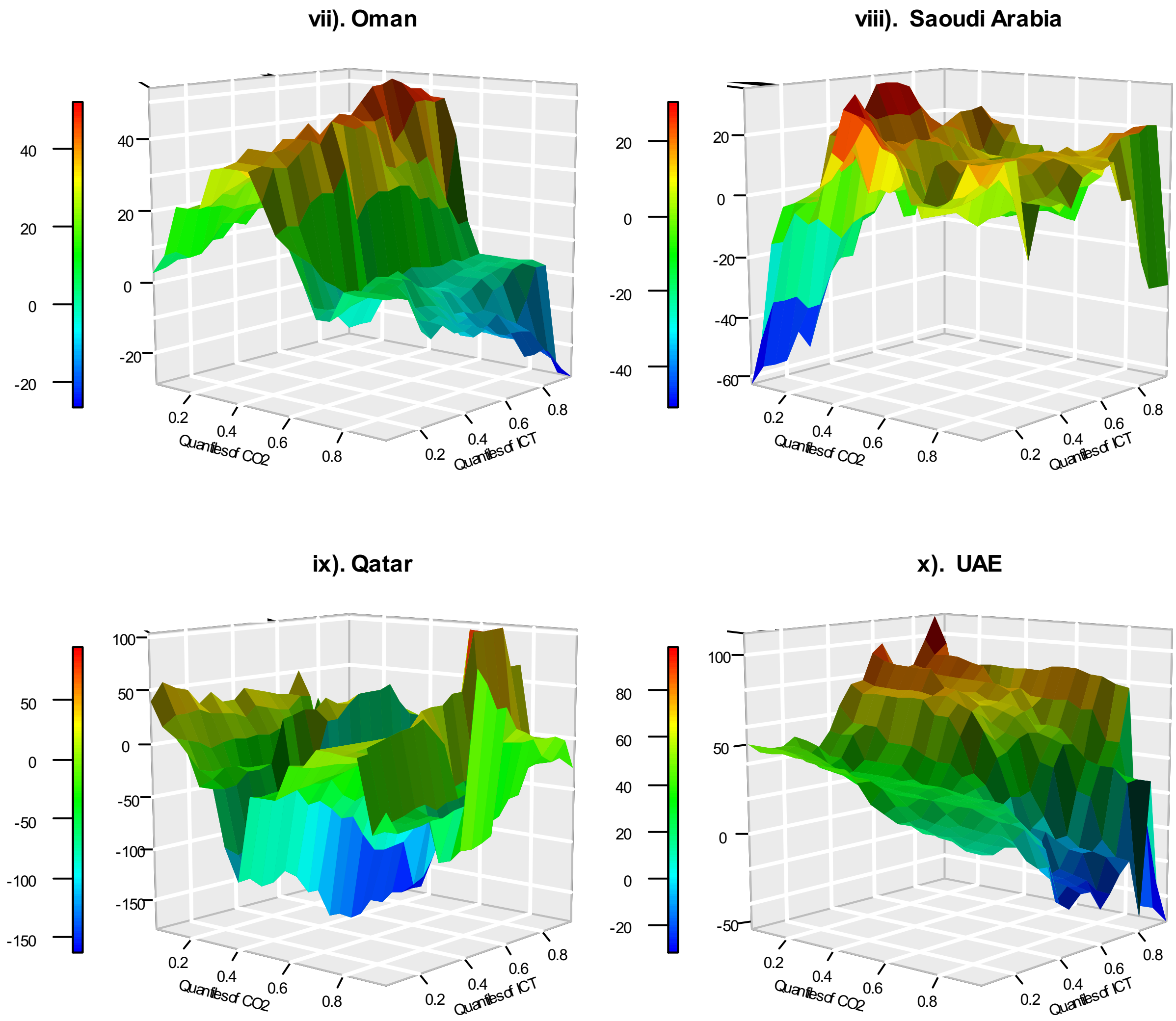


Figure 6: Quantile on Quantile plots of ICT and CO_2 emissions for the top ten net energy exporting MENA countries.

4.2 Wavelet Empirical Results

4.2.1 Wavelet Coherence Analysis

The wavelet approach complements the QQ regression by providing insights into how the relationship between ICT and CO2 emissions varies not only across emission levels but also over time and frequency scales. While the QQ analysis highlights heterogeneity across different levels of emissions, the wavelet analysis shows that the strength and direction of the ICT-CO_2 emissions relationship evolve over time. Initially, ICT development contributed to increasing emissions, but over time, it began to contribute to sustainability.

Fig. 7 illustrates the wavelet coherence results, showing a strong positive correlation between ICT and CO_2 emissions at higher frequencies (short term) during the early years of the sample period (1994–2000). This indicates that, in the short term, the expansion of ICT infrastructure, such as the establishment of data centers and server farms, resulted in increased energy consumption and environmental degradation. These findings align with those of Kartal et al. (2024), who observed a similar pattern, where green bonds and energy prices initially contributed to rising emissions in their analysis of geopolitical risks and global CO_2 emissions.

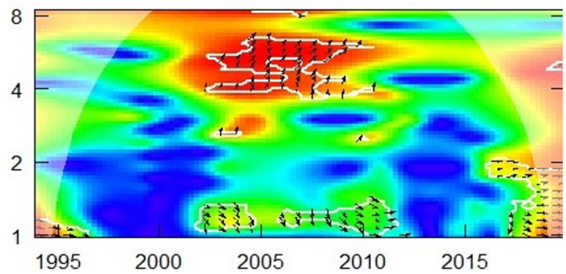
However, at lower frequencies (long-term), particularly after 2005, the coherence between ICT and CO_2 emissions diminishes, and in some periods, a negative relationship emerges. This suggests that over time, as ICT technologies became more energy-efficient and countries in the MENA region implemented more sustainable energy policies, the environmental impact of ICT usage decreased. This pattern aligns with the findings of Magazzino et al. (2021), who observed a similar shift in ICT's impact on environmental outcomes over time in the European Union, and with Kartal et al. (2024), who highlighted the long-term benefits of integrating green financial mechanisms into CO_2 reduction strategies.

Furthermore, the lead-lag relationship between ICT and CO_2 emissions, examined by using wavelet analysis, shows that in most nations, ICT initially led CO_2 emissions in the short term (1994–2005). This data supports the hypothesis put forth by Kartal et al. (2024) in their analysis of the energy-intensive sectors, which is that rises in digital infrastructure demand necessitated increased energy consumption, which in turn drove increases in CO_2 emissions. But in 2010, some nations, like Saudi Arabia and the United Arab Emirates, saw a shift in the direction of influence, with ICT adoption starting to help reduce emissions due to advances in green technology and more stringent environmental laws. This is in line with the work of Sadorsky (2012), who found that ICT's long-term advantages are more obvious once green.

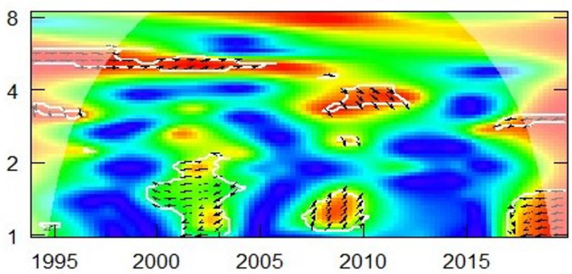
These wavelet-based insights underscore the evolving role of ICT in the environmental landscape of the MENA region. In the short term, ICT expansion increases CO_2 emissions due to its energy demands. However, over time, as ICT technologies mature and countries adopt more sustainable practices, ICT contributes to reducing emissions, especially when integrated with renewable energy sources.

These results emphasize that while ICT adoption initially increases emissions due to the infrastructure expansion required, its long-term benefits, particularly when combined with sustainable energy practices, make it a critical tool for reducing CO_2 emissions. This underscores the need for policies that promote ICT development in alignment with broader environmental objectives, as the effectiveness of ICT varies across countries and quantiles depending on the stage of development and energy policy frameworks in place.

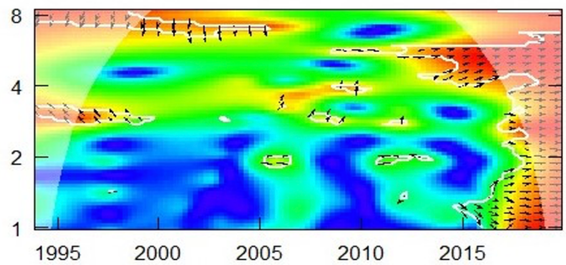
1. Algeria



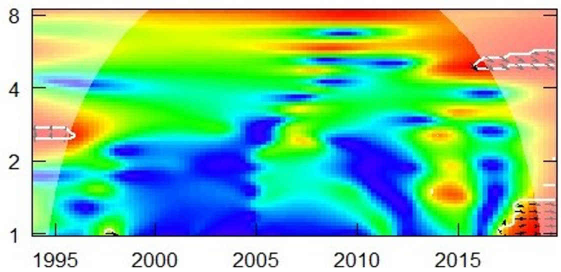
2.Bahrain



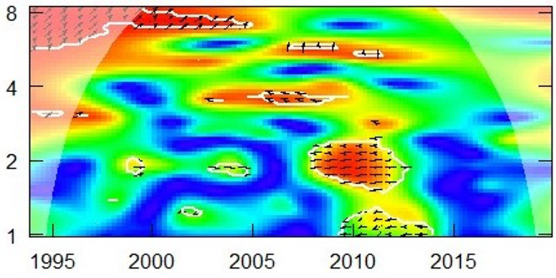
3. Iran



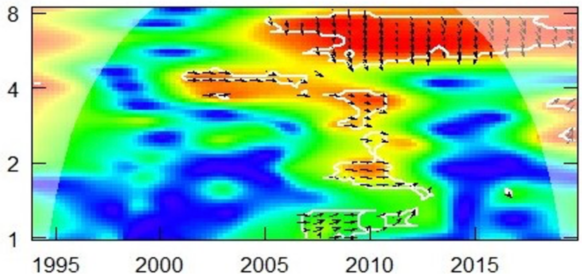
4. Irak



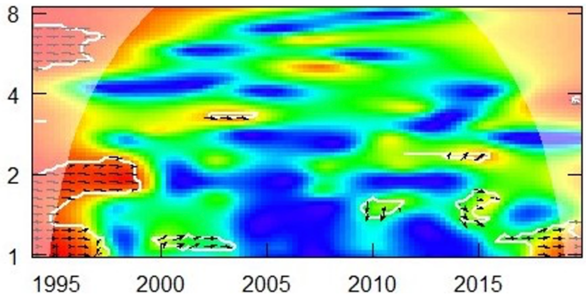
5. Kuwait



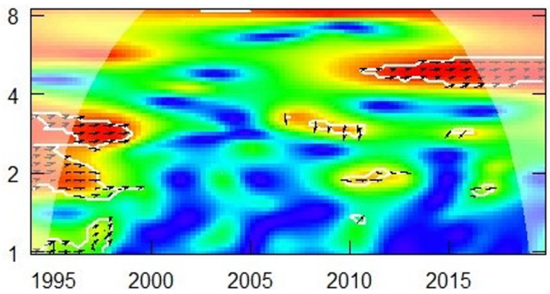
6. Libya



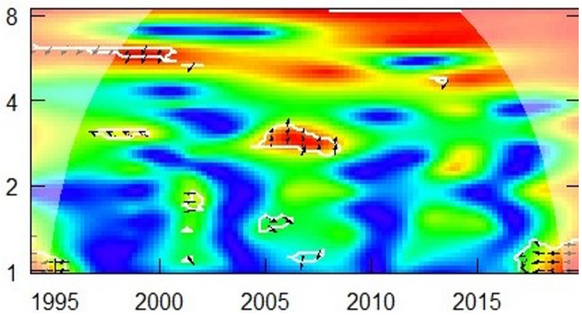
7. Oman



8. Saudi Arabia



9. Qatar



10. UAE

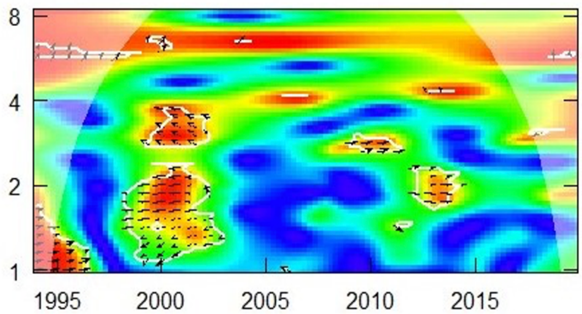


Figure 7: Wavelet coherence plots

Notes: X-axis represents the time over the period 1994–2019 whereas, Y-axis refers to the frequencies (measured in quarters). The thick white contour represents the 5% significance level against the red noise. red color corresponds to a strong co-movement while blue color corresponds to weak co-movement.

4.2.2 Wavelet Local Multiple Correlation (WLMC) Method

The Wavelet Local Multiple Correlation (WLMC) analysis was conducted over various time horizons, covering short-term (1–4 quarters), medium-term (4–8 quarters), and long-term (8–16 quarters) periods. The results, visualized in **Fig. 8** as a heatmap, highlight the evolving correlations between ICT and CO2 emissions over time in the ten net energy-exporting countries of the MENA region.

Countries such as Oman, Libya, Kuwait, and Iran exhibit strong positive correlations (CV > 0.5) between ICT and CO_2 emissions across the medium- and long-term scales. This suggests that in these countries, ICT development has contributed to increased CO_2 emissions, likely due to the energy consumption required for expanding digital infrastructure. These findings align with those of Magazzino et al. (2021) and Sadorsky (2012) who noted that ICT growth tends to drive electricity consumption, resulting in higher emissions unless green technologies are integrated into ICT expansion strategies.

Conversely, Bahrain and Qatar consistently show negative correlations between ICT and CO_2 emissions throughout the study period, indicating that ICT advancements in these countries have likely contributed to emissions reductions. This may be attributed to stronger policy focus on sustainability and the integration of renewable energy into ICT infrastructure. These results align with the work of Alnaser (2015), who discussed Bahrain's proactive approach to sustainable energy, and Alalouch et al. (2019), who emphasized Oman's emphasis on innovation-driven sustainability.

Interestingly, two specific periods, 1995Q1-2005Q4 and 2008Q1–2013Q4, show no significant correlation between ICT and CO_2 emissions. These periods coincide with global events such as the Iraq War and the global financial crisis, which may have shifted national priorities away from ICT development and environmental initiatives. This observation suggests that global shocks can disrupt the relationship between technological advancement and environmental sustainability, highlighting the vulnerability of ICT-driven sustainability efforts to external crises (Avom et al., 2020).

The WLMC results demonstrate significant heterogeneity across countries and timeframes, showing that the correlation between ICT and CO_2 emissions is not constant throughout the study period. This variability implies that the impact of ICT on emissions is influenced by external factors such as policy frameworks, energy market conditions, and technological advancements (Berkhout & Hertin, 2001; Hilty et al., 2006; Ben Lahouel et al., 2024).

For instance, while ICT contributes to increased emissions in certain periods for countries like Oman and Iran, the opposite is observed in Bahrain and Qatar, where ICT advancements have contributed to emissions reductions. This heterogeneity underscores the need for country-specific policies that consider each country's unique economic and technological context.

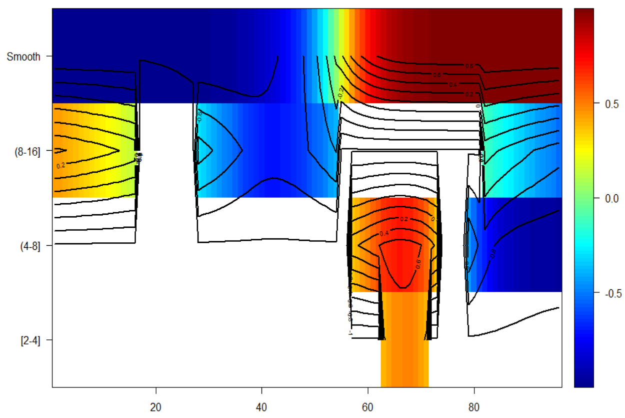
The WLMC analysis adds another layer of insight by illustrating how the relationship between ICT and CO_2 emissions changes over time and across various frequencies, in contrast to the QQ regression results. This analysis indicates that the ICT-CO_2 emissions relationship is time-dependent, despite the QQ findings highlighting how the influence of ICT differs among emission quantiles. There are periods when the correlation between ICT and CO_2 emissions is more pronounced, and others when it is less significant, particularly during global crises.

These findings have important implications for policy development in the MENA region. Countries such as Oman, Libya, Kuwait, and Iran should focus on improving the energy efficiency of their ICT sectors to decouple ICT growth from rising emissions. On the other hand, Bahrain and Qatar, which have already achieved a negative correlation between ICT and emissions, can serve as models for integrating ICT with renewable energy and sustainable practices (Mingay, 2007 and Lee & Brahmasrene, 2014).

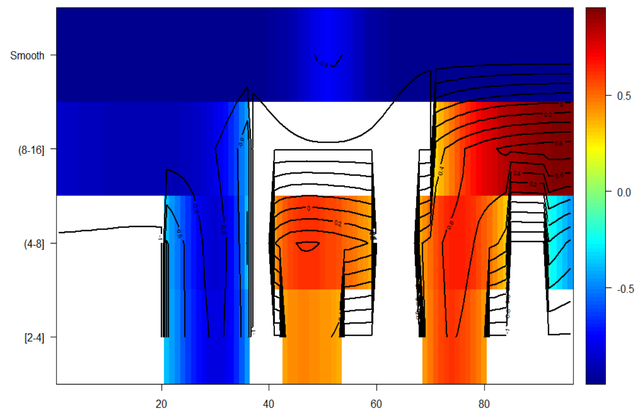
Additionally, the periods of no correlation during global events underscore the importance of ensuring that ICT and environmental strategies are resilient to external shocks. Governments should design policies that ensure progress toward sustainability even during crises, as discussed by Amri et al. (2019), who examined the relationship between ICT, productivity growth, and CO_2 emissions in Tunisia.

Overall, the WLMC analysis complements previous research, particularly Kartal et al. (2024) and Magazino et al. (2019), who investigated the dynamic relationship between green bonds, energy prices, and CO_2 emissions using a similar wavelet-based approach. The time-varying effects of ICT on emissions observed here reinforce the complexity of the ICT-environment relationship, suggesting that ICT can drive sustainability when supported by appropriate institutional frameworks and complementary policies (OECD, 2020).

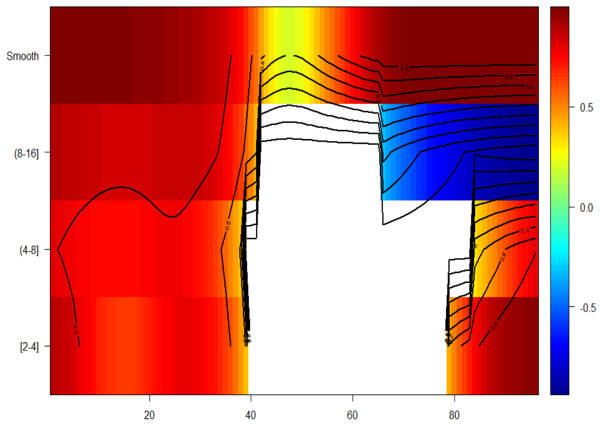
CO2 vs ICT (UAE)



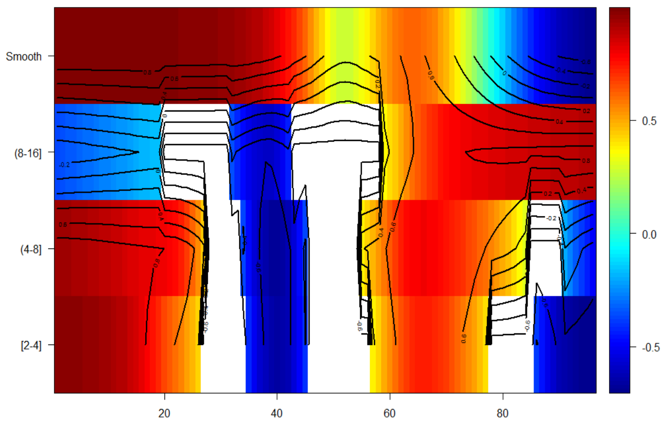
CO2 vs ICT (QATAR)



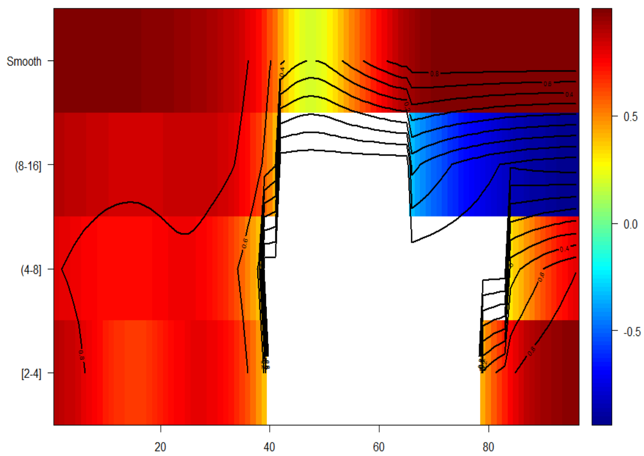
CO2 vs ICT (OMAN)



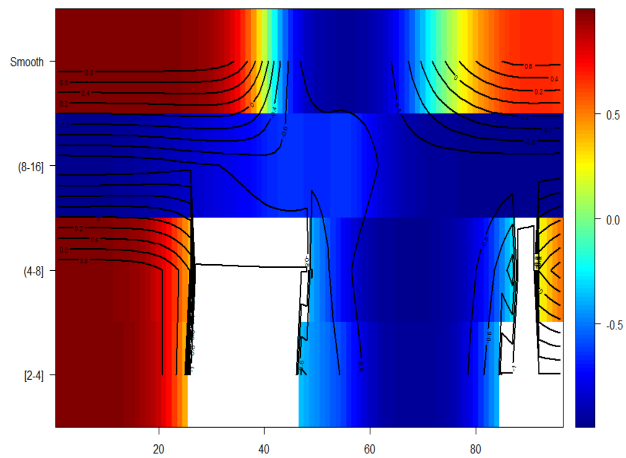
CO2 vs ICT (S.ARABIA)



CO2 vs ICT (LIBYA)



CO2 vs ICT (KUWAIT)



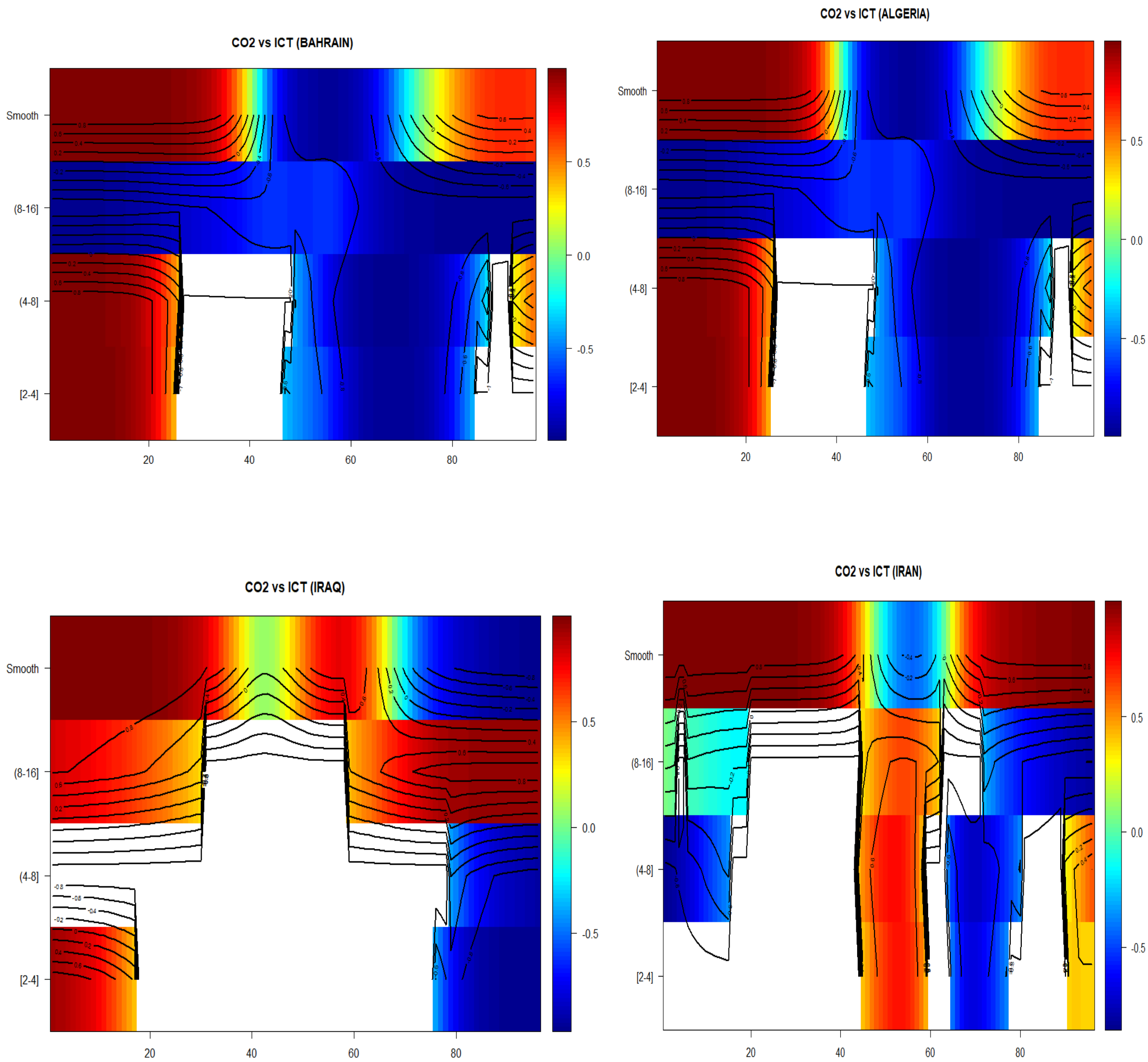


Figure 8: **Wavelet Local Multiple Correlation analysis (WLMC) between CO2 emission and ICT for the for the top ten net energy-exporting nations in the MENA region for the period 1994-2019.**

5. Conclusion

This study investigates the relationship between ICT development and CO_2 emissions in ten net energy-exporting MENA countries from 1994 to 2019, using advanced econometric techniques, including Quantile-on-Quantile (QQ) regression, Wavelet Coherence analysis, and Wavelet Local Multiple Correlation (WLMC). These methodologies provide a nuanced understanding of the dynamic interactions between ICT and environmental outcomes across different emission levels, timeframes, and frequencies.

The QQ regression results show a heterogeneous and non-linear relationshipbetween ICT and CO_2 emissions. ICT is more effective in reducing emissions at both the lowest and highest quantiles, with countries like Bahrain and Qatar benefiting more from high ICT penetration. Conversely, nations such as Algeria and Iraq, with weaker ICT infrastructure, exhibit less pronounced environmental benefits.

The wavelet coherence analysis deepens this understanding by revealing that, in the short term, ICT adoption increased emissions due to the energy demands of early digital infrastructure. However, in the long term, this correlation weakens, and ICT begins to mitigate emissions, especially in countries like Saudi Arabia and the UAE, where energy-efficient ICT policies have been implemented.

Further, the WLMC results highlight temporal heterogeneity, showing strong positive correlations in countries like Oman, Libya, Kuwait, and Iran, while Bahrain and Qatar exhibit negative correlations, reflecting the success of ICT-driven environmental strategies. The WLMC also uncovered periods of decoupling between ICT and emissions during global crises, such as the Iraq War and the global financial crisis, underscoring the vulnerability of ICT-driven environmental efforts to external shocks.

These findings suggest that ICT's role in environmental sustainability evolves over time: short-term increases in emissions give way to long-term reductions as technologies advance and sustainable practices are adopted. Policymakers should not view ICT in isolation but rather integrate it with broader green energy strategies to maximize environmental benefits.

From a policy perspective, the study indicates that MENA countries can leverage ICT to reduce emissions, but the success of such efforts depends on factors such as energy policies, digital infrastructure, and global events. Countries like Bahrain and Qatar have demonstrated that ICT can effectively reduce emissions when integrated with sustainability-focused policies, whereas countries like Algeria and Iraq must invest in both digital and environmental strategies to fully realize ICT's potential for emissions reduction.

While this study contributes to the understanding of the ICT-CO_2 emissions nexus, there are limitations, including potential data biases, particularly in countries with less developed ICT ecosystems. Future research could expand the analysis to include additional variables, such as renewable energy adoption and governance quality, to further explore ICT's role in promoting sustainable development.

In conclusion, the combination of QQ regression, wavelet coherence, and WLMC methodologies offers a comprehensive perspective on the ICT-CO_2 emissions relationship in the MENA region. The results highlight the potential for ICT to contribute to emissions reduction, but emphasize the need for tailored, long-term strategies that address both the short-term challenges and long-term opportunities of digital transformation in fostering environmental sustainability.

References

Alalouch, C., Aspinall, P., & Smith, H. (2019). The influence of sustainable building design on occupants' perceptions of environmental quality in indoor environments: A framework for real-time measurement of human comfort in offices. *Sustainability*, **11**(3), 738-749.

Alnaser, W. E. (2015). Renewable energy: Reality, prospects and challenges for Bahrain. *Energy*, **93**, 1602-1606.

Amri, F., Agboola, O. P., Gozgor, G., & Hammami, S. (2019). ICT, productivity growth, and CO2 emissions: Evidence from Tunisia. *Technological Forecasting and Social Change*, **148**, 119734.

Asongu, S. A., & Odhiambo, N. M. (2018). Environmental degradation and inclusive human development in sub-Saharan Africa: The role of clean energy consumption. *Environmental Science and Pollution Research*, **25**(26), 26058-26073.

Avom, D., Ongo Nkoa, B. E., & Pholo Bala, A. (2020). ICT, financial development, and carbon emissions: Evidence from developing countries. *Environmental Science and Pollution Research*, **27**, 6918–6938.

Berkhout, F., & Hertin, J. (2001). Impacts of information and communication technologies on environmental sustainability: Speculations and evidence. *Journal of Industrial Ecology*, **6**(2), 139-154.

GeSI (2015). SMARTer 2030: ICT Solutions for 21st Century Challenges. *Global e-Sustainability Initiative (GeSI)*.

Hilty, L. M., & Aebischer, B. (2015). ICT for sustainability: An emerging research field. *Advances in Intelligent Systems and Computing*, **310**, 1-34.

Hilty, L. M., Arnfalk, P., Erdmann, L., Goodman, J., Lehmann, M., & Wäger, P. A. (2006). The relevance of information and communication technologies for environmental sustainability: A prospective simulation study. *Environmental Modelling & Software*, **21**(11), 1618-1629.

Kartal, M. T., Polanco-Martínez, J. M., Yalçınkaya, R., & Zhang, Z. (2024). Dynamic relationship between green bonds, energy prices, geopolitical risk, and disaggregated CO2 emissions: Evidence from the globe by novel WLMC approach. *Environmental Science and Pollution Research*.

Kemp, R., & Pearson, P. (2008). Measuring eco-innovation. *Final Report MEI Project*. Maastricht: UNU-MERIT.

Klimova, A., Rondeau, E., Andersson, K., Porras, J., Rybin, A., & Zaslavsky, A. (2016). The impact of the Internet of Things on sustainable development goals: A statistical analysis. *Sustainability*, **8**(9), 871.

Lee, J. W., & Brahmasrene, T. (2014). ICT, CO2 emissions, and economic growth: Evidence from a panel of ASEAN. *Global Economic Review*, **43**(2), 93-109.

Magazzino, C., Mele, M., & Schneider, N. (2021). Assessing the relationship between ICT and CO2 emissions in EU economies: A machine learning approach. *Environmental Science and Pollution Research*, **28**, 27489-27500.

Magazzino, C., & Cerulli, G. (2019). Convergence and stationarity in the CO2 emissions of MENA countries. *Journal of Economic Studies*, **46**(1), 96-117.

Mingay, S. (2007). Green IT: The new industry shock wave. *Gartner RAS Core Research Note*, **12**.

Moghadam, A., & Dehbashi, S. (2018). The role of information and communication technology in reducing environmental harm: An analysis for the MENA region. *Environmental Economics and Policy Studies*, **20**(2), 225-243.

OECD (2020). The role of ICT in achieving environmental goals. *Organisation for Economic Co-operation and Development*.

Sadorsky, P. (2012). Information communication technology and electricity consumption in emerging economies. *Energy Policy*, **48**, 130-136.

Said, A., Alam, M., & Shamsuddin, M. (2018). Information and communications technology (ICT) and environmental sustainability in high-income economies: The role of renewable energy. *Journal of Cleaner Production*, **197**, 242-253.

Shahbaz, M., Solarin, S. A., Mahmood, H., & Arouri, M. (2016). Does financial development reduce CO2 emissions in Malaysian economy? A time series analysis. *Economic Modelling*, **47**, 166-178.

Shahbaz, M., Shahzad, S. J. H., Ahmad, N., & Alam, S. (2017). Financial development and environmental quality: The way forward. *Energy Policy*, **105**, 490-502.

Shabani, Z. D., & Shahnazi, R. (2019). Energy consumption, CO2 emissions, information and communications technology, and gross domestic product in Iranian economic sectors: A panel causality analysis. *Energy*, **169**, 1064-1078.

Sinha, A., & Shahbaz, M. (2020). Technological progress and environmental degradation: A panel data analysis for MENA region. *Journal of Cleaner Production*, **252**, 119847.

Tone, K. (2011). Slacks-based measure of efficiency in data envelopment analysis. *European Journal of Operational Research*, **130**(3), 498-509.

Zhou, G. (2010). Financial development and environmental sustainability. *Journal of Environmental Economics and Management*, **60**(2), 236-248.

Appendix C: **DEA model to construct ICT index using Super-efficiency SBM model.**

Thus, following Tone (2011), the output-oriented SBM model is presented as follows:

For the i[th] DMU, the X_{ij} and Y_{rj} are vectors of input and output. The slacks-based measure (SBM) model was initially introduced by Tone (2001) to solve non-radial problems in DEA by adding input and output slacks.

$$\frac{1}{\rho_0^*} = \max_{\lambda, s^-, s^+} \left(1 + \frac{1}{s}\sum_{r=1}^{s} \frac{s^+}{y_{ro}}\right), \qquad (1)$$

subject to

$$x_{io} = \sum_{j=1}^{n} x_{ij}\lambda_j + S_i^- \qquad (i = 1, \ldots, m),$$

$$y_{ro} = \sum_{j=1}^{n} y_{rj}\lambda_j - S_r^+ \qquad (r = 1, \ldots, s),$$

$$\sum_{j=1}^{n} \lambda_j = 1,$$

$$\lambda_j \geq 0\ (\forall j),\ S_i^- \geq 0\ (\forall i),\ S_r^+ \geq 0\ (\forall r) \qquad (2)$$

where S_i^- and S_r^+ are slack vectors corresponding to input excesses (input slacks) and output shortfalls (output slacks) in the i[th] DMU. x_{io} and y_{ro} represent the input and output in the frontier O, and ρ_0^* denotes the efficiency of the DMU under consideration.

When running a DEA model, the problem of discriminating between efficient DMUs arises. To deal with this problem, Tone (2002) proposes a super-efficiency SBM model that can be calculated as follows:

$$\delta_o^* = \min_{\bar{x}, \bar{y}, \lambda} \left(\frac{1}{s}\sum_{r=1}^{s} \bar{y}_r / y_{ro}\right)^{-1} \qquad (3)$$

subject to

$$\overline{x_i} \geq \sum_{j=1, j\neq o}^{n} x_{ij}\lambda_j \quad (i = 1, \dots, m)$$

$$\overline{y_r} \leq \sum_{j=1, j\neq o}^{n} y_{rj}\lambda_j \quad (r = 1, \dots, s)$$

$$\sum_{j=1}^{n} \lambda_j = 1, \quad \bar{x} \geq x_o, \bar{y} \leq y_o, \bar{y} \geq 0, \lambda \geq 0. \quad (4)$$

Appendix C

Table A1. DEA scores for the ICT index calculated using the Super-efficiency SBM model.

Year	Algeria	UAE	Qatar	S. Arabia	Libya	Oman	Kuwait	Iraq	Iran	Bahrain
1994	0.163	1.128	0.205	0.622	0.078	0.103	1.126	0.910	0.910	0.600
1995	0.163	1.045	0.206	0.513	0.059	0.104	1.009	0.990	0.990	0.659
1996	0.163	1.051	0.206	0.666	0.027	0.079	0.702	0.100	0.100	0.407
1997	0.163	1.064	0.206	0.637	0.016	0.120	0.617	0.105	0.105	0.333
1998	0.163	1.093	0.206	0.530	0.017	0.132	0.451	0.121	0.121	0.316
1999	0.163	1.176	0.206	0.422	0.016	0.179	0.437	0.111	0.111	0.370
2000	0.163	1.127	0.205	0.385	0.020	0.209	0.466	0.111	0.111	0.390
2001	0.164	1.127	0.205	0.385	0.020	0.209	0.466	0.111	0.111	0.390
2002	0.164	1.142	0.290	0.503	0.033	0.236	0.529	0.111	0.111	0.544
2003	0.164	1.101	0.345	0.646	0.053	0.258	0.689	0.111	0.117	0.597
2004	0.163	1.087	0.380	0.649	0.133	0.264	0.684	0.111	0.148	0.608
2005	0.231	1.138	0.443	0.690	0.201	0.289	0.610	0.111	0.209	0.647
2006	0.258	1.177	0.519	0.688	0.197	0.297	0.541	0.111	0.271	0.621
2007	0.256	1.076	0.537	0.617	0.188	0.361	0.521	0.111	0.305	0.567
2008	0.237	1.030	1.017	0.587	0.281	0.363	0.498	0.112	0.356	0.563
2009	0.226	1.028	1.049	0.612	0.450	0.451	0.593	0.112	0.394	0.687
2010	0.241	1.010	1.069	1.005	0.560	0.491	0.673	0.112	0.413	0.648
2011	0.261	1.044	1.063	0.583	0.430	0.476	1.001	0.129	0.460	0.639
2012	0.287	1.071	1.058	0.642	0.367	0.523	0.789	0.154	0.496	0.816
2013	0.311	1.022	0.827	0.823	0.361	0.523	1.012	0.181	0.591	1.001
2014	0.329	1.033	0.649	1.004	0.369	0.528	1.039	0.205	0.657	0.958
2015	0.355	1.053	0.603	1.009	0.399	0.533	1.010	0.290	0.696	0.922
2016	0.381	1.066	0.603	1.006	0.404	0.504	0.710	0.238	0.763	1.004
2017	0.439	1.035	0.670	0.823	0.392	0.565	1.000	0.392	0.855	1.013
2018	0.439	1.101	0.670	0.823	0.014	0.566	0.126	0.492	0.855	1.213
2019	0.439	1.077	0.670	0.823	0.000	0.566	0.002	0.593	0.855	1.313
Average	0.249	1.081	0.543	0.680	0.196	0.343	0.665	0.240	0.427	0.685