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المجلة العلمية
لكلية الدراسات الاقتصادية والعلوم السياسية

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دورية علمية محكمة

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Does the digital economy have implications for environmental sustainability? Empirical evidence from Egypt [1]

هل الاقتصاد الرقمى له تأثير على الاستدامه البيئية: دليل تجريبى من مصر

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(1) تم تقديم البحث في 2024/10/19، وتم قبوله للنشر في 2025/5/6.

Abstract

One of the sustainable development goals of Egypt's Vision 2030 is to enhance environmental sustainability. Reducing CO2 emissions is the main objective of strengthening this sustainability, which is being worked on using developed digital technologies. Therefore, the digital economy and environmental sustainability are gaining significance and becoming more linked. Based on the argument that information and communication technologies (ICT) could serve as a tool to achieve low-carbon development, this study empirically investigates the relationship between CO2 emissions and ICT (the proxy indicator for the digital economy) in the context of GDP and renewable energy consumption (REC) in Egypt. Using the ARDL approach over the period 2000-2023, the results suggested that ICT has a substantial impact on reducing CO2 emissions, therefore emphasizing its positive environmental advantages. Also, the study outcomes supported the evidence that REC helps enhance environmental quality. Thus, energy-efficient ICT devices (i.e., smart applications) and other key inventions related to Internet use are required in Egypt to control CO2 emissions. Typically, Egypt would do much better to develop institutional and regulatory reforms for better environmental management than just trust that the digital economy and renewable energy consumption will automatically solve environmental problems.

Key words: Digital economy, ICT, environmental sustainability, ARDl approach, Egypt.

الملخص

يعد تعزيز الاستدامة البيئية أحد أهداف التنمية المستدامة في رؤية مصر 2030. ويعتبر تقليل انبعاثات ثاني أكسيد الكربون الهدف الرئيسي في تعزيز هذه الاستدامة، ويجرى العمل على تحقيق ذلك باستخدام التقنيات الرقمية المتطورة. ولذلك، يكتسب الاقتصاد الرقمي والاستدامة البيئية معاً أهمية ويصبحان أكثر ارتباطًا. وبناءً على الجدل بأن تكنولوجيا المعلومات والاتصالات يمكن أن تكون بمثابة أداة لتحقيق التنمية منخفضة الكربون، تبحث هذه الدراسة تجريبياً في العلاقة بين انبعاثات ثاني أكسيد الكربون وتكنولوجيا المعلومات والاتصالات (ICT) (أحد مؤشرات الاقتصاد الرقمي) في سياق الناتج المحلي الإجمالي (GDP) واستهلاك الطاقة المتجددة (REC) في مصر. وباستخدام منهجية الانحدار الذاتي للفجوات الزمنية الموزعة (ARDL) خلال الفترة 2000–2023، قد أشارت النتائج إلى أن تكنولوجيا

المعلومات والاتصالات لها تأثير كبير على تقليل انبعاثات ثاني أكسيد الكربون، وبالتالي التأكيد على مزاياها البيئية الإيجابية. كما دعمت نتائج الدراسة الدليل بأن استهلاك الطاقة المتجددة يساعد في تحسين جودة البيئة. وبالتالي، فإن أجهزة تكنولوجيا المعلومات والاتصالات الموفرة للطاقة (أي التطبيقات الذكية) والاختراعات الرئيسية الأخرى المتعلقة باستخدام الإنترنت مطلوبة في مصر للسيطرة على انبعاثات ثاني أكسيد الكربون. ومن الأفضل لمصر أن تعمل على تطوير الإصلاحات المؤسسية والتنظيمية لتحسين الإدارة البيئية بدلاً من مجرد الثقة في أن الاقتصاد الرقمي واستهلاك الطاقة المتجددة سوف يحل المشاكل البيئية تلقائياً.

الكلمات المفتاحية: الاقتصاد الرقمي، تكنولوجيا الاتصالات والمعلومات، الاستدامة البيئية، منهجية ARDL، مصر.

INTRODUCTION

With the rapid development of digital technologies, the digital economy is gradually becoming the engine of economic growth. As a new economic mode, the relationship between the evolving digital economy and environmental sustainability is receiving more attention in policy debates. This increased interest can be justified by the fact that information and communication technologies (ICT) have significantly improved human interactions and brought several innovations that seem to boost economic growth (Sassi and Goaied, 2013; Asongu et. al., 2016). Based on the argument that ICT could also serve as a tool to achieve low-carbon development, it is necessary to move towards maximizing potential gains from digitalization while mitigating environmental harms and facilitating sustainability; i.e. the transition to a more digital economy and, on the other, the transition to a low-carbon economy (Muench et al, 2022; UNCTAD, 2023).

The United Nations Framework Convention on Climate Change (UNFCCC), 2016 primarily highlighted ICTs as a means to share information, knowledge, and good practices among countries; to enable the development of low-carbon energy technologies; to improve energy efficiency and support various adaptation efforts (UNFCCC, 2016). Similarly, the 2023 outcome document of the UNFCCC has recognized the importance of digital transformation and increased access to technologies to achieve the goals set out in the 2016 Agreement (UNFCCC, 2023)– without considering its direct environmental impact (UNCTAD, 2024).

The environmental impact of ICT has no unanimity. Two conflicting arguments in this regard: ***the first argument*** is that ICT may improve environmental performance through improvements in energy efficiency, gains in productivity, and improvements in renewable energy production and use. This positive effect allows reducing the rate of greenhouse gas (GHG) emissions (Houghton, 2010). ***The second argument*** is that the higher levels of ICT spread could affect negatively environmental performance (Mingay, 2007).

Assessing the trade and sustainable development interface between digitalization and environmental sustainability needs the evolving digital economy to be as environmentally sustainable as possible; i.e., it is essential to acknowledge the dynamic nature of digital technologies and their applications (UNCTAD, 2019; Global Enabling Sustainability Initiative and Deloitte, 2019). In particular, continuing digitalization creates many new opportunities for harnessing data and digital technologies to foster trade and development and mitigate adverse development and environmental impacts, at the same time, the importance of ensuring that the digital ecosystem is as environmentally sustainable as possible increases further. Against a backdrop of multiple environmental crises and the digital solutions leveraged to tackle them, it is increasingly important to consider how to reduce the environmental footprint of digitalization itself (United Nations, 2021; UNCTAD, 2024).

Based on the World Bank's Tech analysis of 16 indicators (such as broadband access, quality, affordability, and market competition) across the MENA countries, Egypt is rated as "emerging" in digital infrastructure (UNCTAD, 2024). Since Egypt's ambition is to accelerate digital transformation and embrace the digital economy as the new driver of growth and job creation, it adopted in 2018, the new ICT Sustainable Development Strategy 2030 (MCIT, 2018). Egypt has an established ICT sector, which has experienced growth, especially in recent years; the contribution of ICTs to the gross domestic product (GDP) grew 16.7% year-on-year in fiscal year (FY) 2018/19 compared with FY 2017/18 (MCIT, 2020). When benchmarked against other sectors, the ICTs grew at a rate of 16.3% year-on-year in FY 2022/23, to become the fastest-growing state sector among the country's sectors for five consecutive years (MCIT, 2023).

On the other side, Egypt pays great attention to the challenges of climate change and GHG emissions since they represent obstacles to accomplishing sustainable development goals. In this regard, Egypt has taken many procedures both globally and locally. Globally, Egypt ratified the UNFCCC in 1994 to be among the first countries to respond. It also ratified the Kyoto Protocol in 2005, the Paris Agreement in 2017, and the Doha Amendments of Kyoto Protocol in 2020 (Iwata and Okada, 2014; UNFCCC, 2016; UNCTAD, 2024). Locally, the National Committee for Clean Development Mechanism (CDM) was formed in 2005 as one of the Kyoto Protocol mechanisms. In addition, the Low Emission Development Strategy (LEDS) was launched in 2018 to be linked with the Sustainable Development Strategy launched in 2016. In 2022, Egypt launched the National Climate Change Strategy (NCCS) 2050 (Ministry of Environment, 2005, 2016, 2018, 2022).

In the context of advancing environmental Sustainability in Egypt, this paper attempts to reveal empirically the nexus of digital economy and CO2 emissions. The paper is organized as follows: ***Section 1*** is an introductory one. ***Section 2*** deals with the survey of empirical literature. ***Section 3*** introduces a descriptive analysis of the data used for measurement. ***Section 4*** discusses the theoretical foundation and methodology used. ***Section 5*** draws the main conclusions.

LITERARURE REVIEW

The ICT sector contributes directly and indirectly to sustainable development goals' economic, social, and environmental aspects. ICT has become the basis for monitoring climate change, mitigating and adapting its effects, and moving towards a green circular economy based on ICTs, environmental sustainability, and climate change. In this regard, it is important to understand the carbon emission impacts of ICT, while addressing climate change challenges (Zhou et al., 2019). The connections between ICT and environmental sustainability are complicated. ICT influences the environment via three main channels: ***the first*** is through the use effect; i.e. the wastes of processing, distribution, and installation of ICT equipment significantly could contribute to an increase in the rate of CO2 emissions (Røpke and Haunstrup, 2012; Lennerfors et al., 2015; Shabani and Shahnazi, 2019; Shahnazi and Shabani, 2019). ***The second*** is through the substitution effect, i.e., reorganization of the production process to keep pace with evolving digital technologies. The argument here is that the substitution effect reduces energy efficiency, and hence reduces CO2 emissions (Salahuddin et al., 2016; Ozcan and Apergis, 2018; Danish et al., 2018a; Shabani and Shahnazi, 2019). ***The third*** is through the cost effect; i.n., ICT increases demand for other goods and services due to a decrease in prices and an increase in the return of CO2 emissions. Meanwhile, improving ICT boosts trade activities and flow, facilitating new communication channels and this may influence the environmental performance (Ozcan, 2018; Shabani and Shahnazi, 2019).

Numerous empirical studies found contradictory evidence of the environmental impact of ICT. Some literatures have suggested that ICT mitigate the rate of CO2 emissions, and therefore the ICT sector advances environmental sustainability. For instance, **Amri et al. (2019)** investigated the linkage between carbon dioxide emissions, total factor productivity, and ICT in Tunisia. Using the autoregressive distributed delay (ARDL) with the breakpoint approach over the period (1975-2014), the results suggested an insignificant effect of ICT on CO2 emissions. As a result, their recommendation to policymakers is to expand in ICT sector. **Haseeb et al. (2019)** examined the impact of ICTs, globalization, electricity consumption, financial development, and economic growth on environmental performance by using 1994–2014 panel data of BRICS economies. Using the dynamic seemingly unrelated regression (DSUR) model, the results suggested that ICTs have a significant, adverse impact on CO2 emissions, and therefore ICT positively contributes to environmental quality. **Xu et al. (2022)** used simultaneous spatial equations and the generalized 3-stage least square (GS3SLS) approach to assess the links between environmental performance and digital economy in 287 prefecture-level cities in China over the period (2008 – 2018). Their results suggested that digital economy mitigates environmental degradation through the effects of innovative and green development. **Raihan et al. 2024** examined the impact of CIT on CO2 emissions in the G-7 region from 1990 to 2019. Using panel ARDL approach, the results suggested that CIT (the proxy of digital economy) significantly reduces CO2 emissions (See also, Zhang and Liu, 2015; Ozcan and Apergis, 2018; Lu, 2018).

On the other side, some studies have found evidence of the adverse environmental impacts of ICT. For instance, **Salahuddin et al. (2016)** estimated the short- and long-run effects of ICT and economic growth on

CO_2 emissions using 1991–2012 panel data of OECD. The results of Dumitrescu-Hurlin (DH) causality test supported the argument that ICT use stimulates CO_2 emissions. They recommend that OECD countries use ICT equipment not only to reduce their carbon footprint, but also to exploit ICT-enabled emissions abatement potential to reduce emissions in other sectors, such as the power, energy, agricultural, transport, and service sectors. **Park et al. 2018** investigated the impact of ICT, on CO_2 emissions in the context of a model for financial development, economic growth, and trade openness in selected European Union (EU) countries. Using a pooled mean group (PMG) estimator for panel data from 2001 to 2014, the results suggested that ICT has a long-run relationship with CO_2 emissions and lowering environmental quality. They recommended that there is an urgent need to mitigate CO_2 emissions of CIT to maintain sustainable development in EU countries. **Danish et al. (2018b)** investigated the impact of ICTs, economic growth, and financial development on environmental quality in emerging economies using panel mean group (MG) and augmented mean group (AMG) estimation methods over the period (1990-2015). Their results suggested that the ICTs significantly affect CO_2 emissions. They recommend that Policy thresholds with the R&D in ICT sector be required to mitigate the rate of CO_2 emissions.

Zhou et al. (2019) developed an embodied carbon analysis framework by integrating input-output approaches to explore the extent to which and how ICT drives CO_2 emissions at the sector level. Using China as a case study, they found that the ICT sector is far from being environment-friendly. **Avom et al. (2020)** used the STIRPAT model to estimate both the effect and the transmission channels of ICT on CO_2 emissions in 21 Sub-Saharan African countries over the period (1996 – 2014). Their results suggested that using ICT significantly stimulates CO_2 emissions. They recommended that to mitigate the adverse effects of ICT on environmental quality, governments should design policies to improve energy efficiency, promote the use of renewable energy, and provide financial incentives for green technology development. **Weili et al. (2022)** examined the effect of ICT on carbon emission in the Belt and Road countries from 2000 to 2019 using OLS, fixed effect, and dynamic system generalized method of moments (GMM), and generalized least square (GLS) models. Their results suggested that ICT increases carbon dioxide emissions. Their recommendation to the Belt and Road countries is to improve the ICT sector which could enhance environmental quality.

From the earlier discussion, it could be concluded that the environmental impact of ICT is not clear; also, no one knows exactly what role ICT will play in the future and its effects on environmental quality. Further investigation into the impact of ICT on CO2 emissions is needed. In an attempt to resolve the debate on this issue, this paper examines the impact of ICT on CO2 emissions in Egypt using a strong methodology to reveal the extent to which the digital economy in Egypt impacts environmental quality; the paper is the first to empirically investigate such a relationship in Egypt.

DATA

The framework for investigating the relationship between digital economy and environmental sustainability in the context of GDP and renewable energy consumption (REC) requires using data on CO2 emissions (the dependent variable that measures environmental pollution), and (GDP, ICT, and REC), the regressors that affect the environment performance.

The indicators of ICT goods are considered one of the major indicators of digital economy; they include two sub-indicators: ICT goods exports (% of total goods exports), and ICT goods imports (% of total goods imports). ICT enhances trade activities and helps promote importing, which is less significant than promoting exporting (Sun et al., 2024). Thus, the ICT goods imports indicator is used here as the unit of measurement of digital economy. The time series data source of Egypt was obtained from the UNCTAD database.

Following Hao et al. (2021), Leitão et al. (2021), and Chen et al. (2022), REC is measured here as a percentage of overall energy consumption. The time series data source of GDP, REC, and CO2 was obtained from the World Bank database. The time span of the analysis is from 2000 to 2023, resulting in 24 annual observations.

It is important to discuss the descriptive statistics of the variables adopted in the study to provide background information on the variables. Table 1 provides some descriptive statistics of the mentioned variables. As shown in Table 1, ICT has the highest coefficient of variation (12.9), reflecting its high and rapid variability over the period (2000-2023). The CO2 emissions have, in contrast, the lowest coefficient of variation (1.4) which reflects their stagnation and relative stability between 2000 and

2023. From the Jarque-Bera test, all variables are normally distributed with a confidence of 95%, as the p-value of the test is larger than 5%.

Table 1: Descriptive statistics.

Statistics	CO_2 emissions	GDP	ICT	REC
Mean	12.53	8.07	1.37	1.80
Maximum	12.73	8.34	1.75	2.12
Minimum	12.14	7.83	0.94	1.59
Std. Dev.	0.17	0.16	0.18	0.15
Coefficient of variation	1.4%	1.9%	12.9%	8.3%
Jarque-Bera	3.835	1.136	0.612	1.626
Probability	0.147	0.567	0.736	0.444

Graphically, Figure (1) documents the trends in CO2 emission, per capita GDP (constant 2015$), $ICT_{\text{goods imports}}$ (% of total goods imports), and REC (% of total energy consumption) of Egypt over the period (2000-2023). It has been observed that each of CO2 emissions and GDP are increasing over time, while ICT is fluctuating ups and downs, and REC is decreasing.

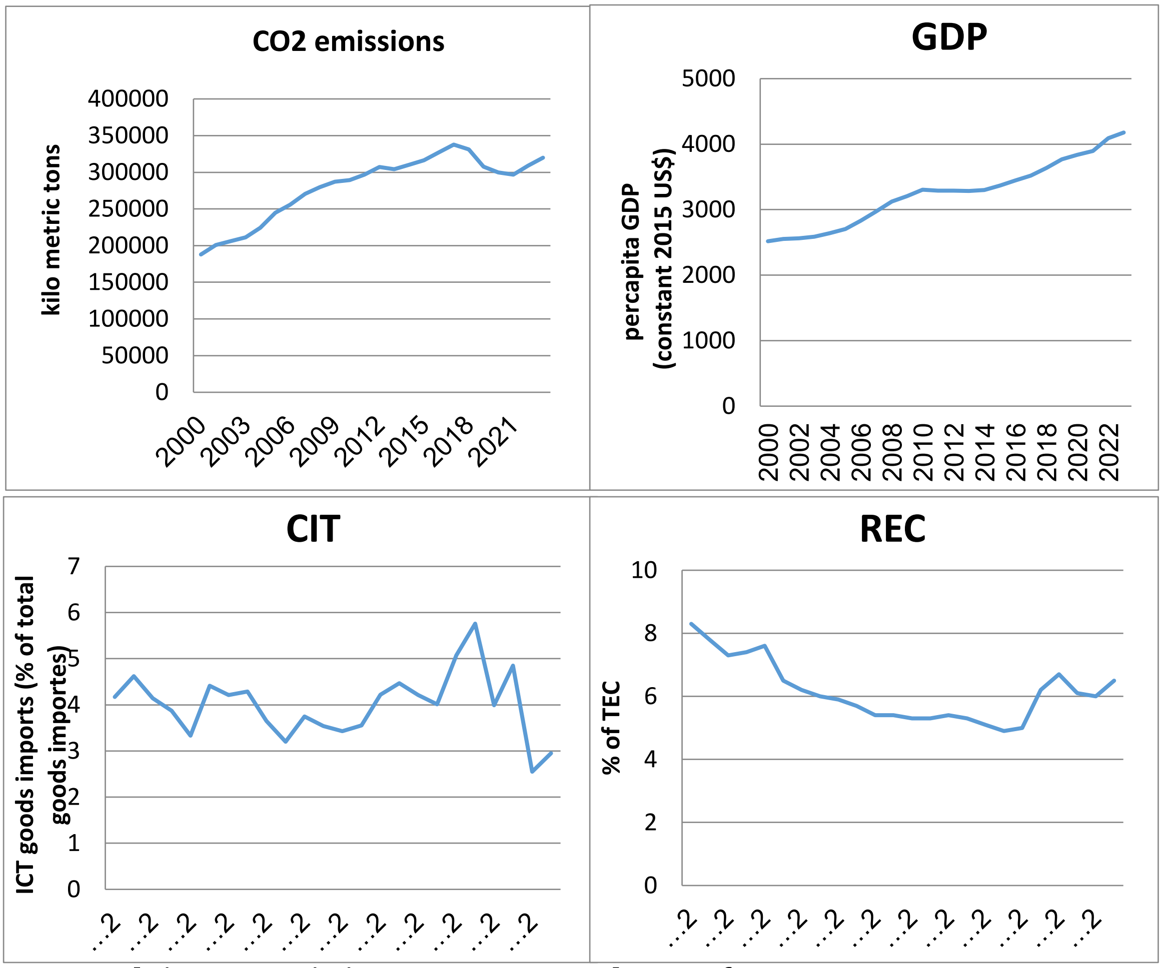


Fig 1: <u>Trends in CO2 emissions, GDP, *ICT*, and REC of Egypt, 2000-2023.</u>
Sources: Sources: UNCTAD database, World Bank database.

It should be noted that Egypt's CO2 emissions have increased dramatically over the entire analysis period; the emissions surged by over 81% between 2000 and 2023. Similarly, Egypt's share of global CO2 emissions has increased from about 0.47% in 2000 to about 0.63% in 2023. It has been noted that the increasing percentage of Egypt's CO2 emissions through this period was much higher than the global average of 0.36%. As a result, it could be concluded that Egypt was a source of CO2 emissions, not a store of them during this period.

ECONOMETRIC METHODOLOGY

The increase in CO2 emissions is undisputedly one of the main causes of global warming and environmental degradation. As an interesting, related concept, the Environmental Kuznets Curve (EKC) explains the environmental-economic nexus. More specifically, the EKC interprets how economic activities affect environmental quality in both the short run and long run. The EKC states that there is an inverted-U-shaped relationship between pollution and per capita income. It assumes that pollution initially increases with income, but eventually declines as income continues to rise. However, there is no consensus in the literature about the income level where the curve starts to decline, in other words, the exact point at which pollution starts to decline (Dinda, 2004).

Grossman and Krueger (1991) were the first to use the (EKC) hypothesis to investigate the relationship between CO2 emissions and economic growth. They validated the EKC assumption and demonstrated that in the initial stages of economic growth, CO2 emissions increase, however after a certain threshold level, these emissions begin to decline, and environmental quality improves. Mathematically, the EKC null hypothesis states that GDP in linear form may positively affect CO2 emissions, but in its quadratic form, it negatively impacts CO2 emissions. Panayotou (1993) first named this inverted U-shaped relationship ‘Environmental Kuznets Curve’.

Numerous literatures have examined the EKC hypothesis using various datasets and econometric approaches. However, the empirical outcomes of these literatures are mixed and inconclusive. Many papers have investigated the EKC assumption with energy consumption (see, for instance, Apergis and Payne, 2010; Ozturk and Al-Mulali, 2015; Jebli et al., 2015; Jebli et al., 2016; Antonakakis et al., 2017), with population (see, for instance, Alam et al., 2016; Adu and Denkyirah, 2018), and by trade (see for instance, Al-Mulali et al., 2015; Al-Mulali et al., 2016; Jebli et al., 2015 Jebli et al., 2016). However, only a few papers investigated the impact of ICT on CO2 emissions (see, for instance, Zhang and Liu, 2015; Higón et al., 2017). Accordingly, the EKC hypothesis raises controversies about whether it can be used for policy implications or not; therefore, further investigation of this relationship is justified.

This study investigates the validity of the EKC hypothesis for Egypt when the EKC equation is augmented with GDP, ICT (a proxy indicator for the digital economy) and REC. The EKC hypothesis is examined by integrating GDP, ICT and REC as determinants of CO2 emissions. Accordingly, the linear framework of the model can be expressed as follows:

$$\mathbf{lnCO_{2t} = \beta_0 + \beta_1 lnGDP_t + \beta_2 lnICT_t + \beta_3 lnREC_t + \varepsilon_t \ldots 1}$$

Where: $\mathbf{CO_{2t}}$ is the amount of $\mathbf{CO_2}$ emitted at period t, and expressed in metric tons; $\boldsymbol{GDP_t}$ is per capita GDP at period t; $\boldsymbol{ICT_t}$ is the proxy indicator for the digital economy and expressed by the indicator of ICT goods imports (% of total goods imports); $\boldsymbol{REC_t}$ is measured as a percent of overall energy consumption at period t.

This study uses the Autoregressive Distributed Lag (ARDL) approach, developed by Pesaran et al. (2001), to test the validity of the EKC hypothesis and examine the environmental impact of ICT. Although several econometric approaches have been used to estimate long-run and short-run dynamics, the ARDL approach is preferred due to its advantages. The specification of ARDL is equivalent to a standard error correction model from a statistical point of view. However, the standard errors it produces are likely to be different. Hence, the estimates calculated through ARDL are unbiased. ARDL approach calculates both long-run and short-run estimates at once through a linear transformation technique. ARDL is considered to be the most suitable approach that can be applied only for variables that are integrated of order 1 or zero (I(0) or I(1)). The data sample here is small so ARDL is the best choice to estimate long-run and short-run elasticities. The model estimates the following equation:

$$\begin{aligned}\Delta \mathrm{lnCO2_t} = \alpha_0 &+ \sum_{i=1}^{r1} \alpha_{1i}\Delta lnCO2_{t-i} \\ &+ \sum_{i=1}^{r1} \alpha_{2i}\Delta lnGDP_{t-i} + \sum_{i=1}^{r1} \alpha_{3i}\Delta lnICT_{t-i} + \sum_{i=1}^{r1} \alpha_{4i}\Delta lnREC_{t-i} \\ &+ \beta_1 lnCO_{2\,t-1} + \beta_2 lnGDP_{t-1} + \beta_3 lnICT_{t-1} + \beta_4 lnREC_{t-1} \\ &+ \beta_5 break_t + \varepsilon_t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2\end{aligned}$$

n initial step of the time series analysis is to validate the stationarity assumption. Stationarity assumption is tested using both unit root tests; the traditional unit root tests (Phillips-Perron (PP), Augmented Dickey-Fuller (ADF), Dickey-Fuller GLS (DF-GLS)), and the unit root tests with one structural break (Zivot and Andrews, 1992). Table 2 displays the results of traditional unit root tests, and Table 3 displays the results of the Zivot-Andrews unit root test. From the results, it could be concluded that the variables are I(0) and I(1), therefore specification and the estimation of the ARDL model is possible; with a confidence of 95%.

Table 2: Results of traditional unit root tests.

Variables	**Dickey Fuller-GLS**		**Augmented Dickey–Fuller**		**Phillips–Perron**	
	Intercept and trend	Intercept	Intercept and trend	Intercept	Intercept and trend	Intercept
$\ln CO_2$	-1.664	-0.531	-1.618	-1.85	-1.296	-3.019**
$\ln GDP$	-3.659**	-0.361	-3.005	-0.439	-1.804	-0.012
$\ln ICT$	-3.087*	-3.07***	-2.89	-2.96*	-2.874	-2.95*
$\ln REC$	-1.22	-1.49	-0.195	-2.22	-0.51	-2.22
$\Delta\ln CO_2$	-4.77***	-3.67***	-3.69**	-4.78***	-5.44***	-3.789***
$\Delta\ln GDP$	-4.45***	-2.42**	-5.33***	-4.44***	-5.37***	-4.403***
$\Delta\ln ICT$	-7.14***	-6.59***	-6.84***	-6.94***	-6.84***	-6.944***
$\Delta\ln REC$	-5.83***	-4.12***	-4.48**	-4.09***	-6.44***	-3.34**

*10%, **5%, ***1% significance. T-statistic reported.
Note: The appropriate lag lengths were selected according to the Akaike Information Criterion (AIC).

Table 3: Results of Zivot-Andrews unit root test.

Variables	**Trend**	**Break date**	**Intercept**	**Beak date**	**Intercept and trend**	**Beak date**
$\ln CO_2$	-3.53	2012	-3.85	2018	-4.06	2013
$\ln GDP$	-4.02	2008	-4.305	2021	-3.86	2021
$\ln ICT$	-4.21	2022	-4.52	2021	-4.96*	2018
$\ln REC$	-4.34*	2016	-4.35*	2016	-4.74	2014
$\Delta\ln CO_2$	-4.67**	2022	-5.98***	2013	-5.77***	2018
$\Delta\ln GDP$	-6.17***	2017	-5.35***	2021	-7.81***	2017
$\Delta\ln ICT$	-9.02***	2020	-9.53***	2019	-9.05***	2017
$\Delta\ln REC$	-5.7***	2009	-7.17***	2019	-5.55**	2019

*10%, **5%, ***1% significance. T-statistic reported.
Note: The appropriate lag lengths were selected according to the Akaike Information Criterion (AIC).

The cointegration test within the ARDL model is running to test for long-run equilibrium relationships between the key variables. For this, we need first to estimate the ARDL model by the ordinary least square method, then calculate the F-Statistic associated with the null hypothesis of no cointegration ($\boldsymbol{H0}: \boldsymbol{\beta_1} = \boldsymbol{\beta_2} = \boldsymbol{\beta_3} = \boldsymbol{\beta_4} = \mathbf{0}$) against the alternative hypothesis of cointegration ($\boldsymbol{H1}: \boldsymbol{\beta_1} \neq \boldsymbol{\beta_2} \neq \boldsymbol{\beta_3} \neq \boldsymbol{\beta_4} \neq \mathbf{0}$), and finally compare the calculated F Statistic with the two critical bound values given by Pesaran et al. (2001). Table 4 displays the result of the bound cointegration test. The results reveal that there is a cointegration relationship between CO_2, GDP, ICT, and REC since F-statistic (6.125) is exceeds the upper critical bound value reported by Pesaran et al. (2001).

Table 4: Results of bound cointegration test.

Model to estimate	$\mathbf{lnCO_{2t}} = \boldsymbol{f}(\mathbf{lnGDP_t}, \boldsymbol{lnICT_t}, \mathbf{lnREC_t})$
F-statistic	6.125
K	3
I(0) value	4.01
I(1) value	5.07

The cumulative sum of the recursive residuals (CUSUM) and the cumulative sum of the square of the recursive residuals (CUSUMQ) tests are conducted to examine the stability of the ARDL model. Furthermore, the validity of the ARDL model is controlled by applying serial correlation, heteroscedasticity, and normality tests. The estimated results of both long-run and short-run ARDL are presented in Table 5. The results suggested that: firstly, ICT is negatively correlated with $\boldsymbol{CO_2}$ emissions in both the short-run and long-run. Specifically, the results demonstrate that a 1% increase in LnICT will lower $\mathbf{ln}\boldsymbol{CO_2}$ by 0.143% in the short run and 0.059% in the long run. This negative correlation is statistically significant, highlighting the impact of the digital economy on reducing $\boldsymbol{CO_2}$ emissions. Secondly, GDP is not significantly correlated with $\boldsymbol{CO_2}$ emissions in both the short-run and long run. Thirdly, REC is negatively correlated with $\boldsymbol{CO_2}$ emissions in both the short-run and long run. Specifically, the results demonstrate that a 1% increase in LnREC will lower $\mathbf{ln}\boldsymbol{CO_2}$ by 0.68% in the short run and 0.287% in the long run. This negative correlation is statistically significant, highlighting the impact of REC on reducing $\boldsymbol{CO_2}$ emissions. The error correction term is significant and negative at 95% confidence and equal -0.42, this means that in the short-run, 42% deviation of the

CO_2 emission from its long run equilibrium level is corrected each year in the short run.

Table 5: Results of long and short-run analysis ARDL (1,0,0)

Variables	Coefficient	Standard error	T-statistic	p-Values
Long-run analysis				
Constant	7.687806	2.171160	3.540874	0.0027
CO2(-1)	-0.417012	0.136443	-3.056303	0.0075
Ln*GDP*	-0.242655	0.262706	-0.923674	0.3694
Ln*REC*	-0.287002	0.089875	-3.193332	0.0057
Ln*ICT*	-0.059456	0.002961	-20.0776686	0.0000
BREAK	-0.027763	0.002703	-10.2723203	0.0000
Short-run analysis				
Ln*GDP*	-0.581889	0.725277	-0.802299	0.4341
Ln*REC*	-0.688233	0.097656	-7.047495	0.0000
Ln*ICT*	-0.142575	0.0099130	-14.38266	0.0000
BREAK	-0.027763	0.015923	-1.743523	0.1004
ECT(-1)	-0.417012	0.077312	-5.393891	0.0001
R2	0.736			
Adjusted R2	0.695			
F-statistic(P-value)	17.675 (0.000)			
Diagnostic tests				
Serial correlation	1.39		0.2810	
Normality	0.879		0.644	
Heteroscedasticity	1.027		0.443	

*10%, **5%, ***1% significance.

In addition, Table 5 presents the results of diagnostic tests. The results indicated that there is no autoregressive heteroscedasticity and no serial correlation. Moreover, the residuals of the estimated ARDL model are normally distributed. These diagnostic tests confirmed the validity and stability of the estimated ARDL model. Figures 2 and 3 show the CUSUM and CUSUMQ plots, respectively, which confirm the stability of the ARDL model.

Fig. 2. CUSUM plot

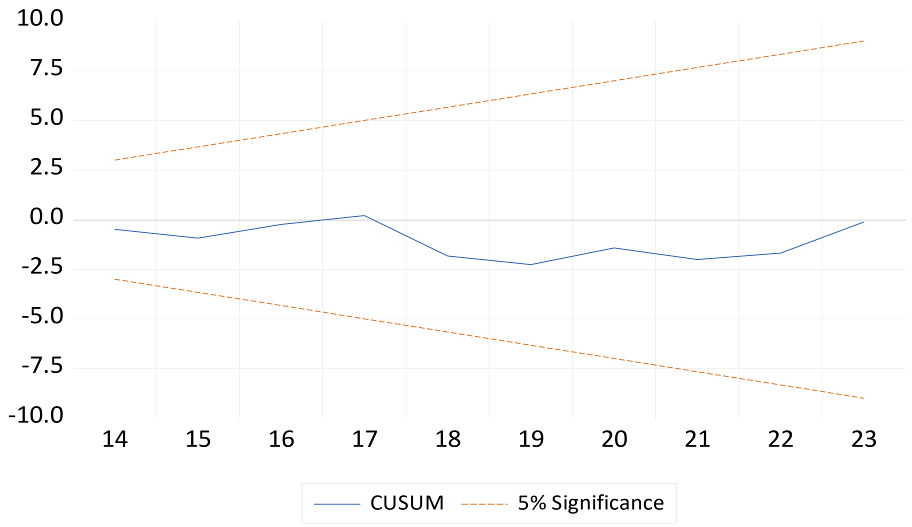
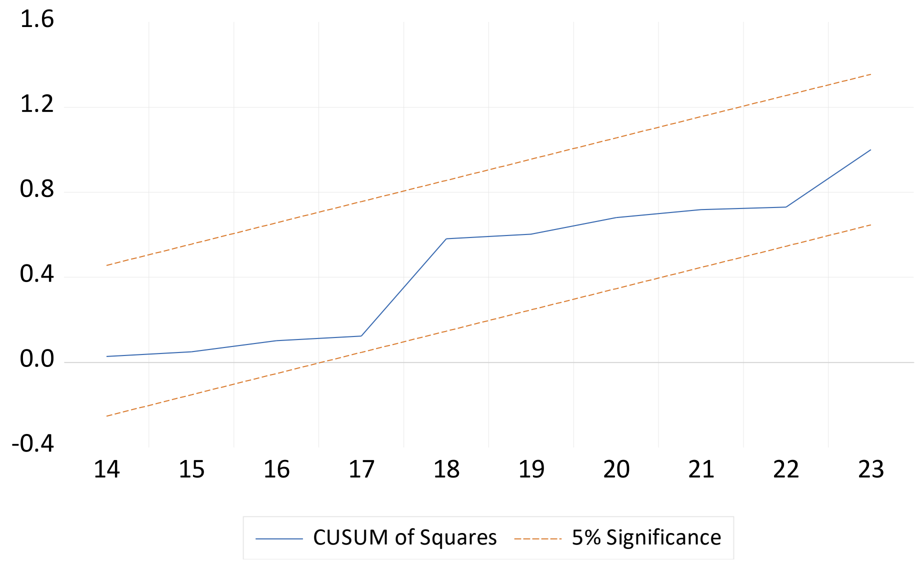


Fig. 3. CUSUMQ plot.



CONCLUSIONS AND POLICY IMPLICATIONS

This paper has examined how increasing ICT penetration in Egypt could contribute to environmental sustainability by decreasing CO_2 emissions. Using the ARDL model to investigate both short-term and long-term effects over the period 2000-2023, the results suggested that ICT (the proxy of the digital economy) has a substantial impact on reducing CO_2 emissions, therefore emphasizing its positive environmental advantages. Diagnostic tests were conducted to verify the accuracy of the ARDL results and clearly confirmed the validity and stability of the estimated ARDL model. This empirical evidence is consistent with previous literature (Zhang and Liu, 2015; Ozcan and Apergis, 2018; Haseeb et al., 2019; Raihan et al., 2024).

The negative correlation between ICT and CO2 emissions has important policy consequences. The main policy implication is that the government in Egypt needs to give high importance to the expansion of digital technology across many sectors to attain environmental sustainability. As it is rated as "emerging" in digital infrastructure, Egypt faces a particular challenge; since it is less equipped to harness digitalization to mitigate environmental risks while also being exposed to many of the potential environmental costs associated with digitalization. Hence, Egypt should focus on developing the digital infrastructure across all sectors and how to make digitalization and activities related to the ICTs more sustainable, i.e. moving towards more environmentally sustainable economic activities needs digital tools to become more efficient and resilient in the long run.

Furthermore, it is recommended that Egypt move with effective policy tools towards achieving its national schemes like the nationwide ICT strategy "Digital Egypt" launched in 2017. The strategy strives to boost Egypt to benefit from the digital economy through universal, equitable, and affordable access to ICT tools and applications to impact the lives and livelihoods of Egyptians and develop a competitive, innovative, and agile ICT industry.

In line with the findings of this study, it is recommended that Investment should be enhanced in renewable energy such as solar and wind energy. The energy-efficient ICT devices (i.e., smart applications) and other key inventions related to Internet use are required in Egypt to control CO2 emissions. This policy implication is consistent with the empirical evidence from previous literature. For instance, Chang et al., (2022) investigated whether ICT and renewable energy help enhance environmental quality in the US, UK, China, Russia, Canada, Australia, Sweden, Norway, Switzerland, and Italy using econometric techniques. Their results provided strong evidence that carbon dioxide emissions, ICT, and RE use have a bidirectional causal relationship in most circumstances. Several ICTs and RE strategies have been established and explored to profit from the possible positive influence of ICT and RE usage on environmental quality. Green energy projects, with the help of ICT, can reduce dependency on fossil fuel consumption. Furthermore, green ICT is poised to alter the way ICT business will be conducted in the future. There will be increasing pressure on the ICT industry, from regulators to manage their environmental footprints better. Finally, effective coordination among ICT, energy, and growth policies is recommended to enhance environmental sustainability in Egypt.

It is worthwhile that future studies investigate whether the established findings withstand empirical scrutiny within Egypt-specific frameworks. Such extensions are relevant for more targeted policy implications. Future studies could also extend this work by identifying additional transmission channels, particularly contextual ones, through which ICT penetration affects other environmental outcomes than CO2.

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