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Determinants of CO_2 emissions: empirical evidence from Egypt

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Abstract

This paper aims to explore the main determinants of environmental quality in Egypt by utilizing the data covering the years from 1971 to 2014. These dynamics were explored by utilizing the ARDL, wavelet coherence and Gradual shift causality approaches. The ARDL bounds test revealed cointegration among series. Findings based on the ARDL revealed; (i) positive and significant interaction between energy usage and CO_2 emissions; (ii) no evidence of significant link was found between urbanization and CO_2 emissions; (iii) no significant link was found between gross capital formation and CO_2 emissions; and (iv) GDP growth impact CO_2 emissions positively in Egypt. Furthermore, findings from the wavelet coherence technique provide supportive evidence for the ARDL estimate. The Gradual shift causality test revealed one-way causality from CO_2 emissions to energy consumption and economic growth, while there is evidence of feedback causality between CO_2 and gross capital formation. Based on these findings, policymakers in Egypt need to formulate environmental policies to promote sustainable urbanization and clean energy without undermining economic growth.

Keywords Economic growth · Environmental quality · Wavelet coherence

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1 Introduction

The industrial revolution has transformed global economies from organic human and animal-powered production techniques into inorganic production processes which are commonly based on non-renewable resources for energy use, such as fossil fuels which greatly accelerate global warming through trapping heat in the atmosphere via generating greenhouse gases (GHGs). Both for environmentalists and policymakers, global warming turned out to be one of the major environmental issues in the last couple of decades. The increase in the rate of GHGs emitted into the earth's atmosphere around the globe arises from the increase in economic activities in both developed and developing countries, albeit human economic activities has a detrimental influence on the environment. The primary contents of GHGs trapped in the atmosphere are carbon dioxide (CO_2), methane(CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFC), hydrofluorocarbons (HCFC) and sulphur hexafluoride (SF_6). Among other GHGs, CO_2 arising mainly from fossil-fuel combustion, cement production, and land-use conversion, has been ranked the number one source of global warming based on its strong heat-trapping ability, since it has the highest concentration in the earth's atmosphere (World Bank 2018). Achieving higher living standards is the main target of developing countries, which can be attained by faster economic growth. Faster economic growth can be achieved through increased gross capital formation by increasing investment, creating job opportunities, and generating employment, which constitute higher savings bringing confidence for bigger investments to be undertaken, stimulating output production. This process generates a chain effect providing a continuous increase in the output production, thus, economic growth (Levine and Renelt 1992; Taraki and Arslan 2019; Al-Mulali and Ozturk 2015). Concurrently, faster economic growth indicates faster urbanization and increased energy use, which in turn stimulates CO_2 emissions mostly in developing countries due to the overuse or misallocation of non-renewable energy sources. Therefore, this issue turned out to be of concern both for academics and policymakers. The effectiveness of decreasing CO_2 emissions depends strongly on the dedication of major emitters worldwide. Regulating for CO_2 emissions has become more complicated since it is a by-product of energy production; therefore preventive methods aimed at CO_2 emissions would have a damaging consequence on growth in an economy, especially in developing countries.

Over the years, several studies (Ozturk and Acaravci 2010; Farhani and Ben Rejeb 2012; Saboori et al. 2012; Arouri et al. 2012; Saboori and Sulaiman 2013; Kivyiro and Arminen 2014; Odugbesan and Adebayo 2020; Ozturk and Acaravci 2010; Esso and Keho 2016; Bekun et al. 2019; Adedoyin et al. 2020; Khan et al. 2020; Wasti and Zaidi 2020; Siddique et al. 2016; Akinsola and Adebayo 2020; Adebayo et al. 2020; Kirikkaleli and Kalmaz 2020; Adebayo 2020; Umar et al. 2020) have been conducted on these interconnections. However, the findings of those studies achieved different outcomes. Based on this, the paper intends to examine the long-run and causal impact of energy consumption, gross capital formation, GDP growth and urbanization on CO_2 emissions by asking fundamental questions such as: What is the impact of energy consumption, gross capital formation, GDP growth and urbanization CO2 emissions? Therefore, this paper explores the links between CO_2 emissions and its determining factors (energy consumption, gross capital formation, GDP growth, and urbanization) in Egypt by deploying the ARDL techniques to catch the short and long-run dynamics. Furthermore, this study contributes to the literature by utilizing the novel wavelet coherence technique to analyze the interconnection and causality simultaneously between CO_2 and its determinants. Utilizing the wavelet coherence is conducted for the first time in the case of Egypt in regards to CO_2 emissions and its determinants at different frequencies and time periods. Additionally, a robustness check was conducted utilizing the FMOLS and the DOLS to catch the long-run influence of the GDP growth, urbanization, energy consumption, and gross capital formation on CO_2 emissions in Egypt. The ARDL outcomes revealed that energy consumption and economic growth exert positive impact on CO_2 emissions while urbanization and gross capital formation exerts an insignificant impact on CO_2 emissions. In addition, the wavelet coherence test provide supportive evidence to the ARDL results. In order to capture the causal linkage between CO2 emissions and its regressors, we utilized Gradual shift causality test proposed by Nazlioglu et al. (2016). Unlike the traditional causality tests, Fourier Toda-Yamamoto causality takes into consideration the effect of structural break(s) using a Fourier approximation in a Granger causality analysis. The remaining sections of this paper is as follows: The next section discusses Egypt economy and trends in the economic indicators. Section 3 entails a synopsis of studies. The empirical methodology follows in the fourth section, which is accompanied by empirical findings in the fifth section, while the sixth section concludes the paper.

2 Background of the study

Egypt is a developing country that is ranked as the 3rd largest economy in Africa, following Nigeria and South Africa, with a GDP amounting $US302.256 billion, a population of 100 million, and a GDP per capita of $US 3046. Furthermore, Egypt is the largest oil-consuming country of Africa, with 41% electricity consumption and 45% oil sourced primary energy consumption (EIA 2014). Over the years from 1971 to 1985, there have been a continuous increase in the GDP followed by the oil price crash in 1986 which caused fiscal deficits of almost 15% of the GDP. Over the years between 1986 and 1991, GDP continued to decrease until the efficient and well-managed implementation of the Economic Reform and Structural Adjustment Programme (ERSAP) put in force, leading to a reduction in inflation, improvement of the current account balance and encouragement of large-scale infrastructure investment. The increase in GDP continued until 2000 and decreased due to external and internal economic and political factors, such as global economic slowdown and insecurities in the region arising from the Israeli-Palestinian political conflict. After 2000, the speed of economic reforms, such as monetary, tax, privatization, fiscal, tax and new enterprise legislation, has aided Egypt to move towards a more market-oriented economy and contributed to rising foreign direct investment. In 2004, the implementation of a well-functioning foreign exchange market removed formal and informal constraints on access to foreign exchange, which had long hindered business. These initiatives also revitalized the capital markets and insurance sector (IMF 2015). Since the removal of President Hosni Mubarak in 2011, the country has witnessed various economic turbulence. In 2016, Egypt witnessed a fall in the GDP which is due to the long-term supply-and-demand-side effect of the global economic crisis on the country's economy (World Bank 2017). In 2018 and 2019, the country experienced a GDP growth rate of 5.3% and 5.6%, respectively (World Bank 2020). Also, energy consumption and urbanization dropped by 2.47% and 1%, respectively in 2014, while gross capital formation and trade increased by 15.71% and 6.6% in 2018 (World Bank 2020). CO_2 emissions per capita in Egypt correspond to 2,32 tons per capita in 2016, a rise of 0.06 over the figure of 2,27 tons of CO_2 per capita recorded in 2015; this symbolizes a 2.5% change in CO_2 emissions per capita (World Bank 2020).

Recently, Egypt is categorized by rapid economic growth with an increasingly urban population, a rigid demand for energy, and increased CO_2 emissions. It can be easily seen from the figures above representing the trends of GDP growth, energy consumption, gross capital formation, urbanization and CO_2 emissions that breakpoints rise and fall at similar years. Egypt needs to reorganize national environmental policies, particularly those attributed to the reduction of CO_2 emissions, which highlights the relevance of this paper. These similar series of trends make Egypt an interesting country to reinvestigate the main determinants of environmental degradation and interaction among the main indicators by utilizing recently developed techniques for the short run and long-run dynamics to serve as a source for the policymakers to design sustainable and effective policies.

3 The summary of previous studies

Energy is the primary source for economic growth. Nevertheless, the misuse of energy resources produces environmental degradation which is high as illustrated by the CO_2 emission levels. A critical review of all studies linked with environmental degradation is not visible; thus, only literature that investigates the link among the CO_2 emissions, growth, urbanization and energy consumption and gross capital formation are highlighted in this paper. The econometric procedures and techniques deployed to analyze the link between CO_2 emissions and its determinants are found under studies on panel, cross-sectional and time series. Findings based on CO_2 emissions and their determinants vary as a result of disparate methods employed, study periods covered, and the nation(s) in focus. The first academic study aiming to explore the causal interconnection between economic growth and environmental degradation is known to be the research of Grossman and Krueger (1995), which identifies an inverse U-shaped connection between growth, and environmental degradation. According to their findings, environmental degradation increases at the early phase of economic growth, and subsequently decreases as the level of economy reaches a threshold (Grossman and Krueger 1995). This finding corresponds with the environmental Kuznets curve (EKC) hypothesis. The EKC theory indicates that the interconnection between real output and CO_2 emissions demonstrates an inverted U-shape, suggesting an increase in CO_2 emissions as real GDP increases at the early stages of growth and a decline in pollution as the real output rises after improvement in environmental regulations both at an inter-governmental and international stage, while technological advancement and better public awareness reduce environmental pollution (Kirikkaleli and Kalmaz 2020). There are several studies based on the foundation laid by these researchers to examine the links between environmental degradation and economic growth. Some studies confirmed the inverse U-shape relation between economic growth and CO_2 emissions, which is an indicator for environmental degradation (Narayan and Narayan 2010; Saboori et al. 2012; Lee and Lee 2009; Aeknarajindawat et al. 2020); while there are also studies which could not confirm the validity of the EKC hypothesis (Mikayilov et al. 2018; Wang et al. 2019; Adedoyin et al. 2020). Further studies have also included energy consumption to explore the interconnection between CO2 emissions, growth and energy consumption; despite the observed outcomes are different (Esso and Keho 2016; Bekun et al. 2019; Adedoyin et al. 2020; Khan et al. 2020; Wasti and Zaidi 2020; Siddique et al. 2016; Saboori and Sulaiman 2013). Recently, researchers have also included gross capital formation and urbanization in their framework to analyze the link between CO_2 emission, growth, and energy consumption, gross capital formation and urbanization (Bekhet et al. 2017; Paramati et al. 2017; Rahman and Ahmad 2019; Raggad 2018; Raheem and Ogebe 2017; Zhu et al. 2018).

Recently, several studies have utilized the wavelet tools to investigate the interconnections between CO_2 emissions and its determinants. For instance, for the case of Mexico, Adebayo (2020) explored the interconnection between CO_2 emissions, economic growth, gross capital formation, energy usage and trade openness. The investigator used wavelet coherence, and findings show that an increase in energy consumption and economic growth triggers CO_2 emissions. Furthermore, Kirikkaleli (2020), using wavelet coherence confirmed that energy consumption, economic growth, and trade openness increase CO_2 emissions in Turkey. In China, Umar et al. (2020) explored the linkage between CO_2 emissions, economic growth and financial development using Bayer and Hanck cointegration and wavelet coherence. The empirical outcomes show that financial development enhances environmental quality while economic growth has a negative impact on environmental quality. Odugbesan and Adebayo (2020) examined the long-run and causal impact of financial development, economic growth, and energy usage on CO_2 emissions in South-Africa using wavelet tools. Their empirical outcomes show that financial development and economic growth deteriorate the quality of the environment. For the case of China, Kirikkaleli (2020) examined the linkage between CO_2 emissions and economic growth using T-Y causality and wavelet coherence. The outcomes of the study reveal that increase in CO_2 emissions is accompanied by an increase in economic growth. A summary of such research is portrayed in Table 1.

The summarized literature in Table 1 shows that there are several studies investigating the link between economic growth and environmental degradation in addition to the investigation of the determinants of environmental conditions, which pertains to the increasing recognition of environmental concerns. Despite there have been several studies in the academic literature, to the best of our knowledge, no past studies have combined these variables utilizing the wavelet coherence technique to

Table 1 A synopsis of the related studies

Authors	Duration	Nation (s)	Technique (s)	Outcome(s)
Ozturk and Acaravci (2010)	1971–2007	Europe	Bounds Cointegr. & Granger Causality	Differing results
Farhani and Ben Rejeb (2012)	1973–2008	15-MENA Economies	Panel cointegration & Causality	$Y \rightarrow CO_2$
Saboori et al. (2012).	1980–2009	Malaysia	ARDL & Causality	Presence of EKC hypothesis $Y \rightarrow CO_2$
Arouri et al. (2012)	1981–2005	MENA region	Panel Cointegr.	Presence of EKC hypothesis ENE increase CO_2
Saboori and Sulaiman (2013)		ASEAN	Bounds Cointegr. & Granger Causality	$CO_2 \leftrightarrow$ ENE
Kivyiro and Arminen (2014)	1971–2009	Sub-Saharan Africa	Bounds test & Granger Causality	Differing Results
Maji and Habibullaha (2015)	1980–2015	Nigeria	Bounds Test	Co-integration is present
Esso and Keho (2016).	1971–2010	12-Sub-Sahara African nations	Bounds Cointegr. & Granger Caus. test.	Dissimilar result
Siddique et al. (2016)	1983–2013	South Asia	Panel Cointegr. & Granger Caus. test.	Y increase CO_2 ENE increase CO_2
Siddique et al. (2016)	1983-–2013	South Asia	Panel Cointegr. & Granger Caus. test.	Y increase CO_2 ENE increase CO_2
Wang et al. (2016)	1995–2017	ASEAN	Panel Granger causality	URB $\rightarrow$ ENE, CO_2
Raheem and Ogebe (2017)	1980–2013	20 African countries	PMG	URB increase CO_2
Paramati et al. (2017)	1995–2012	Developed & developing economies	Panel regression	EKC hypothesis hold Tourism-led economic growth GCF increase CO_2
Mikayilov et al. (2018)	1992–2013	Azerbaijan	Johansen, ARDLBT, DOLS, FMOLS & CCR	EKC hypothesis does not hold $Y \rightarrow CO_2$
Rauf et al. (2018)	1968–2016	China	Bounds Coint.	Y & URB decrease CO_2
Raggad (2018)	1971–2014	Saudi Arabia	Bounds Coint.	Y increases CO_2 URB reduces CO_2
Aeknarajindawat et al. (2020)	1988–2017	Malaysia	ARDL	Y increase CO_2
Rahman and Ahmad (2019).	1980–2016	Pakistan	NARDL	EKC hypothesis hold GCF increase CO_2
Bekun et al. (2019)	1960–2016	South-Africa	Bayer and Hanck co-integration, ARDL bounds test & Granger causality	ENE $\rightarrow CO_2$

Table 1 (continued)

Authors	Duration	Nation (s)	Technique (s)	Outcome(s)
Adedoyin et al. (2020)	1990–2014	BRICS economies	PMG-ARDL	EKC hypothesis does not hold ENE increase CO_2
Khan et al. (2020)	1965–2015	Pakistan	ARDL	ENE increase CO_2 Y increase CO_2
Wasti and Zaidi (2020)	1971–2017	Kuwait	ARDL, Granger Causality	CO_2-Y ENE-Y $CO_2 \leftrightarrow$ ENE Y $\rightarrow CO_2$
Cai et al.(2018).	1970–2015	G7 Nations	Bounds Cointegr. & Bootstrap.	Dissimilar results
Topcu et al. (2020).	1980–2018	122 countries	Panel VAR and Granger causality approaches.	GCF increase Y
Aeknarajindawat et al. (2020)	1988–2017	Malaysia	ARDL	Y increase CO_2
Kirikkaleli and Kalmaz (2020).	1960–2020	Turkey	Bayer & Hanck coint., Gregory & Hansen coint.	EKC hypothesis hold URB $\rightarrow CO_2$
Odugbesan and Adebayo (2020)	1971–2016	South Africa	ARDL, Wavelet Coherence	Y & URB URB increase CO_2 FD increase CO_2
Adebayo (2020)	1971–2016	Mexico	ARDL, Wavelet Coherence	GCF increase CO_2 Y increase CO_2 EN increase CO_2
Umar et al. (2020)	1965–2017	China	Wavelet Coherence, Continuous Wavelet Coherence	Financial development decrease CO_2
Kirikkaleli (2020)	1969–2016	China	Wavelet Coherence, Continuous Wavelet Coherence	Y increase CO_2

Source Authors own compilation

URB Urbanization, *ENE* energy consumption, *CO2* carbon emission, *TOP* trade openness, *Y* economic growth, → unidirectional causality, ↔ Feedback causality

Table 2 Summary of the variable statistics

	Y	ENE	CO_2	GCF	URB
Mean	1657.875	569.0235	1.582465	1.86E+10	2.262423
Median	1580.228	563.9777	1.456218	1.48E+10	2.112295
Maximum	2648.294	911.4886	2.569092	4.45E+10	3.152554
Minimum	742.5578	217.0404	0.644916	1.61E+09	1.698601
SD	599.3733	212.6120	0.584447	1.30E+10	0.439404
Skewness	0.172148	0.038336	0.182992	0.720437	0.597574
Kurtosis	1.989135	2.071870	1.941350	2.417682	2.195323
Jarque–Bera	2.090712	1.590059	2.300254	4.427886	3.805784
Probability	0.351567	0.451568	0.316597	0.109269	0.149137
Observations	44	44	44	44	44

Source Authors own compilation

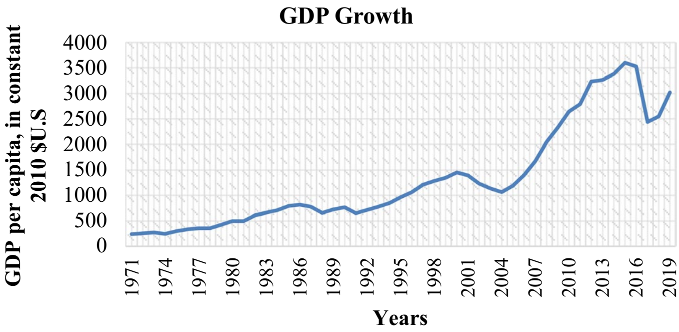

Fig. 1 GDP growth trend

explore the interconnection between CO_2 emissions and its determining factors in the case of Egypt. Therefore, our study provides new insights into the academic literature. The main questions addressed here are what interconnection exists between CO_2 emissions and its determinants and to verify the EKC theory concerning Egypt.

4 Data and methodology

The motive behind this research is to verify the impact of GDP growth, urbanization, energy consumption and gross capital formation between 1971 and 2014. Table 2 depicts a brief summary of the variables utilized. CO_2 emissions and energy consumption were gathered from the OECD (2020) and the remaining variables from the World Bank (2020). The variables' natural logarithm was taken to reduce skewness. The variables trend is depicted in Figs. 1, 2, 3, 4, and 5 correspondingly.

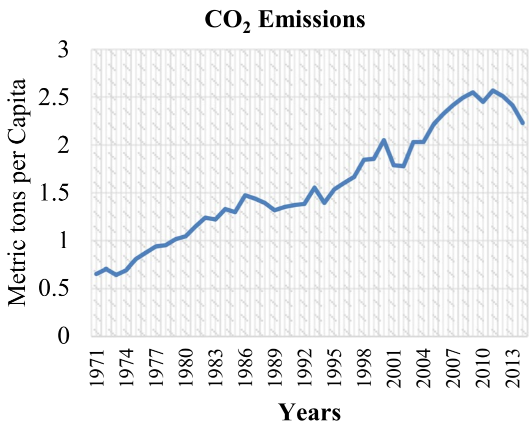

Fig. 2 CO_2 emission trend

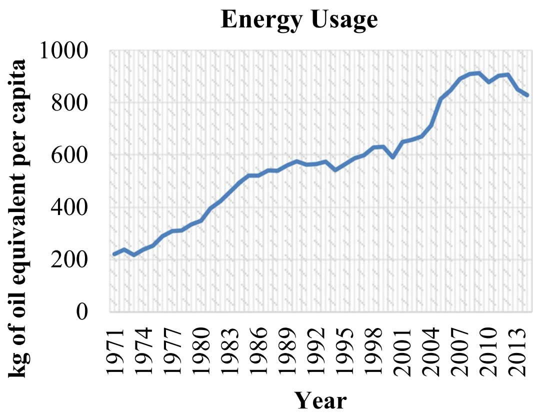

Fig. 3 Energy consumption trend

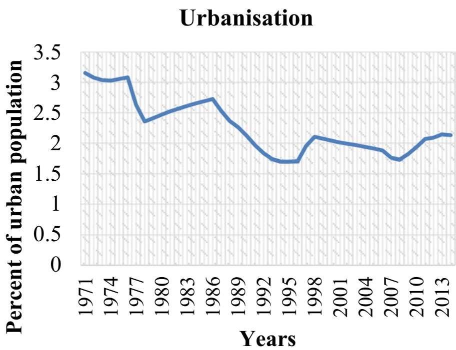

Fig. 4 Urbanisation trend

The GDP growth and energy consumption economic function is portrayed in Eq. 1 as follows 1:

$$CO_2 = f(Y, ENE, GCF, URB) \tag{1}$$

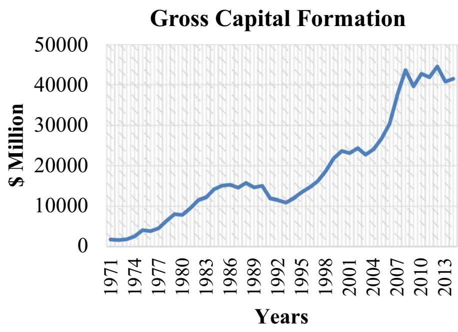

Fig. 5 Gross capital formation trend

Equation 2 depicts the econometric model as,

$$CO_2 = \vartheta_0 + \vartheta_1 Y_t + \vartheta_2 ENE_t + \vartheta_3 GCF_t + \vartheta_4 URB_t + \varepsilon_t \tag{2}$$

In Eq. 2, CO_2, Y, ENE, GCF, URB illustrates Carbon emissions, economic growth, energy usage, gross capital formation and urbanization, where t denotes time and ε represents the error term. The unit root tests were utilized to verify the stationarity characteristics of the variables under consideration in our study. Therefore, the study deployed the ADF test introduced by Dickey and Fuller (1979), the PP test proposed by Phillips and Perron (1988), and the KPSS test suggested by Kwiatkowski et al. (1992). Furthermore, the effect of structural break was considered; thus, the ZA unit root test initiated by Zivot and Andrews (2002) and the LM test initiated by Lee and Strazicich (2003) were used. These unit root tests can detect one and two structural breaks, respectively.

The Auto-Regressive Distribution Lag (ARDL) is more suitable compared to other cointegrating tests. The ARDL works perfectly when the indicators deployed are I(0) or I(1) or both. This technique is appropriate since various lag lengths can be utilized, the problem of autocorrelation is solved and it can deal with small sample sizes, by estimating the ECT, which shows the adjusted speed from disequilibrium in the short run to the equilibrium in the long-run. As stated by Pesaran et al. (2001), the F-statistics is based on two critical values, and they are the lower bound I(0) and the upper bound critical values I(1). Whenever the computed F-stat is lower than the 1(0), or in between I(0) and I(1), there is no cointegration. Therefore, we accept the null hypothesis. However, for variables to be cointegrated in the long-run, the F-stat must be greater than the lower and upper bound critical values.

The Eq. (3) below depicts the ARDL[1] Bounds tests is premised on the approach of the ARDL which is depicted the following framework:

[1] In ARDL testing, five different cases usually surface. The first scenario is the application of the bound test with trend and intercept, the second case is the application of bounds test with restricted intercept and without trend, the third case is without unconstrained determinist interception and trend, the fourth scenario is the application of the bounds test with an unconstrained determinist interception and limited trend, and the fifth scenario is the application of the bounds test with an unconstrained interception and limited trend.

$$nCO_{2t} = \vartheta_0 + \sum_{i=1}^{t} \vartheta_1 \Delta InCO_{2t-i} + \sum_{i=1}^{t} \vartheta_2 \Delta InY_{t-i} + \sum_{i=1}^{t} \vartheta_3 \Delta InENE_{t-i} + \sum_{i=1}^{t} \vartheta_4 \Delta InGCF_{t-i} + \sum_{i=1}^{t} \vartheta_5 \Delta InUBB_{t-i} + \varepsilon_t \quad (3)$$

In Eq. 3, the variables' short-run dynamic coefficients is depicted by θ_{II}, while the long-run are illustrated by $\vartheta's$ and the lags lengths is depicted by t. The ECM was integrated into the short-run parameter of the ARDL framework, which converts Eqs. 3 into 4 as follows:

$$\Delta InCO_{2t} = \vartheta_0 + \sum_{i=1}^{l} m_1 \Delta InCO_{2t-i} + \sum_{i=1}^{l} m_2 \Delta InY_{t-i} + \sum_{i=1}^{l} m_3 \Delta InENE_{t-i} + \sum_{i=1}^{l} m_4 \Delta InURB_{t-i} + \sum_{i=1}^{l} m_5 \Delta InGCF_{t-i} + \varphi ECT_{t-i} + \varepsilon_t \quad (4)$$

In Eq. 4, variables' coefficients in the short-run is represented by $m_i(i = 1 \dots 4)$ error correction term is represented by ECT_{t-1}, the coefficient of the ECT is illustrated by φ which must be statistically significant and also negative. To verify whether the model is fit, several diagnostic tests were carried out including serial correlation, Ramsey RESET, normality and heteroscedasticity tests. Furthermore, the stability of the models was tested utilizing CUSUM and the CUSUM of squares. Also, the study deploys the FMOLS and DOLS which were created by Phillips and Hansen (1990) and Stock and Watson (1993), respectively as a robustness check for the ARDL framework.

The time–frequency dependency information between the CO_2 emissions (CO_2) and GDP growth (Y), energy consumption (ENE),) gross capital formation and urbanization (URB) was explored by deploying the wavelet tools initiated by Goupillaud et al. (1984); thus, making it possible for this paper to simultaneously explore the correlation and causality between CO_2, and URB, GCF, Y and ENE in the case of Egypt. According to Kalmaz and Kirikkaleli (2019) and Adebayo and Beton Kalmaz (2020), the main novelty of the wavelet techniques is the one-dimensional decomposition of time series data bidimensional time-frequency sphere. This makes the short run and long-run link between the time series identifiable. The current research utilizes a wavelet ϖ method, which is a portion of the family of the Morlet wavelet. The ϖ is illustrated by Eq. 5 as follows,

$$\varpi(t) = \pi^{-\frac{1}{4}} e^{-i\varpi t} e^{-\frac{1}{2}t^2} \quad (5)$$

Where w stands for the frequency utilized on the restricted time series; p(t), n = 0, 1 2, 3…….N-1; and $\sqrt{-1}$ is portrayed by i. As stated by Kirikkaleli and Gokmenoglu (2019), there is transformation by the time into the time–frequency domain, which links to modification in wavelet.ϖ is transformed; thereby, advanced into $\varpi_{k,f}$. Equation 6 illustrates this explanation;

$$\varpi_{k,f}(t) = \frac{1}{\sqrt{h}}\varpi\left(\frac{t-k}{f}\right), k,f \in R, f \neq 0 \tag{6}$$

p(t), which is the time-series data is added. Hence, Eq. 7 indicates the function of the continuous wavelet:

$$\varpi_p(k,f) = \int_{-\infty}^{\infty} p(t)\frac{1}{\sqrt{f}}\varpi\left(\frac{t-k}{f}\right)dt, \tag{7}$$

According to Mutascu (2018), after the addition of the coefficient ψ to the Eqs. 8, 9 is redeveloped.

$$p(t) = \frac{1}{C_\varpi}\int_0^{\infty}\left[\int_{-\infty}^{\infty}\left|\mathfrak{w}_p(a,b)\right|^2 da\right]\frac{db}{b^2} \tag{8}$$

In order to capture the vulnerability of GDP growth, energy consumption, urbanisation and CO_2 emission, wavelet power spectrum (WPS) which is depicted in Eq. 9 is utilized.

$$WPS_p(k,f)\left|W_p(k,f)\right|^2 \tag{9}$$

In Eq. 10, the cross-wavelet transform (CWT) method changed the time-series variable;

$$W_{pq}(k,f) = W_p(k,f)W_q(k,f) \tag{10}$$

where $W_p(k,f)$ and $W_q(k,f)$ portray the two time-series indicators. The squared wavelet coherence is illustrated in Eq. 11:

$$R^2(k,f) = \frac{\left|S\left(f^{-1}W_{pq}(k,f)\right)\right|^2}{S\left(f^{-1}\left|W_p(k,f)\right|^2\right)S\left(f^{-1}\left|W_q(k,f)\right|^2\right)} \tag{11}$$

If the $R^2(k,f)$ gets closer to 0, it designates zero correlation between both series. Nevertheless, at any time $R^2(k,f)$ move closer to 1; showing that there is an indication of connection at a particular scale, which is demonstrated by a spherical, thick black line and also explained by a warmer color (red). Information about the collaboration sign is not provided by the $R^2(k,f)$ values. Consequently, Torrence and Compo (1998) "offered a method by which Wavelet coherence can be captured applying differences via deferrals signs in two-time series wavering" (Pal and Mitra 2017). The WTC at different phases is shown by Eq. 12 as follows:

$$\phi_{pq}(k,f) = \tan^{-1}\left(\frac{L\left\{S\left(f^{-1}W_{pj}(k,f)\right)\right\}}{O\left\{S\left(f^{-1}W_{pj}(k,f)\right)\right\}}\right) \tag{12}$$

Table 3 Unit root (T& I)

Tests	Y	Order	ENE	Order	CO_2	Order	GCF	Order	URB	Order
ADF	−7.79*	I(1)	−6.04*	I(1)	−7.79*	I(1)	−3.37***	I(0)	−3.60**	I(1)
PP	−7.78*	I(1)	−6.07*	I(1)	−7.78*	I(1)	−4.99*	I(1)	−3.48***	I(1)
KPSS	0.13***	I(0)	0.15**	I(0)	0.13**	I(0)	0.12***	I(0)	0.15**	I(0)

Source Authors own compilation

*, ** and *** denote the significance level of 1%, 5% and 10% correspondingly

An imaginary operator and a real part operator are symbolized by L and O correspondingly.

In order to capture the causal interconnection between CO_2 emissions and its determinants, we employed Fourier Toda–Yamamoto causality test is developed by Nazlioglu et al. (2016). This causality test is often referred to as the "gradual shift causality test." Unlike the traditional causality tests, Fourier Toda-Yamamoto causality takes into consideration the effect of a structural break(s) using a Fourier approximation in a Granger causality analysis.

5 Empirical findings

Before exploring the impact of the determinants of CO_2 emissions, the ADF, PP, KPSS, ZA and LM unit root tests were deployed to capture the integration order amongst the series of variables under consideration. Table 3 illustrates the conventional unit root tests at trend and intercept, while Table 4 reveals the unit root tests with a structural break(s) at trend and intercept. The outcomes of the conventional unit root tests reveal that all the variables are non-stationary at level. However, after taking the first difference, all the variables are stationary. Furthermore, after taking into account the effect of the structural break(s), all the indicators are non-stationary at level. However, after taking the first difference, all the variables are stationary.

The unit root test results confirm the existence of stationarity of the series under at mixed levels of either at level or first-order integration, I(0) or I(1), which is appropriate for utilizing the ARDL based bounds cointegration approach.

ARDL bounds test results to explore the cointegration link among the variables, in the long run, are depicted by Table 5 below.

In Table 5, the proof of cointegration between CO_2 emissions and energy consumption, GDP growth, gross capital formation and urbanization surfaced. The model (1,1,1,1,0) is significant as the F-statistic (5.072*) is higher than the 1% level upper critical bounds (UCB). Furthermore, serial diagnostic tests were conducted on the model. It is clear from Table 5 that the model scale through these diagnostic tests. Thus, we fail to reject the null hypothesis in all the diagnostic tests (Serial correlation, Normality, Heteroscedasticity, and Ramsey) conducted. The CUSUM and CUSUMsq tests are depicted in Figs. 6 and 7 respectively. The outcomes show that at 5% level of significance, the CUSUM and CUSUMsq are stable.

Table 4 Unit root tests with structural break(s) (T & I)

Tests	Y	Order	ENE	Order	CO_2	Order	GCF	Order	URB	Order
ZA	−6.547* [1995]	I(1)	−7.104* [2004]	I(1)	−9.397 [2003]	I(1)	−7.206* [1994]	I(1)	−4.89*** [1979]	I(1)
LM	−6.216** [1990] {2008}	I(1)	−6.396** [1981] {1994}	I(1)	−7.851* [1998] {2002}	I(1)	−5.962* [1989] {1992}	I(1)	−5.911*** [1984] {1994}	I(1)

Source Authors own compilation

*, ** and *** denote the significance level of 1%, 5% and 10% correspondingly

Table 5 Results of the ARDL based bounds test of cointegration

Model specification	$CO_2 = f(Y, ENE, GCF, URB)$
F-statistic	5.072*
Inference	(1,1,1,1,0)
Cointegration	Yes
Serial correlation	0.13 (0.26)
Normality	0.16 (0.91)
Heteroscedasticity	1.18 (0.33)
Ramsey	0.50 (0.61)

Notes For serial correlation, Breusch–Godfrey serial correlation test is done with H_0: No serial correlation is present in the residuals. For normality, Chi square test is done with H_0: residuals are normally distributed

For heteroscedasticity, Breusch–Pagan–Godfrey test is done with H_0: residuals variance are all equal

Source Authors own compilation

*When the assumption 'restricted intercept and trend in data' is considered

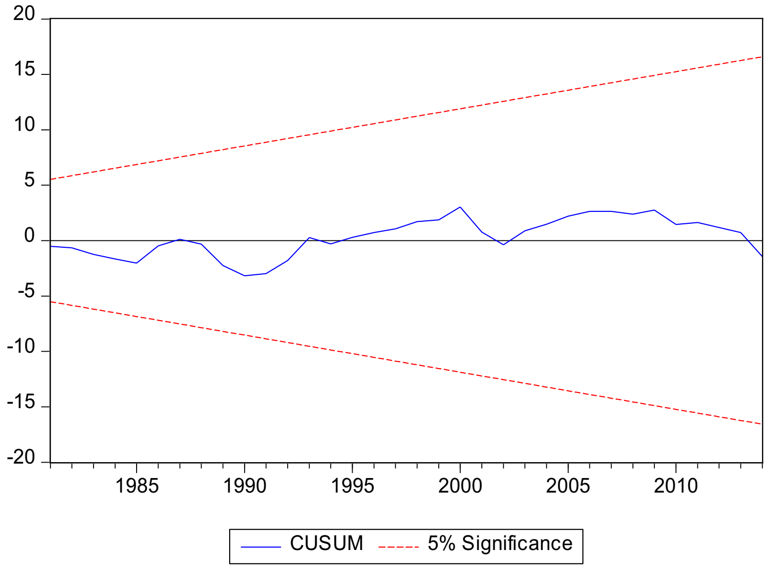

Fig. 6 CUSUM

This paper employs the Schwarz Criterion (SIC) in selecting the optimal lag because it produces results that are more parsimonious than the Akaike Information Criteria (AIC). Since the cointegration is present in at least two vectors, this study

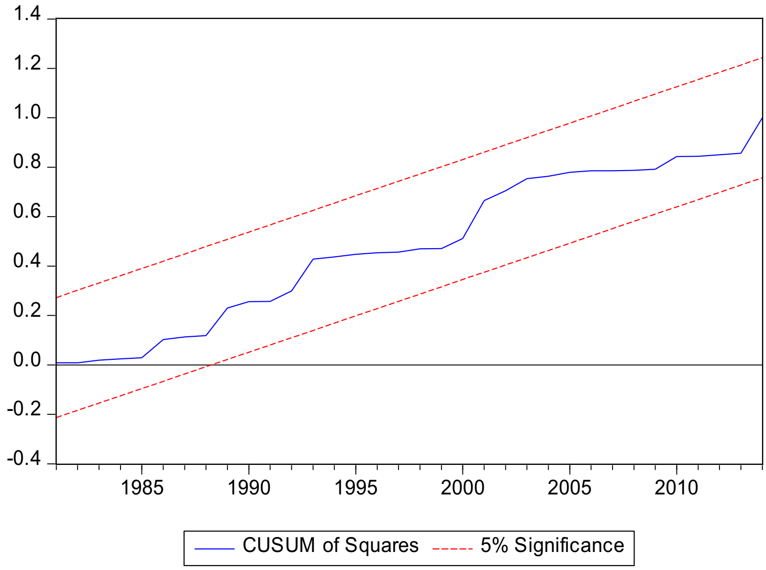

Fig. 7 CUSUM of square

Table 6 ARDL short-run and long-run estimates

Variable	Coefficient	Dependent variable: CO	
		SE	T-statistic
Constant	−6.5406	1.4877	−4.3964*
Y	3.9341	1.1323	3.4741*
ENE	0.9237	0.4020	2.2976**
GCF	0.1308	0.1356	0.9649
URB	0.2047	0.1904	1.0751
ECT	−0.9036	0.1702	−5.3082

Source Authors own compilation

* and ** signifies significance level of 1% and 5% respectively

further investigates the long-run effect of energy consumption and urbanization on the GDP growth and gross capital formation on CO_2 emissions in the case of Egypt, which is illustrated in Table 6 below.

The findings represented in Table 6 show that; (i) the GDP growth positively influences CO_2 emissions. This implies that when other variables are held constant, a 3.9% increase in CO_2 is the result of the 1% increase in GDP growth. Thus, increasing in economic expansion harms the quality of the environment. This finding aligns with past studies (Kalmaz and Kirikkaleli 2019; Mikayilov et al. 2018; Aeknarajindawat et al. 2020; Khan et al. 2020; Wasti and Zaidi 2020; Siddique et al. 2016; Adebayo et al. 2020). (ii) There is a positive and significant interaction between energy consumption and CO_2 emissions. This means that a 0.92% increase

Table 7 Robustness check for the ARDL coefficients

FMOLS				DOLS		
Variable	Dependent variable: CO_2			Dependent variable: CO_2		
	Coefficient	SE	T-stat (P)	Coefficient	SE	T-stat (P)
Constant	−6.372	1.406	−5.528*	−6.540	1.206	−5.421*
Y	4.103	0.746	5.496*	3.934	0.918	4.284*
ENE	0.975	0.266	3.655*	0.923	0.326	2.833**
GCF	0.129	0.095	1.359	0.130	0.109	1.189
URB	0.123	0.130	0.950	0.204	0.154	1.325

Source Authors own compilation

* and ** signifies significance level of 1% and 5% respectively

in CO_2 emissions is the result of a 1% increase in energy consumption. Therefore, energy consumption deteriorates the environmental quality in Egypt. This finding corresponds to previous studies (Khan et al. 2020; Wasti and Zaidi 2020; Adedoyin et al. 2020; Kalmaz and Kirikkaleli 2019). (iii) No evidence of a significant link was found between urbanization and CO_2 emissions. This finding is in line with past studies (Fan et al. 2006; Martínez-Zarzoso and Maruotti 2011; Li and Lin 2015); but still there are some studies that found different results in the literature (Raheem and Ogebe 2017; Raggad, 2018; Zhu et al. 2018). (iv) CO_2 emissions are not impacted by gross capital formation. This outcome does not correspond to past studies (Bekhet et al. 2017; Paramati et al. 2017; Rahman and Ahmad, 2019; Topcu et al. 2020). As anticipated, the ECM is statistically significant with the right signs, which is -0.90. This illustrates that short-run shocks can be adjusted back to the equilibrium in the long run by 90%.

In order to verify the consistency of the ARDL long run estimation, this study deployed the FMOLS and DOLS as a robustness check. Table 7 below illustrates the findings based on the FMOLS and DOLS. The findings from both the FMOLS and DOLS are consistent with the ARDL long run result.

In order to simultaneously capture both the correlation and causality between CO_2 and its determining factors in Egypt between 1971 and 2014, this study utilized the wavelet coherence technique which is depicted in Figs. 8, 9, 10 and 11 respectively. This method is obtained from econophysics and it merges information regarding time and frequency domains. According to Kirikkaleli (2020), this technique is sourced from mathematics by combining information on both time and frequency domain causality methods to gather earlier unseen information. Hence, the current research enables correlation and causality in the short and long-run between the dependent variable, which is CO_2 emissions and its determinants of GDP growth, energy consumption, gross capital formation and urbanization in Egypt to be explored. In Figs. 8, 9, 10 and 11, the cold color (blue) illustrates no link between the variables, whereas a high dependency among the variables is portrayed by the warmer color (yellow). The causality and correlation direction is portrayed by arrows enclosed by the thick black line

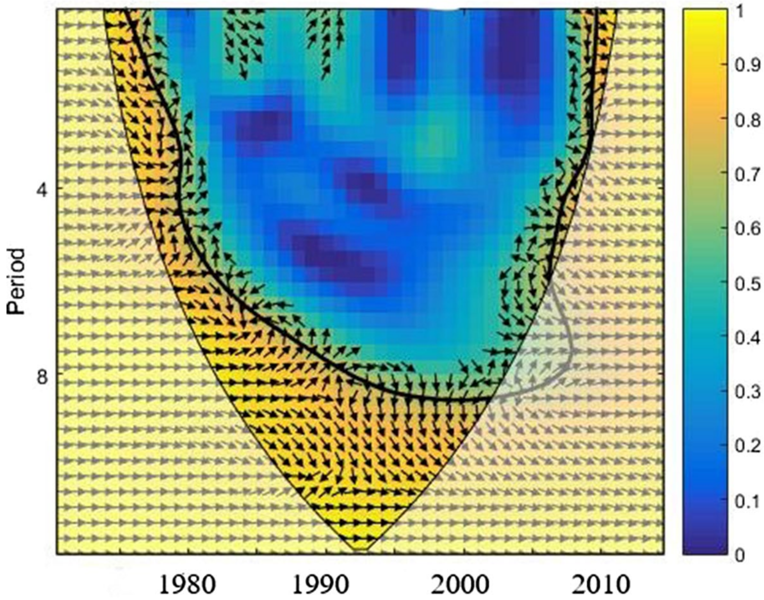

Fig. 8 Wavelet coherence: CO_2 & ENE

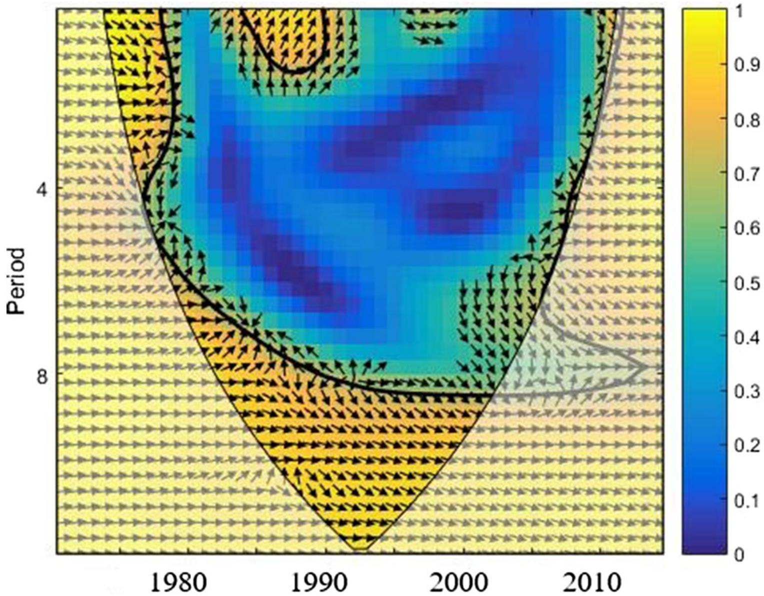

Fig. 9 Wavelet coherence: CO_2 & GCF

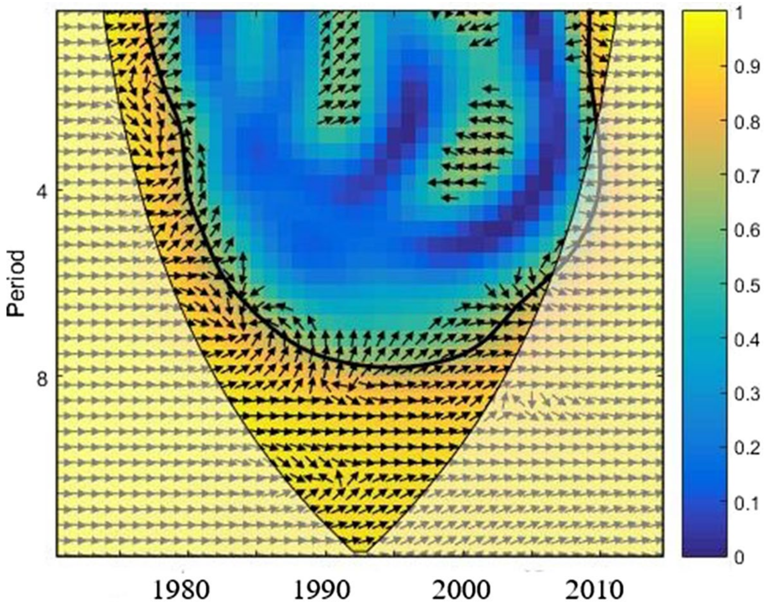

Fig. 10 Wavelet coherence: CO_2 & ENE

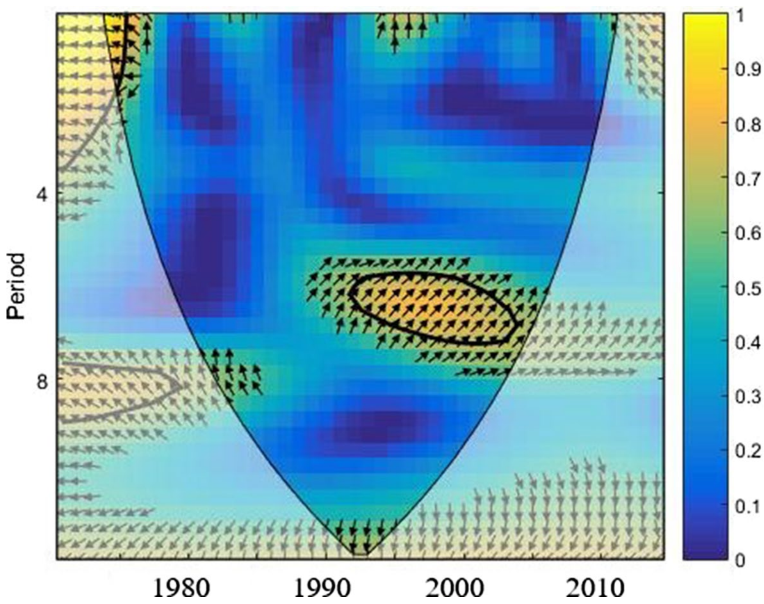

Fig. 11 Wavelet coherence: CO_2 & URB

Table 8 Gradual shift causality test

Direction of causality	Wald-stat	*P* value	Decision
$CO_2 \rightarrow Y$	18.191	0.0111**	Reject H_o
$Y \rightarrow CO_2$	7.4209	0.3864	Do not reject H_o
$CO_2 \rightarrow ENE$	12.363	0.0892***	Reject H_o
$ENE \rightarrow CO_2$	9.9939	0.1889	Do not reject H_o
$CO_2 \rightarrow GCF$	14.672	0.0404**	Reject H_o
$GCF \rightarrow CO_2$	20.216	0.0051*	Reject H_o
$CO_2 \rightarrow URB$	10.873	0.1442	Do not reject H_o
$URB \rightarrow CO_2$	7.5517	0.3737	Do not reject H_o

→ indicates the direction of causality. *, ** and *** denote the 10%, 5% and 1% significance levels, respectively

in the wavelet coherence analysis. Furthermore, negative correlation is depicted by leftward arrows whilst positive correlation is illustrated by rightward arrows. Also, when arrows are rightward and up or leftward down, the second variable causes the first variable, whereas when there is rightward and down or leftward and up, the first variable causes the second variable. In Fig. 9, between 1972 and 1990, at different scales the arrows are pointing to the right, which shows a positive correlation between GDP growth and CO_2 emissions. Also, the rightward and down arrows indicate that CO_2 led GDP growth. In Fig. 9 between 1972 and 1976 at different scale, there is a positive correlation between CO_2 and GCF. Also, between 1982 and 1984 at the short term (high-frequencies), there is evidence of positive correlation between CO_2 and GCF. Rightward and down arrows in this period indicate that CO_2 led GCF. In Fig. 10 between 1972 and 1983, at different scales, rightward arrows portray a positive correlation between energy usage and CO_2 emission. The rightward and up arrows show that energy consumption led CO_2 emissions during this timeframe. Also, between 1990 and 1993, and between 2003 and 2010 in the short term (high-frequencies), a positive correlation between energy consumption and CO_2 emission surfaced. The rightward and up arrows shows that energy consumption causes CO_2 emissions. Lastly, in Fig. 11, between 1993 and 2001, there is confirmation of a positive correlation between CO_2 emission and urbanization; despite there is confirmation of a negative correlation between CO_2 emissions and urbanization between 1972 and 1976. The rightward and down arrows between 1992 and 2001 indicate that $C0_2$ emissions causes URB.

This study also explores the causal linkage between CO_2 emissions and their determinants (energy consumption, economic growth, urbanization, and gross capital formation). The outcomes of the Gradual Shift Causality Test is revealed in Table 8. The outcomes revealed; (i) one-way causality from CO_2 emissions to economic growth; (ii) unidirectional causality from CO_2 emissions energy consumption; (iii) bidirectional causality between CO_2 emissions and gross capital formation.

6 Conclusion

Utilizing Egypt as a case study, the investigators explored the interconnections between CO_2 emissions and energy consumption, gross capital formation, and urbanization by deploying time series data stretching over 44 years (1971–2014). The study used the ARDL based bounds tests to analyze the long-run cointegration since the variables are integrated at mixed level, i.e., I(0) and I(1). A cointegration between the dependent and independent variables is confirmed by the bounds test. After the cointegration is verified, the ARDL technique was deployed to examine the long-run interaction between CO_2 emissions and its determinants. Furthermore, the FMOLS and DOLS are employed as a robustness check for the ARDL in the long-run. Findings from the ARDL reveals that both energy consumption and economic deteriorates environmental quality. Additionally, the wavelet coherence technique, which is a current technique in econophysics, was utilized to examine both the correlation between CO_2 emissions and its determinants. The outcomes of the wavelet coherence revealed positive correlation between CO_2 emissions, and energy consumption, gross capital formation and economic growth while no significant correlation was found between CO_2 emissions and urbanization. In order to capture the causal linkage between CO_2 emissions and its regressors, we utilized Gradual shift causality test proposed by Nazlioglu et al. (2016). Unlike the traditional causality tests, Fourier Toda-Yamamoto causality takes into consideration the effect of structural break(s) using a Fourier approximation in a Granger causality analysis. Findings from the Gradual shift causality test revealed one-way causality from CO_2 emissions to economic growth. Furthermore, there is unidirectional causality from CO_2 emissions energy consumption while there is evidence of bidirectional causality between CO_2 emissions and gross capital formation. Based on the findings, the energy policy in Egypt has a vital role to play in raising both the environmental issues induced by CO_2 emissions and the economic circumstances. The proportion of production of renewable energy in total energy production with suitable energy policies can be increased in Egypt since it is an advantaged nation for renewable energy sources, including biomass, solar, wind, and hydropower produced from large dams over the Nile. High levels of CO_2 emissions in Egypt are caused by two main factors. Firstly, due to the inefficiency of Egypt's energy usage, the intensity of energy is high. Secondly, the total energy output relies on non-renewable sources rather than renewable sources. Carbon intensity should be minimized with a higher share of renewable energy sources for energy generation so that CO_2 emissions can be lessened by effective energy policies, including carbon taxes increment for the manufacturing industry; because those taxes can in turn offer financial support to the manufacturing industry, research and development for technological developments aimed at decreasing intensity of energy and/or for the creation of renewable energy sources. In addition, in order to promote sustainable urbanization in Egypt, clean energy, economic and environmental policies must be formulated to steer urban development growth in Egypt without undermining economic growth and maintaining a reduction in carbon emissions to achieve better environmental quality. Lastly, policymakers may also suggest mechanisms such as carbon taxes, emissions trading systems, carbon capture and storage etc. The limitation faced in this study is the non-availability of data beyond the study period; while this research allows for the identification of strong research evidence utilizing ARDL, DOLS, FMOLS, and wavelet coherence techniques. Additional research should be conducted in other developing nations around the globe by using different proxies of environmental degradation.

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