Contents list available at IJRED website
Int. Journal of Renewable Energy Development (IJRED)
Journal homepage: http://ejournal.undip.ac.id/index.php/ijred

Research Article

Investigating the Causal Linkage Among Economic Growth, Energy Consumption and CO_2 Emissions in Thailand: An Application of the Wavelet Coherence Approach

Tomiwa Sunday Adebayo[a]*, Gbenga Daniel Akinsola[b]

[a]*Faculty of Economic and Administrative Science, Department of Business Administration, Cyprus International University, Northern Cyprus, Mersin 10- Turkey*

[b]*Faculty of Economics and Administrative Science, Department of Business Management, Girne American University, Northern Cyprus, Mersin 10-Turkey*

ABSTRACT. The study aims to explore the causal linkage between CO_2 emissions, economic growth and energy consumption in Thailand utilizing the wavelet coherence approach, conventional Granger and the Toda-Yamamoto causality techniques. In this study, time-series data spanning the period between 1971 and 2018 were used. No prior study has used the wavelet coherence approach to collect information on the association and causal interrelationship among these economic variables at different frequencies and timeframes in Thailand. The study objectives are structured to answer the following question: Does economic growth and energy consumption lead to CO_2 emissions in Thailand. The findings revealed that: (a) Changes in economic growth led to changes in CO_2 emissions in Thailand at different frequencies (different scales) between 1971 and 2018. (b) A bidirectional causal relationship between CO_2 emissions and energy consumption. (c) A positive correlation between CO_2 emissions and energy usage in the short and long-run between 1971 and 2018. (d) A positive correlation between GDP growth and CO_2 emissions in the short and long-run between 1971 and 2018. The study suggested that Thailand should initiate stronger policies towards enhancing the efficiency of energy and energy-usage programs to minimize unnecessary energy waste.

Keywords: CO_2 emissions, Energy consumption, Economic growth, Toda-Yamamoto Causality, Wavelet coherence technique

Article History: Received: 13th July 2020; Revised: 30th August 2020; Accepted: 3rd Sept 2020; Available online: 12th Sept 2020
How to Cite This Article: Adebayo, T.S.and Akinsola, G.D. (2021) Investigating the Causal Linkage Among Economic Growth, Energy Consumption and CO_2 Emissions in Thailand: An Application of Wavelet Coherence Approach. *Int. Journal of Renewable Energy Development*, 10(1), 17-26
https://doi.org/10.14710/ijred.2021.32233

1. Introduction

Global warming, an indicator of climate change, has been one of the most popular and debated subjects in scientific research and politics in recent years. As stated by the International Panel on Climate Change (IPCC) (1996), rising carbon emissions (CO_2) as a greenhouse gas (GHG) have largely led to climate unrest and global warming. Environmental concerns linked to rising emissions have been discussed extensively. It is no longer surprising that global warming is the most crucial issue threatening the planet today. In an attempt to minimize global warming and its detrimental effects on the environment as a whole, many nations have ratified the Kyoto Protocol, and efforts have been made to minimize emission levels. The Paris Agreement initiated by the United Nations in December 2015 represents a significant milestone in measures aimed at fighting global warming and reducing the impact of greenhouse gas emissions. As a result of increasing knowledge of the effects of CO_2 emissions and climate change on the environment, people, private organizations, and policymakers have begun to increasingly focus on resolving these environmental concerns. CO_2 emissions are aggregated GHG emissions created or produced explicitly or implicitly by a product, event, individual, or organization. The world now understands the cultural, social, and political value of these pollutants and the necessity to reduce them to mitigate climate change. Thailand's economy relies on exports such as machinery, rubber, and gems, which contribute more than two-thirds of the nation's GDP. Thailand is an emerging economy with a GDP and GDP per capita of US$505 billion and US$7,273.56, respectively, in 2018 (World Bank, 2020). Thailand's economy is the 8th largest in Asia, and its population was 69.43 million in 2018 (World Bank, 2020). Thailand's level of GHGs in 2014 was reported to be approximately 337 $MtCO_2$. In this respect, Thailand's national GHGs accounted for just 0.84% of global emissions in 2012 and 0.64% of global emissions in 2015. Furthermore, between 1990 and 2012, Thailand's share of cumulative emissions was 0.75 percent. In Thailand, the CO_2 emissions per

* Corresponding author: twaikline@gmail.com

capita was 4.06 metric tons in 2018. In 1999, CO_2 emissions per metric tons was 2.75 metric, which increased to 4.06 metric tons in 2018, which represents an annual increase of 2.13%. CO_2 emissions in Thailand also rose in 2018, as the energy sector released 196.5 tons of CO_2 in 2018, representing a 0.73% upsurge compared to 2017 (EPPO, 2019). Although several studies have been conducted to investigate the causal relationship between economic growth, energy consumption and CO_2, the results have been mixed with conflicting findings. Meanwhile, in reference to Odugbesan and Rjoub (2020), this issue of conflicting and unreliable results can be avoided if the author can deploy a novel technique for analysis. Thus, this study employed the wavelet coherence technique to ensure a reliable outcome. The technique of wavelet coherence has the ability to overcome the limitation of the "Fourier transform" in the analysis of nonstationary time series. Therefore, this study to examine the correlation and causal linkage between CO_2 emissions and energy consumption and economic growth by asking the following questions: What is the influence of GDP growth on CO_2 emissions? Does energy consumption trigger CO_2 emissions? Furthermore, the wavelet coherence was used to simultaneously investigate the correlation and causality between CO_2 emissions and energy consumption and economic growth in Thailand. To the best of our knowledge, no study has previously used the wavelet coherence approach to obtain information on the dynamic correlation and/or causality among CO_2 emissions and energy consumption and economic growth in Thailand at different frequencies and different time periods. Therefore, this study fills this gap in the literature. The rest of the paper is organized as follows: the introduction is presented in the first part; the second part covers the literature review; the third part covers the data and methodology; the fourth part presents the interpretation and discussion of the results, while the last section covers the conclusion and policy recommendations based on the empirical findings.

2. Synopsis of the related studies

Prior studies on environmental degradation have investigated the interaction between CO_2 emissions, energy consumption and economic growth. They used the environmental Kuznets Curve (EKC) hypothesis to analyse the interaction between GHG emissions, economic growth and energy consumption in the long-run. The EKC hypothesis was centred on the Inverted-U interconnection between the level of carbon emissions and the country's income. Grossman and Krueger (1995) were the first researchers to introduce the EKC hypothesis to explore the association between per capita income and environmental variables. However, their empirical analysis was questionable with respect to the EKC hypothesis, as it drew different conclusions. Several studies have found evidence supporting the EKC hypothesis, which have drawn different conclusions. Certain researchers have presented arguments supporting the EKC hypothesis (Zambrano-Monserrate et al. 2016; Rauf et al. 2018; Pata, 2018; Rana & Sharma, 2019; Cosmas et al. 2019; Wasti & Zaidi, 2020; Bekun et al. 2020). Though, some studies refute the EKC hypothesis (Ozatac et al. 2017; Sarkodie, 2018; Dogan & Inglesi-Lotz. 2020; Koc & Bulus, 2020; Leal & Marques 2020). Over the years, several studies have incorporated energy consumption in their framework to investigate the interaction amongst CO_2 emissions, energy usage and economic growth. For instance, in Turkey, Gökmenoğlu and Taspinar (2016) explored the interconnection between FDI inflows, growth, energy use, and CO_2 emissions from 1974 to 2010. The investigators deployed the Toda-Yamamoto causality technique and their findings revealed a two-way causality between CO_2 emissions and energy use as well as between CO_2 emissions and FDI inflows. Furthermore, a one-way causality was found between real growth and FDI inflows and between energy use and real growth. Uddin et al. (2016) investigated the relationship between trade openness, GDP growth, energy usage and CO_2 emissions in Sri Lanka between 1971 and 2006. Their findings based on the VECM causality revealed a one-way causality between CO_2 and GDP growth in the long-run. At the same time, in the short-run, there was evidence of a unidirectional causality from energy use to growth, from trade openness to CO_2 emissions and from energy use to GDP growth. The study of Dogan and Turkekul (2016) analysed the linkage between CO_2 emissions, energy consumption, real output, the square of real output, trade openness, urbanization, and financial development in the USA. Their findings indicated that there is a feedback causality (i) between CO2 emissions and real output, (ii) between CO_2 emissions and energy consumption, and (iii) between CO_2 and urbanization. Saboori and Sulaiman (2013) examined the cointegration and causal relationship between economic growth, CO_2 emissions, and energy consumption for each ASEAN-5 country individually. They found that economic growth, CO_2 emissions, and energy consumption were cointegrated in all five countries, and that a positive relationship existed between CO_2 emissions and energy consumption in both the short- and long-run. Economic growth was only associated with a reduction in CO_2 emissions in Singapore and Thailand, with the opposite occurring in Indonesia and Philippines. Hanif (2018) studied the influences of economic growth, urban expansion, and the consumption of fossil fuels, solid fuels, and renewable energy on CO_2 emissions in Sub-Saharan Africa economies from 1995 to 2015 by utilizing the GMM model to examine the association among the study variables. The results indicated that the consumption of fossil and solid fuels positively impacted the CO_2 emissions while renewable energy helped to decrease the CO2 emissions. Heidari et al. (2015) used the Panel Smooth Transition Regression approach, which accounts for heterogeneity and time instability, to examine the relationship between EC, CO_2 and GDP in the ASEAN-5 countries. Nonlinearity was detected with two threshold parameters. Environmental degradation became greater with economic growth in regime one, while the situation was reversed in regime two. In both regimes, the results indicated that energy consumption Granger caused CO_2 emissions. Ang (2008) examined the long-run relationship and causality between output growth, growth in pollutant emissions, and energy consumption growth in a single country study for Malaysia. The author found positive relationship between CO_2 emissions and economic growth. Utilizing PMG and Granger Causality, Khoshnevis and Ghorchi (2018) investigated the causal linkage between CO_2 emissions and renewable energy, financial development, trade openness and economic growth in 25 African countries. The outcomes revealed a unidirectional causality from renewable energy to CO_2 emissions and from real output to CO_2 emissions. Akadiri et al. (2019) examined the causal interconnection amongst CO_2 emissions, economic growth and energy usage in Iraq using data from the period between 1972 and 2013. The investigators used the Toda-Yamamoto causality test and the findings revealed a one-way causality from GDP growth to energy usage and from CO_2 emissions to energy usage. The findings of Mukhlis (2020) and Adebayo et al. (2020) in Indonesia and the MINT economies, respectively, corroborated with the findings of Akadiri et al. (2019). In the ASEAN-5 economies, Munir (2020) investigated the linkage between CO_2 emissions and economic and energy usage data between 1980 and 2016. The findings revealed a feedback causality running from growth to CO_2 emissions in Malaysia, the Philippines, Singapore and Thailand. Furthermore, a one-way causality was detected running from growth to energy usage in Indonesia, Malaysia and Thailand, while in Singapore; there was evidence of a one-way causality from growth to energy usage. Recently, some researchers have utilized the wavelet tools to examine the causal linkages amongst CO_2 emissions, energy usage and economic growth. For instance, Kalmaz and Kirikkaleli (2019) explored the interconnection between CO_2 emissions and urbanization, real growth, trade and energy usage in Turkey using yearly data for the period between 1960 and 2016. The investigators utilized the wavelet coherence technique and their findings revealed a feedback causality between CO_2 emissions and urbanization, and also between energy usage and CO_2 emissions in Turkey, whereas a one-way causality was found running from real growth to CO_2 emissions. Using wavelet tools, Ali et al. (2020) explored the linkage between renewable energy, CO_2 emissions and growth in Malaysia. Their findings revealed a positive correlation between growth and CO_2 emissions accompanied by a feedback causality. Furthermore, a negative correlation was found between renewable energy and CO_2 emissions. Additionally, they found evidence of a one-way causality from renewable energy to CO_2 emissions. It is evident from the studies examined that the causal interconnection among GDP growth, energy use and CO_2 emissions has been extensively studied. Nevertheless, the usage of the wavelet coherence technique to examine the association and causality between CO_2 emissions, energy usage, and GDP growth has never been explored in the context of Thailand. The key advantage of wavelet coherence is that it helps the current research reveal the interconnection and causal linkage at different periods and frequencies. Thus, the identified gaps in the literature can be addressed, which will contribute to the ongoing research into Thailand.

3. Data and Method

3.1. Data

In this study, we use time-series data stretching from 1971 to 2018. The variables used are carbon emissions (CO_2), energy consumption (EN) and economic growth (GDP). The variables are gathered from the database of the World Bank. A short description of the time-series variables is shown in Table 1. All the variables demonstrate normal distribution because they are close to 0. Furthermore, they are platykurtic because they are less than 3. The Jarque-Bera statistic measures the difference between the skewness and kurtosis of the time series with those from the normal distribution. Based on this, both CO_2 emissions and energy consumption illustrate normal distribution, while GDP growth does not reflect normal distribution.

3.2. Methodology

The aim of this research is to utilize the time-frequency dependence to explore the causal linkage between CO_2 emissions, economic growth and energy consumption in Thailand. As a conceptual study, the authors examine the integration order of energy consumption, real growth, CO_2 emissions using the Dickey and Fuller, (1979), and Perron, and Ng, (1996) unit root tests. Additionally, the Zivot and Andrews (2002) as well as the Lee and Strazicich (2003) unit-root tests are utilized to examine the presence of structural break(s) in the time-series. With respect to the main aim of this study, the investigators explored the time-frequency dependence between CO_2 emission and real growth and energy consumption in Thailand by employing the wavelet coherence approach. The main novelty of wavelet coherence is that the approach combines both time-domain causality and frequency domain causality. Therefore, this allows the present study to capture the long- and short-run causal links between CO_2 emissions, energy consumption and economic growth in Thailand. It is well-known that if there is a structural break(s) in the time series, inaccurate findings are usually generated by using traditional causality tests. Therefore, this study utilized the wavelet coherence approach to avoid these issues. The main advantage of wavelet coherence is that the decomposition of one-dimensional time data into the bi-dimensional time-frequency sphere is allowed. Thus, we can capture the long-run and short-run causal interactions between CO_2 emissions, GDP growth and energy consumption in Thailand at the same time. A multi-scale decomposition technique brings out a natural framework to show frequency-dependent behaviour for examining the interconnection between CO_2 emissions, economic growth and energy consumption (Kirikkaleli & Gokmenoglu, 2020). This research offers the opportunity to reveal the long-term, medium-term and short-term causal association among CO_2 emissions, economic growth and energy consumption. Goupillaud et al. (1984) first presented the methods. The present study utilizes the ϖ wavelet method, which is part of the Morlet wavelet family. The equation of a wavelet ϖ, which is part of the Morlet wavelet family, is as follows:

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

The frequency used is illustrated by w based on the restricted time-series; i demonstrates p (t), n = 0, 1, 2, 3…N-1; and $\sqrt{-1}$. According to Kirikkaleli (2020) and Adebayo and Kalmaz (2020), there is a time transformation to the time-frequency domain that correlates with the wavelet. ϖ is changed; therefore, it is transformed into $\varpi_{k,f}$, as demonstrated in Equation 2.

$$\varpi_{k,f}(t) = \frac{1}{\sqrt{h}} \varpi\left(\frac{t-k}{f}\right), \ k, f \in \mathbb{R}, f \neq 0 \tag{2}$$

Table 1.
Descriptive statistics

	CO_2	EN	GDP
Mean	2.259036	1041.226	3167.245
Median	2.469342	1001.532	3267.887
Maximum	4.214834	1991.594	6370.015
Minimum	0.507018	360.5937	946.8831
Std. Dev.	1.330604	572.5851	1672.103
Skewness	0.043235	0.335812	0.262203
Kurtosis	1.416319	1.651243	1.794982
Jarque-Bera	5.031043	4.540450	3.454144
Probability	0.080821	0.103289	0.177804
Sum	108.4337	49978.85	152027.8
Sum Sq. Dev.	83.21387	15409124	1.31E+08
Observations	48	46	48
	Correlation Matrix		
CO_2	1	0.988	0.985
EN	0.988	1	0.991
GDP	0.985	0.991	1

The time-series p(t) is incorporated. Hence, the continuous wavelet function is illustrated by Equation 3:

$$\varpi_p(k,f) = \int_{-\infty}^{\infty} p(t)\frac{1}{\sqrt{f}}\varpi\left(\overline{\frac{t-k}{f}}\right)dt, \quad (3)$$

According to Alola and Kirikkaleli (2019), when ψ, which is the coefficient, is integrated into the equation, Equations 4 and 5 are reinstated.

$$p(t) = \frac{1}{C_\varpi}\int_0^\infty \left[\int_{-\infty}^{\infty} |\varpi_p(a,b)|^2 \, da\right]\frac{db}{b^2} \quad (4)$$

Equation 5 is used to capture the vulnerability of energy usage, CO_2 emission and GDP growth. The wavelet power spectrum (WPS) is illustrated as follows;

$$WPS_p(k,f)|W_p(k,f)|^2 \quad (5)$$

The Cross-Wavelet Transformation (CWT) process has transformed the time-series in Equation 5 into 6.

$$W_{pq}(k,f) = W_p(k,f)\overline{W_q(k,f)} \quad (6)$$

where: $W_p(k,f)$ and $W_q(k,f)$ stand for the two time-series, and squared wavelet coherence is represented in Equation 7:

$$R^2(k,f) = \frac{\left|S\left(f^{-1}W_{pq}(k,f)\right)\right|^2}{S\left(f^{-1}|W_p(k,f)|^2\right)S\left(f^{-1}|W_q(k,f)|^2\right)} \quad (7)$$

If the $R^2(k,f)$ nears 1, it indicates that either the time-series indicators are correlated or that there is a causal interaction between the time-series indicators at a particular level, enclosed by a black line. Additionally, whenever $R^2(k,f)$ nears 0, it indicates that there is no proof of association or causality between the two variables. However, $R^2(k,f)$ cannot provide any detailed information on the correlation symbol. Hence, Torrence and Compo (1998) developed a method for identifying distinctions in wavelet coherence by using deferral signs in the wavering of two-time sequences. Equation 8 illustrates the equation for the developed wavelet coherence as follows;

$$\phi_{pq}(k,f) = \tan^{-1}\left(\frac{L\left\{S\left(f^{-1}W_{pj}(k,f)\right)\right\}}{O\left\{S\left(f^{-1}W_{pj}(k,f)\right)\right\}}\right) \quad (8)$$

L and O symbolize an imaginary operator and a real part operator, respectively.

When series are co-integrated, it is generally known that there is at least one causal link that may be either unidirectional or bidirectional. The Granger and Toda Yamamoto causality tests were used to capture the causal interactions among the economic variables under consideration. The equation of the conventional Granger causality is illustrated as follows in Equations 9 and 10;

$$Y_t = \alpha_o + \sum_{i=1}^{k1}\alpha_i Y_{t-1} + \sum_{i=1}^{k2}\beta_i X_{t-1} + \varepsilon_t \quad (9)$$

$$X = \delta_o + \sum_{i=1}^{k3}\delta_i X_{t-1} + \sum_{i=1}^{k4}\vartheta_i Y_{t-1} + \mu_t \quad (10)$$

Where k portrays the length of the lag, and the error term is illustrated by ε_t and μ.

The Granger Causality test is not difficult to execute and can be used for empirical studies of several forms. Nevertheless, there are drawbacks to the traditional Granger-Causality. Firstly, a two-variable Granger-Causality test is subject to potential specification bias without considering the impact of other variables. As Gujarati (1995) noted, a causality test is susceptible to the specification of the model and its lag number. If it were essential and not added in the model, it would show differing outcomes. Thus, because of this issue, the empirical proof of a two-variable Granger causality is fragile. Secondly, as Maddala (2001), Onyibor *et al.* (2018) and Eminer *et al.* (2020) stated, time-series data are often non-stationary. This condition may illustrate the baseless regression issue. Gujarati (2006) also said that the F-test method is not reliable when the variables are integrated, because there is no standard distribution for the test statistics. While researchers can still use t-statistics to check the significance of individual coefficients, it may not be possible to use the F-statistics to measure the Granger causality jointly. Enders (2004) demonstrated that in some specific cases, it is appropriate to use the F-statistics to jointly check the first differential VAR whenever the two-variable VAR has two lagged lengths and one variable is found to be non-stationary. In Toda and Phillips (1994), other weaknesses of these tests were addressed. Toda and Yamamoto (1995) proposed an interesting new technique that requires the estimation of the augmented VAR, which guarantees the asymptotic distribution of the Wald statistics (asymptotic χ2 distribution). Thus, Equations 11 and 12 illustrate the equation for the Toda Yamamoto causality test as follows;

$$Y_t = \delta_o + \sum_{i=1}^{m} \vartheta_i Y_{t-1} + \sum_{i=m+1}^{m+dmax} \vartheta_i Y_{t-1} + \sum_{i=1}^{m} \beta_1 X_{t-1} + \sum_{i=m+1}^{m+dmax} \beta_1 X_{t-1} + \mu_t \quad (11)$$

$$X_t = \delta_o + \sum_{i=1}^{m} \vartheta_i X_{t-1} + \sum_{i=m+1}^{m+dmax} \vartheta_i X_{t-1} + \sum_{i=1}^{m} \beta_1 Y_{t-1} + \sum_{i=m+1}^{m+dmax} \beta_1 Y_{t-1} + \mu_t \quad (12)$$

Where Y and X are the variables, ϑ, β are the parameters and μ_t and ε_t depict the error terms, respectively. Two steps are involved in the execution of the procedure. The first step consists of specifying the length of the lag (m), while the second step involves the selection of the maximum integration order (dmax) for the system variables. Furthermore, in order to ascertain the lag length, measures such as the AIC, SC, FPE, and HQ are utilized.

4. Results and Discussion

4.1. Unit Root Tests

As stated earlier, the study aims to explore the vulnerability, correlation and causality between real growth, energy usage, and CO_2 emissions in Thailand. The major innovation of this paper is that it explores the causal interaction among CO_2 emissions, energy consumption and economic growth in Thailand, which has not previously been examined by applying the most recently developed econometric techniques. To address this deficiency in the earlier studies and to answer the question "What is the causal linkage between CO_2 emissions and GDP growth and energy consumption in Thailand?, the integration order of the variables used are examined by using the Augmented Dickey-Fuller (ADF) test proposed by Dickey and Fuller, (1979) and the Phillips–Perron (PP) test suggested by Perron and Ng (1996). The results of the ADF and PP unit root test are illustrated in Table 2. The findings reveal that all the variables used are non-stationary at level. However, after taking the first difference, all the variables are found to be stationary. Furthermore, when structural break(s) were considered, the recent and more powerful unit root tests were used, including Zivot-Andrew (ZA) suggested by Zivot and Andrew (2002) and (2002) and Lee-Strazicich (LM) proposed by Lee and Strazicich (2003), which can detect one and two structural break(s), respectively. The results of the ZA and LM unit root tests are illustrated in Table 3. The findings from these tests reveal that there is a structural break(s) in the variables. Additionally, the ZA and LM unit root tests reveal that all indicators used are integrated at mixed order. Based on these findings, employing the time-domain causality techniques will yield a misleading result. Thus, the investigator employed the wavelet coherence technique to ascertain the correlation and causality amongst the time series variables. Furthermore, the study employed both conventional Granger causality and Toda-Yamamoto causality tests as a robustness check for the wavelet coherence technique.

Table 2
Unit Root Tests Without Structural Break (Source: Authors Collation with EViews-11)

		At Level			First Difference		
		CO_2	EN	GDP	CO_2	EN	GDP
ADF	K&T	-2.539	-1.714	-1.506	-4.524^T	-6.059^T	-4.340^T
PP	K&T	-2.215	-1.725	-1.123	-4.492^T	-6.053^T	-4.366^T

T, O and M portrays a significance level of 1%, 5% and 10% respectively

Table 3
Unit Root Tests With Structural Break(s) (Source: Authors Collation with EViews-11)

		At Level			First Difference		
		CO_2	EN	GDP	CO_2	EN	GDP
ZA	K&T	-3.204	-3.72	-5.472^T	-5.556^T	-5.172^T	-4.864^T
		[1988]	[1983]	[1997]	[1997]	[1994]	[2003]
LM	K&T	-5.775	-7.254^T	-5.411	-6.819^M	-5.721	-6.247^O
		[1984]	[1981]	[1985]	[1986]	[1981]	[1993]
		{1993}	{1992}	{2005}	{1984}	{1996}	{2007}

T, O and M portrays a significance level of 1%, 5% and 10% correspondingly. [] and {} depicts the first and second break year respectively

Table 4
Power spectrum (Source: Authors Compilation)

Interpretation	
0-4	Short term period of scale
4-16	Medium-term period of scale
16-32	Long-term period of scale
0.016-0.250	Low-Frequency
0.250-4.00	Medium-Frequency
4.00-64.00	High-Frequency

4.2. Wavelet Power Spectrum

Figures 1, 2 and 3 display the results of the wavelet power spectrum (WPS) for the CO_2 emissions, energy use and real growth variables in Thailand, respectively. The wavelet power spectrum is used in this study to detect the vulnerability in economic growth, CO_2 emissions and energy consumption in Thailand between 1971 and 1981. In Figures 1, 2 and 3, the white cone is the cone of influence (COI) used for interpretation when analysing the wavelet power spectrum (WPS). The significance level is shown by a thick black line calculated based on the Monte Carlo simulations. Table 4 illustrates the interpretation of the wavelet power spectrum. Figure 1 represents the wavelet power spectrum of CO_2 emissions. At scale 0-4, CO_2 emissions are vulnerable between 1987 and 1974. During this period, CO_2 emissions increased by 16.6%. Also, between 1983 and 1990 at scale 0-8, there is evidence of volatility in CO_2 emissions. In this period, CO_2 emissions increased from 0.899 metric tons per capita in 1984 to 1.604 metric tons per capita in 1990, which represents an increase of 79.77%. In addition, between 2010 and 2017 at scale 4-8, there is evidence of volatility in CO_2 emissions. In this period, CO_2 emissions increased by 9.49%. Figure 2 represents the wavelet power spectrum of energy consumption in Thailand. At scale 0-8, from 1980 to 1986, there is proof of volatility in energy consumption. In this period, energy consumption increased by 14.65%.

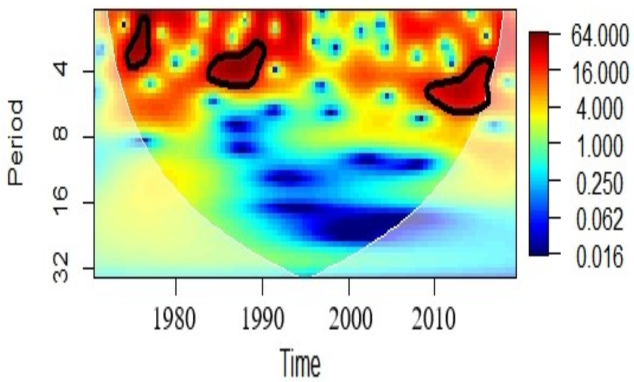

Fig. 1 Power spectrum for CO_2 Emissions (Source: Authors Collation with R-Software)

Furthermore, between 1992 and 1996, at scale 4-8, there is evidence of volatility. During this timeframe, energy consumption increased by 37.18%. Figure 3 depicts the wavelet power spectrum of real growth between 1971 and 2018. In scale periods 0-4, between 1972 and 1974, there is evidence of volatility in economic growth in Thailand. During this period, Thailand was among the fastest growing and most successful developing countries in the world. Rapid growth in production, accompanied by progress in alleviating poverty, was impressive.

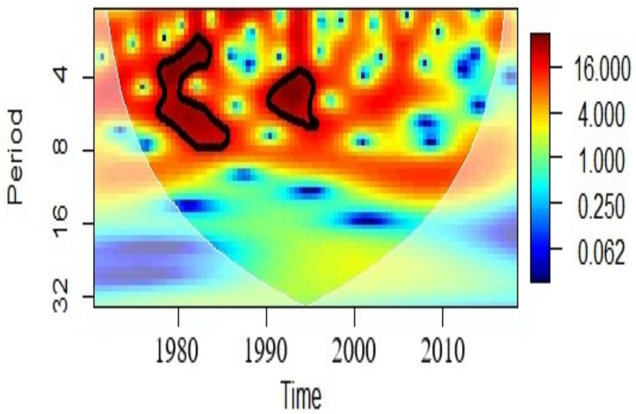

Fig. 2 Power spectrum for Energy Consumption (Source: Authors Collation with R-Software)

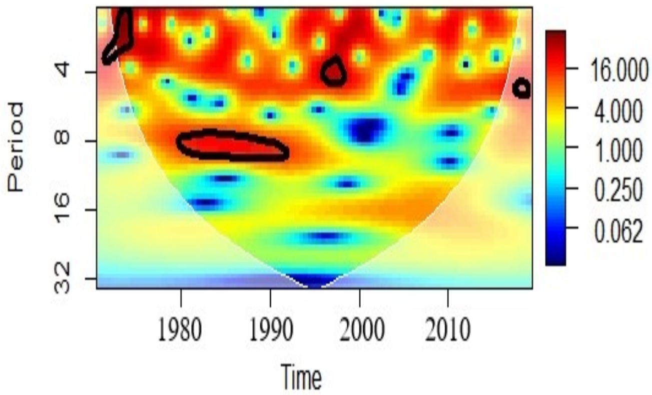

Fig. 3 Power spectrum for Economic Growth (Source: Authors Collation with R-Software)

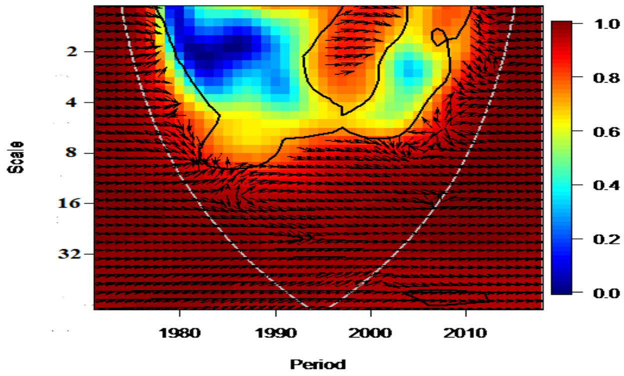

Fig. 4. WTC between CO_2 Emissions & Energy Consumption (Source: Authors Collation with R-Software)

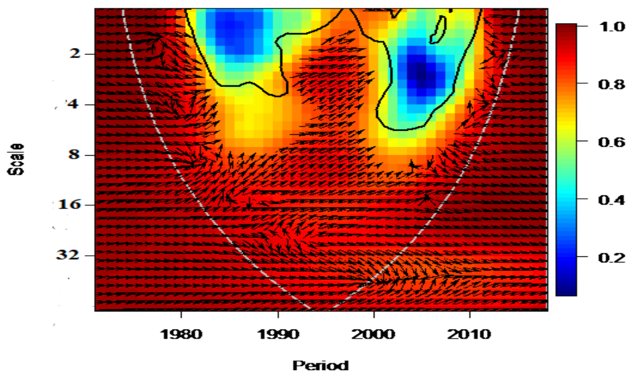

Fig 5. WTC between CO_2 Emissions & Economic Growth (Source: Authors Collation with R-Software)

Furthermore, volatility surfaced between scales 0-4 between 1980 and 1990. In this period, Thailand's economic performance decelerated, partly as a result of the global recession. Although its annual growth rate remained higher than the average for middle-income countries, earlier expectations were not met. The targets of the Fifth Economic Development Plan (1982-86) were not achieved, and serious macroeconomic imbalances persisted. Additionally, at scale 0-4, there is evidence of volatility in economic growth. In this period, the 1997 Asian financial crisis caused the Thai economy to enter into recession.

4.3. Wavelet Coherence

Figures 4 and 5 illustrate the wavelet coherence (WTC) between CO_2 emissions and energy consumption and economic growth and CO_2 emissions in Thailand between 1971 and 2018. In Figures 4 and 5, the white cone is the cone of influence (COI) used for interpretation when analysing wavelet coherence. The significance level is shown by a thick black line calculated based on the Monte Carlo simulations. The thick black contour encloses regions where the wavelet coherence is significant at the 5% level against the red noise estimated from the Monte Carlo simulations using phase randomized surrogate series.

The direction of the arrows captures the phase difference between the two time series. Time and frequency (year) are represented on the horizontal and vertical axes, respectively. Table 5 depicts the interpretation of the wavelet coherence as explained by Aloui *et al.* (2016), Mutascu (2018), Adebayo (2020b), Kirikkaleli, (2020) and Adebayo and Kalmaz (2020). The wavelet coherence method simultaneously explores the correlation and causality between CO_2 and the other indicators. As stated by Kirikkaleli (2020), this method is taken from mathematics and involves the integration of the time and frequency domain information techniques to obtain entirely unexplored information. Thus, the present study allows short-term, medium-term, and long-term correlations and causality between CO_2 emissions and economic growth and energy consumption. In Figures 4 and 5, no correlation between the two time-series is depicted by the cold (blue) colour, whereas proof of correlation is characterized by the warmer (red) colour. In Figure 4, at different scales (different frequencies), between 1973 and 2016, the arrows face the right-hand side, which depicts a positive correlation between CO_2 and energy consumption. Furthermore, the rightward-down and rightward-up arrows illustrate a bidirectional causality between energy consumption and CO_2 emissions. This finding complies with prior studies (Gökmenoğlu & Taspinar 2016; Mirza & Kanwal, 2017; Kalmaz & Kirikkaleli, 2019; Wasti & Zaidi, 2020; Dabachi et al. 2020; Akadiri & Akadiri, 2020; Mukhlis, 2020). In Figure 5, at different scales (different frequencies), between 1971 and 2018, the arrows face the right-hand side, which depicts a positive correlation between CO_2 emissions and economic growth. Furthermore, the right-up arrows provide proof of a one-way causality running from economic growth to CO_2 emissions in Thailand. This indicates that economic growth is an essential predictor of CO_2 emissions in Thailand. This finding complies with prior studies, which found a one-way causality from GDP growth to CO_2 emissions (Khoshnevis & Ghorchi, 2018; Kalmaz & Kirikkaleli, 2019; Dabachi et al. 2020; Raza et al. 2020; Munir, 2020; Adebayo et al. 2020).

4.4. Robustness Check

To capture the causal effect of energy consumption and economic growth on CO_2 emissions in Thailand, pairwise Granger causality and Toda-Yamamoto causality are employed over the period from 1971 to 2018. Although the study earlier employed the Wavelet-Based Granger causality test, which is more reliable when there is evidence of structural break(s) in time series, the pairwise Granger causality and Toda-Yamamoto causality are used as a robustness check. Table 6 illustrates the findings from the Pairwise Granger causality and Toda Yamamoto causality tests. The findings from the pairwise Granger causality and Toda Yamamoto causality tests revealed a bidirectional causality between CO_2 emissions and energy consumption. The findings also reveal that both CO_2 emissions and energy consumption can predict each other. This finding complies with prior studies (Gökmenoğlu & Taspinar 2016; Mirza & Kanwal, 2017; Kalmaz & Kirikkaleli, 2019; Wasti & Zaidi, 2020; Dabachi et al. 2020; Akadiri & Akadiri, 2020; Mukhlis, 2020), which found a bidirectional causality between CO_2 emissions and energy consumption. Furthermore, there is a unidirectional causality from economic growth to CO_2 emissions. This indicates that economic growth is an essential predictor of CO_2 emissions in Thailand. This finding complies with prior studies, which found a one-way causality from GDP growth to CO_2 emissions (Khoshnevis & Ghorchi, 2018; Kalmaz & Kirikkaleli, 2019; Dabachi et al. 2020; Raza et al. 2020; Munir, 2020; Adebayo et al. 2020). It is noteworthy to mention that the results from the pairwise Granger causality and Toda-Yamamoto causality tests provide consistent results in all cases with the Wavelet-Based Granger causality test.

Table 5
Wavelet coherence Interpretation (Source: Authors Compilation)

Direction of Arrows	Interpretation
Right	A positive correlation between the two variable
Left	A negative correlation between the two variable
Right-Up	The second variable causes the first variable.
Right-Down	The first variable cause the second variable
Left-Up	The second variable causes the first variable
Left-Down	The first variable cause the second variable
Short-Term	0-4
Medium-Term	4-8
Long-term	8-32
Low-Frequency	0-2
Medium-Frequency	2-6
High-Frequency	6-1

Table 6
Causality Tests

	Causality Path	Lag	Fstat/MWALD	Probability	Decision
Pairwise Granger Causality	$CO_2 \rightarrow EN$	2	4.1721	0.0269^{O}	Reject Ho
	$EN \rightarrow CO_2$	2	7.1122	0.0022^{T}	Reject Ho
	$CO_2 \rightarrow GDP$	2	1.9443	0.1560	Do Not Reject Ho
	$GDP \rightarrow CO_2$	2	4.9440	0.0119^{0}	Reject Ho
Toda Yamamoto Causality	$CO_2 \rightarrow EN$	2	6.3443	0.0539^{M}	Reject Ho
	$EN \rightarrow CO_2$	2	14.224	0.0008^{T}	Reject Ho
	$CO_2 \rightarrow GDP$	2	3.8887	0.1431	Do Not Reject Ho
	$GDP \rightarrow CO_2$	2	9.8880	0.0071^{T}	Reject Ho

Note: $\rightarrow$ indicates the direction of causality. The optimal lag is selected using AIC. T, 0 and M denote statistically significance at 1%, 5% and 10% levels, respectively.

5. Conclusion

This paper aims to explore the causal linkage between CO2 emissions and energy consumption, and economic growth for the case of Thailand by using time series data covering the years between 1971 and 2018. The study employ the wavelet coherence, Granger and Toda-Yamamoto causality techniques to examine the causal linkage between CO2 emissions, economic growth and energy consumption. The outcomes of this paper demonstrate that changes in economic growth led to changes in CO2 emissions in Thailand at different frequencies (different scales) between 1971 and 2018. Also, energy consumption and CO2 emissions can predict each other. In addition, there is evidence of a positive correlation between CO2 emissions in the short and long-run between 1971 and 2018. Furthermore, a positive correlation was detected between GDP growth and CO2 emissions in the short and long-run between 1971 and 2018. The findings from the conventional Granger and Toda Yamamoto causality techniques provide supportive evidence for the wavelet coherence technique. Based on these outcomes, the government of Thailand should be careful when formulating policies that trigger growth, as they can have a detrimental impact on the environment. In this respect, the government should assist the markets by developing a solid policy structure that provides long-term demand for the mitigation of greenhouse gas pollution and actively encourages the implementation of emerging technologies that contribute to a less carbon-intensive economy, as this will not only keep the country on a sustainable path, but also ensure the preservation of the environment for future generations. In addition, Thailand should initiate stronger policies towards enhancing the efficiency of energy and energy-usage programs to minimize unnecessary energy waste. These would enhance energy security and ensure a reduction in the carbon emissions without having a detrimental effect on economic growth. In addition, the environmental awareness among the citizens in Thailand should be increased, as they should be made aware of the implications of using non-renewable energy, and should be encouraged to utilize renewable energy. The country should set an emission standard for the industries, and should put in place emission monitoring strategies to ensure compliance.

References

Adebayo, T. S., Awosusi, A. A., & Adeshola, I. (2020). Determinants of CO2 Emissions in Emerging Markets: An Empirical Evidence from MINT Economies. *International Journal of Renewable Energy Development*, 9(3), 411-422.

Adebayo, T. S., & Beton Kalmaz, D. (2020). Ongoing Debate Between Foreign Aid and Economic Growth in Nigeria: A Wavelet Analysis. Social Science Quarterly.

Adebayo, T. S. (2020a). Dynamic Relationship between Oil Price and Inflation in Oil Exporting Economy: Empirical Evidence from Wavelet Coherence Technique. *Energy Economics Letters*, 7(1), 12-22.

Adebayo, T. S. (2020b). New Insights into Export-Growth Nexus: Wavelet and Causality Approaches. *Asian Journal of Economics, Business and Accounting*, 32-44.

Adebayo, T , Awosusı, A , Ajayı, T . (2020). Dynamic Aid-Growth Relationship in Nigeria: A Two-Gap Approach . *LAÜ Sosyal Bilimler Dergisi* , 11 (1) , 1-17 . Retrieved from https://dergipark.org.tr/tr/pub/euljss/issue/56663/789055

Akadiri, S. S., Bekun, F. V., Taheri, E., & Akadiri, A. C. (2019). Carbon emissions, energy consumption and economic growth: a causality evidence. *International Journal of Energy Technology and Policy*, 15(2-3), 320-336.

Akadiri, S. S., & Akadiri, A. C. (2020). Interaction between CO2 emissions, energy consumption and economic growth in the Middle East: panel causality evidence. *International Journal of Energy Technology and Policy*, 16(2), 105-118.

Ali, A., Kamarulzaman, R., Soetrisno, F. K., & Razimi, M. S. A. (2020). Wavelet Analysis of Renewable, Non-renewable Energy Consumption and Environmental Degradation as a Precursor to Economic Growth: Evidence from Malaysia. *International Journal of Energy Economics and Policy*, 10(3), 182-189.

Alola, A. A., & Kirikkaleli, D. (2019). The nexus of environmental quality with renewable consumption, immigration, and healthcare in the US: wavelet and gradual-shift causality approaches. *Environmental Science and Pollution Research*, 26(34), 35208-35217.

Bekun, F. V., Agboola, M. O., & Joshua, U. (2020). Fresh Insight into the EKC Hypothesis in Nigeria: Accounting for Total Natural Resources Rent. In Econometrics of Green Energy Handbook (pp. 221-243). Springer, Cham.

Bildirici, M. E. (2017). The causal link among militarization, economic growth, CO 2 emission, and energy consumption. *Environmental Science and Pollution Research*, 24(5), 4625-4636.

Dabachi, U. M., Mahmood, S., Ahmad, A. U., Ismail, S., Farouq, I. S., Jakada, A. H., & Kabiru, K. (2020). Energy Consumption, Energy Price, Energy Intensity Environmental Degradation, and Economic Growth Nexus in African OPEC Countries: Evidence from Simultaneous Equations Models. *Journal of Environmental Treatment Techniques*, 8(1), 403-409.

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American statistical association*, *74*(366a), 427-431.

Dogan, E., & Inglesi-Lotz, R. (2020). The impact of economic structure to the environmental Kuznets curve (EKC) hypothesis: evidence from European countries. *Environmental Science and Pollution Research*, 1-8.

Eminer, F., Adebayo, T. S., & Awosusi, A. A. (2020). Stock Market-Growth Relationship in an Emerging Economy: Empirical Finding from ARDL-Based Bounds and Causality Approaches. *Journal of Economics and Business*, *3*(2), 903-916.

Kalmaz, D. B., & Kirikkaleli, D. (2019). Modeling CO 2 emissions in an emerging market: empirical findings from ARDL-based bounds and wavelet coherence approaches. *Environmental Science and Pollution Research*, 26(5), 5210-5220.

Goupillaud, P., Grossmann, A., & Morlet, J. (1984). Cycle-octave and related transforms in seismic signal analysis. *Geoexploration*, 23(1), 85-102.

Gökmenoğlu, K., & Taspinar, N. (2016). The relationship between CO2 emissions, energy consumption, economic growth and FDI: the case of Turkey. *The Journal of International Trade & Economic Development*, 25(5), 706-723.

Granger, C. W. (1969). Investigating Causal Relations by Econometric Models and Cross-Spectral Methods. *Econometrica* 37, 424–438.

Hanif, I. (2018). Impact of economic growth, nonrenewable and renewable energy consumption, and urbanization on carbon emissions in Sub-Saharan Africa. *Environmental Science and Pollution Research*, *25*(15), 15057-15067.

Orhan, A., Kirikkaleli, D., & Ayhan, F. (2019). Analysis of Wavelet Coherence: Service Sector Index and Economic Growth in an Emerging Market. *Sustainability*, 11(23), 6684.

Kalmaz, D. B., & Kirikkaleli, D. (2019). Modeling CO 2 emissions in an emerging market: empirical finding from ARDL-based bounds and wavelet coherence approaches. *Environmental Science and Pollution Research*, 26(5), 5210-5220.

Khoshnevis Yazdi, S., & Ghorchi Beygi, E. (2018). The dynamic impact of renewable energy consumption and financial development on CO2 emissions: For selected African countries. *Energy Sources, Part B: Economics, Planning, and Policy*, 13(1), 13-20.

Kirikkaleli, D. (2020). The effect of domestic and foreign risks on an emerging stock market: A time series analysis. The North *American Journal of Economics and Fin*ance, 51, 100876.

Kirikkaleli, D., Adedoyin, F. F., & Bekun, F. V. (2020). Nuclear energy consumption and economic growth in the UK: Evidence from wavelet coherence approach. *Journal of Public Affairs*, e2130.

Kirikkaleli, D., & Gokmenoglu, K. K. (2020). Sovereign credit risk and economic risk in Turkey: Empirical evidence from a wavelet coherence approach. Borsa Istanbul Review, 20(2), 144-152.

Kirikkaleli, D. (2019). Time–frequency dependency of financial risk and economic risk: evidence from Greece. *Journal of Economic Structures*, 8(1), 37.

Koc, S., & Bulus, G. C. (2020). Testing validity of the EKC hypothesis in South Korea: role of renewable energy and trade openness. *Environmental science and pollution research*, 27, 29043–29054.

Lee, J., & Strazicich, M. C. (2003). Minimum Lagrange multiplier unit root test with two structural breaks. *Review of economics and statistics*, *85*(4), 1082-1089.

Mirza, F. M., & Kanwal, A. (2017). Energy consumption, carbon emissions and economic growth in Pakistan: Dynamic causality analysis. *Renewable and Sustainable Energy Reviews*, 72, 1233-1240.

Mukhlis, M. (2020). The causality between human capital, energy consumption, CO2 emissions, and economic growth: Empirical evidence from Indonesia. Energy Consumption, CO2 Emissions, and Economic Growth: Empirical Evidence from Indonesia (June 13, 2020).

Munir, Q., Lean, H. H., & Smyth, R. (2020). CO2 emissions, energy consumption and economic growth in the ASEAN-5 countries: A cross-sectional dependence approach. *Energy Economics*, 85, 104571.

Mutascu, M. (2018). A time-frequency analysis of trade openness and CO2 emissions in France. *Energy policy*, 115, 443-455.

Nasreen, S., Mbarek, M. B., & Atiq-ur-Rehman, M. (2020). Long-run causal relationship between economic growth, transport energy consumption and environmental quality in Asian countries: Evidence from heterogeneous panel methods. *Energy*, 192, 116628.

Onyibor, K., Bah, S. I., & Tomiwa, A. (2018). Aid-Growth Relationship: Evidence from a Cointegratıon Analysis for the Five Poorest Countries of the World",LAÜ Sosyal Bilimler Dergisi, 9(2):121-137

Pal, D., & Mitra, S. K. (2017). Time-frequency contained co-movement of crude oil and world food prices: A wavelet-based analysis. *Energy Economics*, 62, 230-239.

Pata, U. K., & Aydin, M. (2020). Testing the EKC hypothesis for the top six hydropower energy-consuming countries: Evidence from Fourier Bootstrap ARDL procedure. *Journal of Cleaner Production*, 121699.

Perron, P., & Ng, S. (1996). Useful modifications to some unit root tests with dependent errors and their local asymptotic properties. *The Review of Economic Studies*, *63*(3), 435-463.

Toda HY, Yamamoto T (1995) Statistical inference in vector autoregressions with possibly integrated processes. *J Econ* 66(1–2), 225–250

Rafindadi, A. A. (2016). Does the need for economic growth influence energy consumption and CO2 emissions in Nigeria? Evidence from the innovation accounting test. *Renewable and Sustainable Energy Reviews*, 62, 1209-1225.

Rana, R., & Sharma, M. (2019). Dynamic causality testing for EKC hypothesis, pollution haven hypothesis and international trade in India. *The Journal of International Trade & Economic Development*, 28(3), 348-364.

Raza, S. A., Shah, N., & Khan, K. A. (2020). Residential energy environmental Kuznets curve in emerging economies: the role of economic growth, renewable energy consumption, and financial development. *Environmental Science and Pollution Research*, 27(5), 5620-5629.

Sarkodie, S. A. (2018). The invisible hand and EKC hypothesis: what are the drivers of environmental degradation and pollution in Africa? *Environmental Science and Pollution Research*, 25(22), 21993-22022.

Sunde, T. (2020). Energy consumption and economic growth modelling in SADC countries: an application of the VAR Granger causality analysis. *International Journal of Energy Technology and Policy*, 16(1), 41-56.

Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological society*, 79(1), 61-78.

Uddin, M. G. S., Bidisha, S. H., & Ozturk, I. (2016). Carbon emissions, energy consumption, and economic growth relationship in Sri Lanka. *Energy Sources, Part B: Economics, Planning, and Policy*, 11(3), 282-287.

Rauf, A., Liu, X., Amin, W., Ozturk, I., Rehman, O. U., & Hafeez, M. (2018). Testing EKC hypothesis with energy and sustainable development challenges: a fresh evidence from belt and road initiative economies. *Environmental Science and Pollution Research*, 25(32), 32066-32080.

Wasti, S. K. A., & Zaidi, S. W. (2020). An empirical investigation between CO2 emission, energy consumption, trade liberalization and economic growth: A case of Kuwait. *Journal of Building Engineering*, 28, 101104.

Zambrano-Monserrate, M. A., Valverde-Bajaña, I., Aguilar-Bohórquez, J., & Mendoza-Jiménez, M. (2016). Relationship Between Economic Growth and Environmental Degradation: Is there an Environmental Evidence of Kuznets Curve for Brazil? *International Journal of Energy Economics and Policy*, 6(2), 208-216.

Zivot, E., & Andrews, D. W. K. (2002). Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. *Journal of business & economic statistics*, *20*(1), 25-44.