



# New insights into an old issue: exploring the nexus between economic growth and CO<sub>2</sub> emissions in China

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## Abstract

It is globally acceptable that carbon dioxide (CO<sub>2</sub>) emissions are one of the greenhouse gases are considered the main factor influencing global warming and environmental degradation. The present study focuses on China, the world's largest carbon emitter. The study aims to capture the time-frequency dependency of economic growth and CO<sub>2</sub> emissions in China for the time period 1950–2016 using a wavelet coherence approach, which allows us to investigate both the long-run and short-run causal links of the estimated variables. In order to capture the long-run and causal linkage between economic growth and CO<sub>2</sub> emissions, the study employs Maki cointegration, wavelet coherence, Toda-Yamamoto causality, Fourier Toda-Yamamoto causality, and nonparametric Granger causality tests. The findings of this study reveal that (i) there is a significant vulnerability between economic growth and CO<sub>2</sub> emissions throughout the 2000s both the short-term and medium-term; (ii) there is long-run cointegration linkage between economic growth and CO<sub>2</sub> emissions in China; (iii) economic growth in China has an important power for predicting CO<sub>2</sub> emissions over the selected study period, especially in the short-term and medium-term; and (iv) it was observed that there is positive correlation between economic growth during the 1980s and 1990s in the short-term only. The outcome of the Toda-Yamamoto causality, Fourier Toda-Yamamoto causality, and nonparametric Granger causality tests underlines that economic growth is a robust policy variable for predicting CO<sub>2</sub> emissions in China.

**Keywords** Economic growth · CO<sub>2</sub> emissions · China · Wavelet coherence

## Introduction

It is globally acceptable that CO<sub>2</sub> emissions are one of the greenhouse gases and considered the main factor influencing global warming and environmental degradation. Environmental sustainability and climate changes are the main environmental issues in the world agenda, and they have attracted researchers to explore the nexus between economic growth and CO<sub>2</sub> emissions. It is known that the burning of fossil fuel, coal, oil, and natural gas is the reason behind rising CO<sub>2</sub> emissions and thus the main reason behind

the deterioration of natural environment. Similarly, Mardani et al. (2019) stated that despite the positive effect of economic growth on leaving standards for both the developed and developing economies, tripling the world economy in the last four decades is blamed for rising CO<sub>2</sub> emissions and decreasing natural resources.

Nowadays, China is the world's largest carbon emitter in the world. In the 13th Five-Year Plan of China, the main target is to significantly shrink its CO<sub>2</sub> emission per unit of GDP by 18% from 2015. Therefore, like in other emerging economies, CO<sub>2</sub> emission reduction is the key for the policymakers in China to achieve the national reduction goal at the minimum cost. The majority of previous studies for the past two decades have used linear and traditional models while estimating the linkage between economic growth and CO<sub>2</sub> emissions. According to the China Renewable Energy Outlook 2019, the targets of COP25 in Madrid and China will increase renewable energy investments, which might reduce the CO<sub>2</sub> intensity of GDP in China and protect the climate. In order to avoid the risks and effects of climate change in the world, the Paris agreement (COP21) was signed by 189 countries in

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2015 to hold the rising global average temperature below 2 °C, and the target will be 1.5 °C (Rhodes 2016). Wang et al. (2019a, b) estimated that China's emissions are likely to reach its peak in the first half of the 2020s by reaching 13 to 16 gigatonnes of CO<sub>2</sub> emissions. This estimation reveals that China is around 5 years ahead of the current Paris target of 2030.

According to Climate Change Performance Index of Germanwatch, the CO<sub>2</sub> reduction and energy consumption of China still did not in expected level in 2019, and this might make the path to reach the Paris climate targets of COP21 more difficult for China. The Paris climate targets is to let both the developed and developing countries put their agenda on one core strategy of continuously reducing the CO<sub>2</sub> intensity of GDP. Previous studies have investigated the nexus between economic growth and CO<sub>2</sub> emissions in the relevant environment literature. However, there is no consensus about whether China will achieve the Paris climate targets by 2030 (Gallagher et al. 2019; Wang et al. 2019a, b). Hence, this study employed the time-frequency dependency to examine the relationship between economic growth and a CO<sub>2</sub> emission in China covering 1950–2016, which has not yet been explored using the wavelet coherence test.

In order to explore the relationship between economic growth and a CO<sub>2</sub> emission in China, the present study contributes to the body of related literature in several ways. First, we broaden both the theoretical and empirical association of the relevant related literature on economic growth and CO<sub>2</sub> emissions. Second, we employed the wavelet coherence techniques to model China's economic growth and CO<sub>2</sub> emissions' dataset from 1950 to 2016. The wavelet analysis has taken both the frequency and time dimension into account simultaneously. In other words, the present study explores the co-movement between economic growth and CO<sub>2</sub> emissions for China's case in the short-run and long-run separately. Regarding the linkage between economic growth and CO<sub>2</sub> emissions, scholars have mainly tested four points of views in both empirical and theoretical studies, namely, growth-led CO<sub>2</sub> hypothesis; CO<sub>2</sub>-led growth hypothesis; feedback causality between economic growth and CO<sub>2</sub> emissions; and no causality between economic growth and CO<sub>2</sub> emissions, the so-called neutrality hypothesis. Also, the majority of earlier empirical studies have used relatively small datasets, but in the present study, we use the largest dataset ever employed, which spans more than a half-century. Third, the present study performed the following econometric techniques of nonparametric Granger causality of Diks and Panchenko (2006) to consider nonlinearity and Fourier Toda-Yamamoto causality of Nazlioglu et al. (2016) in order to take into account structural break. Another novelty of this study is to use linear econometric techniques without taking into account structural breaks and nonlinearity assumption, while exploring causal linkages among the time series variables have been heavily criticized

by Racine and Li (2004) and Shahbaz et al. (2017). Finally, the outcomes of the study delivered valuable insights and recommendations for policymakers to reduce CO<sub>2</sub> emissions while sustaining economic growth.

The empirical analysis also finds that (i) there is a significant vulnerability in economic growth and CO<sub>2</sub> emissions throughout the 2000s in the short-term and medium-term; (ii) there is a long-run cointegration linkage between economic growth and CO<sub>2</sub> emissions in China; (iii) economic growth in China has an essential power for predicting CO<sub>2</sub> emissions over the selected period, especially short-term and medium-term; and (iv) in the short term, we also observe that there is a positive correlation between economic growth during the 1980s and 1990s. Our results are robust and highlight the nonlinear and linear causality running from economic growth to CO<sub>2</sub> emissions in China. The rest of the paper is organized as follows: Section 2 presents a literature review and discusses previous researches upon the relevant issue. Section 3 describes the data and methodology that the present study applied. Section 4 presents the findings of the conducted empirical study, and the conclusions drawn are summarized in Section 5.

## Literature review

In today's world, global warming is a critical issue to deal with. As stated by Wang et al. (2020), continuously reducing the CO<sub>2</sub> intensity of GDP and eventually controlling CO<sub>2</sub> emissions growth are dual targets of the COP21 and the Kyoto protocol without slowing down economic growth. In both agreements, it underlined that global warming could impact on the people living around the world. Throughout the years, the number of theoretical and empirical studies has investigated the CO<sub>2</sub> emissions-growth nexus to describe this relationship better. Regarding the linkage between economic growth and CO<sub>2</sub> emissions, scholars have mainly tested four point of views in both empirical and theoretical studies, namely, growth-led CO<sub>2</sub> hypothesis; CO<sub>2</sub>-led growth hypothesis; feedback hypothesis (two-way causality between economic growth and CO<sub>2</sub> emissions); and no causality between economic growth and CO<sub>2</sub> emissions, the so-called neutrality hypothesis.

The growth-led CO<sub>2</sub> hypothesis argues that economic growth drives CO<sub>2</sub> emissions in a country. The growth-led CO<sub>2</sub> hypothesis is supported by Wasti and Zaidi (2020), Aydoğan and Vardar (2020), Shahbaz et al. (2017), Riti et al. (2017), Shahbaz et al. (2016a, b), Jafari et al. (2015), and Shahbaz et al. (2015). Using the ARDL and Granger causality test, Wasti and Zaidi (2020) identify the relationship between CO<sub>2</sub> emissions, trade

liberalization, gross domestic product, and energy consumption in Kuwait from 1971 to 2017. They find that (i) economic growth causes CO<sub>2</sub> emissions; (ii) there is feedback causality between CO<sub>2</sub> emissions and energy consumption; and (iii) there is unidirectional running from energy consumption to trade liberalization. Aydođan and Vardar (2020) focus on E7 countries while exploring the relationship between CO<sub>2</sub> emissions per capita, economic growth, agricultural value-added, renewable, and non-renewable energy consumption. In the E7 countries, they confirm the validity of the Environmental Kuznets Curve (EKC) hypothesis. Moreover, their findings also indicate that economic growth causes CO<sub>2</sub> emissions per capita. On the other hand, the study by Chontanawat (2020) aims to explore the linkage between energy consumption, CO<sub>2</sub> emissions, and economic output in ASEAN countries in 1971–2015. The study concludes that there is no significant causality running from economic growth to CO<sub>2</sub> emissions.

Furthermore, CO<sub>2</sub>-led growth hypothesis states that CO<sub>2</sub> emissions are the determining factor in causing variations in economic growth. The empirical findings of the studies of Adedoyin et al. (2020), Wang et al. (2016b), Joo et al. (2015), Omri et al. (2014), Alam et al. (2012), and Saboori et al. (2012) strongly support and well document for the CO<sub>2</sub>-led growth hypothesis. Adedoyin et al. (2020) find the relationship between coal rent, economic growth, and CO<sub>2</sub> emissions by taking into account the regulatory quality in the BRICS countries from 1990 to 2014. The outcomes of the Dumitrescu and Hurlin causality test of Adedoyin et al. (2020) support the hypothesis of the CO<sub>2</sub>-led growth hypothesis since they conclude that CO<sub>2</sub> emissions cause economic growth in the BRICS countries. Using a linear causality test, Granger causality test, and a nonlinear causality test, Hiemstra and Jones causality test, Wang et al. (2016b) investigate the relationship between economic growth, energy consumption, and CO<sub>2</sub> emission in China in 1978–2012. The findings of Wang et al. (2016b) reveal a one-way causality running from CO<sub>2</sub> emissions to economic growth in China. Tong et al. (2020), Liu et al. (2019), Acheampong (2018), Al-Mulali and Che Sab (2018), Bakirtas and Cetin (2017), Mirza and Kanwal (2017), Bakirtas and Cetin (2017), and Shahbaz et al. (2015) report that there is the two-way linkage between CO<sub>2</sub> emissions and economic growth, supporting the view of feedback hypothesis. CO<sub>2</sub> emissions and economic growth, according to this hypothesis, are dependent upon each other. Several studies, Gorus and Aydin (2019), Han et al. (2018), Pablo-Romero and De Jesús (2016), Wang et al. (2016a), and Gökmenođlu and Taspınar (2016), have found no causality between CO<sub>2</sub> emissions and economic growth. In other words, these studies support the view of the neutrality hypothesis. Gorus and Aydin (2019) focus on eight oil-rich MENA countries for the period 1975–2014 and investigate

the nexus between CO<sub>2</sub> emissions and economic growth using a panel-based frequency domain causality test. They find that there is no dependency between CO<sub>2</sub> emissions and economic growth. Similarly, the results reported by Gökmenođlu and Taspınar (2016) are also in favor of the neutrality hypothesis for CO<sub>2</sub> emissions and economic growth interactions using the time series data of Turkey over the period from 1974 to 2010.

Notably, China is the world's largest carbon emitter globally; numerous empirical and theoretical studies have been conducted on the case of China on the nexus between CO<sub>2</sub> emissions and economic growth (Table 1). To the best the author's knowledge, no study has been devoted to analyzing the time-frequency dependency of CO<sub>2</sub> emissions and economic growth in China using a wavelet approach. Since the present study also employs Toda-Yamamoto causality, Fourier Toda-Yamamoto causality, and nonparametric Granger causality as robust tests, the outcomes are not sensitive to nonlinearity and structural changes.

From the above-cited studies, one could conclude inconclusiveness among these studies, as mentioned earlier, leaving the subject matter open to further deliberations. Hence, the present paper aims to capture the time-frequency dependency of economic growth and CO<sub>2</sub> emissions in China covering 1950–2016. The study used a wavelet coherence approach, which allows the study to investigate both the long-run and short-run causal links between economic growth and CO<sub>2</sub> emissions in China. Further, the paper employed Maki cointegration test, Toda-Yamamoto causality, Fourier Toda-Yamamoto causality, and nonparametric Granger causality tests as robust causality tests which are presented in detail in the Data and Methodology section.

## Data and methodology

This section explains the data and methodological approach involved in modeling China economic growth and CO<sub>2</sub> emissions' variable. China remains the world's largest carbon emitter producer globally; therefore, many studies have investigated the effects and determinants CO<sub>2</sub> emission. However, to the best the author's knowledge, no study has been conducted to capture time-frequency dependency of economic growth and CO<sub>2</sub> emissions in China using a wavelet coherence approach. In other words, the present study explores the co-movement between economic growth and CO<sub>2</sub> emissions in China. To investigate the relationship among the time series variables, the annual data from 1950 to 2016 are used. The dataset of the CO<sub>2</sub> emissions' variable is extracted from the Carbon Dioxide Information Analysis Centre (CDIAC), while the economic growth dataset is gathered from the Maddison Project Database (MPD). Figure 1 presents the pattern of GDP per capita and CO<sub>2</sub> emissions per capita in China, while

**Table 1** Summary of the nexus between CO<sub>2</sub> emissions and economic growth

Sources	Periods	Countries	Estimator	Causality relationship
Chontanawat (2020)	1971–2015	ASEAN	ECM and Granger causality	EG $\nrightarrow$ CO <sub>2</sub>
Ahmad et al. (2020)	2001–2017	China	DCCEMGE	EG $\leftrightarrow$ CO <sub>2</sub>
Wasti and Zaidi (2020)	1971–2017	Kuwait	ARDL and Granger causality	EG $\rightarrow$ CO <sub>2</sub>
Munir et al. (2020)	1980–2016	ASEAN-5	Dumitrescu and Hurlin causality	EG $\rightarrow$ CO <sub>2</sub>
Saint Akadiri et al. (2020)	1970–2014	Turkey	Toda and Yamamoto causality	EG $\rightarrow$ CO <sub>2</sub>
Tong et al. (2020)	1971–2014	Brazil, India, Mexico, and China	ARDL and Granger causality	EG $\leftrightarrow$ CO <sub>2</sub>
Aydoğan and Vardar (2020)	1990–2014	E7 countries	Granger causality	EG $\rightarrow$ CO <sub>2</sub>
Adedoyin et al. (2020)	1990–2014	BRICS	PMG and Dumitrescu and Hurlin causality	CO <sub>2</sub> $\rightarrow$ EG
Gorus and Aydin (2019)	1975–2014	MENA	Panel Granger causality analysis in the frequency domain	EG $\nrightarrow$ CO <sub>2</sub>
Liu et al. (2019)	1965–2017	India and China	Convergent cross mapping	EG $\leftrightarrow$ CO <sub>2</sub>
Acheampong (2018)	1990–2014	116 countries	PVAR and System-GMM	EG $\leftrightarrow$ CO <sub>2</sub>
Al-Mulali and Che Sab (2018)	1990–2008	Middle East countries	Panel Granger causality test	EG $\leftrightarrow$ CO <sub>2</sub>
Ahmad et al. (2018)	1971–2013	China	Granger causality	EG $\rightarrow$ CO <sub>2</sub>
Han et al. (2018)	1996–2014	China	Granger causality	EG $\nrightarrow$ CO <sub>2</sub>
Bekhet et al. (2017)	1990–2011	GCC countries	ECM and Granger causality	EG $\leftrightarrow$ CO <sub>2</sub>
Mirza and Kanwal (2017)	1971–2009	Pakistan	ECM and Granger causality	EG $\leftrightarrow$ CO <sub>2</sub>
Riti et al. (2017)	1970–2015	China	ECM and Granger causality	EG $\rightarrow$ CO <sub>2</sub>
Bakirtas and Cetin (2017)	1982–2011	MIKTA countries	Panel VAR, Granger causality	EG $\leftrightarrow$ CO <sub>2</sub>
Pablo-Romero and De Jesús (2016)	1990–2011	22 Latin American and Caribbean countries	Panel-based OLS	EG $\nrightarrow$ CO <sub>2</sub>
Shahbaz et al. (2016a, b)	1972–2013	Next 11 countries	Time-varying Granger causality	EG $\rightarrow$ CO <sub>2</sub>
Wang et al. (2016a)	1990–2012	China	Granger causality	EG $\nrightarrow$ CO <sub>2</sub>
Wang et al. (2016b)	1978–2012	China	Hiemstra and Jones causality and Granger causality tests	CO <sub>2</sub> $\rightarrow$ EG
Gökmenoğlu and Taspınar (2016)	1974–2010	Turkey	Toda and Yamamoto causality	EG $\nrightarrow$ CO <sub>2</sub>
Shahbaz et al. (2015)	1980–2012	Sub-Saharan African countries	ECM and Granger causality	EG $\leftrightarrow$ CO <sub>2</sub>
Shahbaz et al. (2015)	1971–2011	Portugal	ECM and Granger causality	EG $\rightarrow$ CO <sub>2</sub>
Jafari et al. (2015)	1980–2007	Bahrain	Toda and Yamamoto causality	EG $\rightarrow$ CO <sub>2</sub>
Joo et al. (2015)	1965–2010	Chile	ECM and Granger causality	CO <sub>2</sub> $\rightarrow$ EG
Omri et al. (2014)	1990–2011	54 countries	GMM	CO <sub>2</sub> $\rightarrow$ EG
Alam et al. (2012)	1972–2006	Bangladesh	ECM and Granger causality	CO <sub>2</sub> $\rightarrow$ EG
Saboori et al. (2012)	1980–2009	Malaysia	ECM and Granger causality	CO <sub>2</sub> $\rightarrow$ EG

The direction of the causality is shown by  $\rightarrow$ ,  $\leftrightarrow$ , and  $\nrightarrow$  symbols

Table 2 presents data sources of variables and summary of the descriptive statistics.

As an initial step, in line with the aim of the present study, the orders of integration of economic growth and CO<sub>2</sub> emissions' variables are captured using the DF-GLS unit root test (developed by Elliott et al. (1996) using GLS de-trending procedure) and Zivot-Andrews unit root test with a single structural break (proposed by Zivot and Andrews 2002).

The next step is to capture the cointegration equation between economic growth and CO<sub>2</sub> emissions in China using the Maki cointegration test (Maki 2012). By taking into account multiple structural breaks, the present study employs the

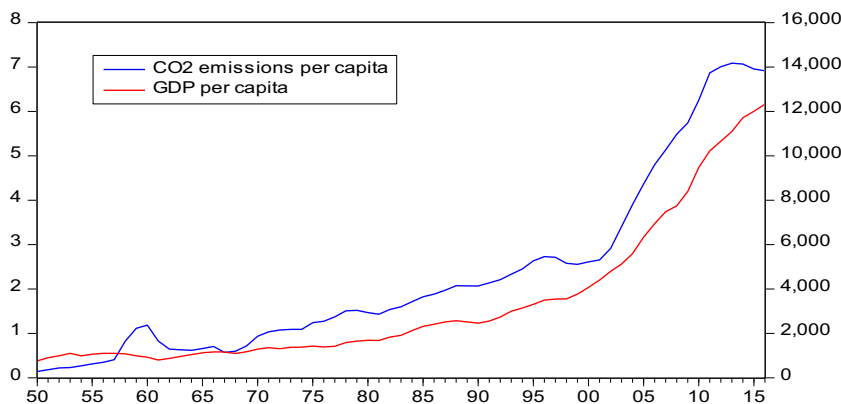
Maki cointegration test to examine the null hypothesis of the cointegrating relationship of CO<sub>2</sub> emissions' variables in China. The present study employed the two separate regression models of the Maki cointegration test: Regime Shift and Regime Shift with Trend. The equation of these regression models are shown below:

Regime Shift:

$$CO_{2t} = \pi + \sum_{i=1}^k \pi_i D_{i,t} + \beta EG_t + \delta t + \sum_{i=1}^k \beta'_i EG_t D_{i,t} + \varepsilon_t \quad (1)$$

$$EG_t = \pi + \sum_{i=1}^k \pi_i D_{i,t} + \beta CO_{2t} + \delta t + \sum_{i=1}^k \beta'_i CO_{2t} D_{i,t} + \varepsilon_t \quad (2)$$

**Fig. 1** GDP per capita and CO<sub>2</sub> emissions per capita in China. Source: CDIAC and MPD



Source: CDIAC and MPD

**Regime Shift with Trend:**

$$CO2_t = \pi + \sum_{i=1}^k \pi_i D_{i,t} + \beta' EG_t + \delta t + \sum_{i=1}^k \delta_i t D_{i,t} + \sum_{i=1}^k \beta'_i EG_t D_{i,t} + \varepsilon_t \tag{3}$$

$$EG_t = \pi + \sum_{i=1}^k \pi_i D_{i,t} + \beta' CO2_t + \delta t + \sum_{i=1}^k \delta_i t D_{i,t} + \sum_{i=1}^k \beta'_i CO2_t D_{i,t} + \varepsilon_t \tag{4}$$

In Eqs. 1–4, "t" denotes the period, i.e.,  $t = 1, 2, 3, \dots, T$ ;  $CO2_t$  is the CO<sub>2</sub> emission per capita variable in China while  $EG_t$  represents the GDP per capita; and  $\varepsilon_t$  is the error term. Here,  $T_{SB, i}$  is for the specific period of each structural break with "k" for the maximum number of breaks obtained (Khan et al. 2020).

In the present study, the empirical approaches applied to the dataset also include continuous wavelet power spectrum and coherence. The wavelet analysis takes both the frequency and time dimension into account simultaneously, which is a useful tool in the econometric analysis since the economic literature studies are widely conducted by either time series analysis or based on frequency domain.

**Table 2** Descriptive statistics

Variable	CO <sub>2</sub> emissions per capita	GDP per capita
Code	CO <sub>2</sub>	EG
Source	CDIAC	MPD
Time	1950–2016	
Mean	2.304645	3371.582
Median	1.596541	1907.000
Maximum	7.084593	12,320.00
Minimum	0.141856	757.0000
Std. Dev.	2.025282	3216.773
Skewness	1.230688	1.532904
Kurtosis	3.402941	4.181278
Jarque-Bera	17.36621	30.13491
Probability	0.000169	0.000000

Besides, employing time-based traditional causality tests and fixed parameters causes erroneous results when there are structural breaks in time series. At this point, determining where structural breaks occur in the modeling technique is quite remarkable. In this context, the Fourier transform is developed by using a different frequency domain approach. In this approach, neglecting the information in the time domain and focusing on the frequency domain pose a critical problem (Orhan et al. 2019). Besides, the wavelet analysis brings the two widely used separated techniques under a unified frame of time and frequency dimension. In other words, the continuous wavelet coherence approach allows the present study to explore how the economic growth and CO<sub>2</sub> emissions in China are related at different frequencies and how their relationship varies over time since the wavelet analysis has taken both the frequency and time dimension into account simultaneously. However, it is worth mentioning that the number of studies in the economic and environment literature employing the continuous wavelet power spectrum and coherence is considerably low compared with the other fields such as medicine and engineering fields. Nevertheless, the continuous wavelet power spectrum and coherence approaches have become more prevalent in recent years since the approach allows for obtaining highly valuable information about the interaction of the economic, financial, and environment time series variables which cannot be observed by the other techniques applied.

As the primary purpose of this study is to investigate the relationship between economic growth and CO<sub>2</sub> emissions, I use the wavelet equation developed by Goupillaud et al. (1984) as follows:  $\psi(t) = \pi^{-\frac{1}{4}} e^{-i\omega_0 t} e^{-\frac{1}{2}t^2}$ ,  $p(t)$ ,  $t = 1, 2, 3, \dots, T$ , where  $\psi$  is applied on limited observations by Kirikkaleli et al. (2020). The simple equation of the continuous wavelet is shown below in equation two. The continuous wavelet is constructed from  $\psi$  with  $k$  and  $f$  parameters for the the time series data  $p(t)$  as follows:

$$W_p(k, f) = \int_{-\infty}^{\infty} p(t) \frac{1}{\sqrt{f}} \psi\left(\frac{t-k}{f}\right) dt, \quad (5)$$

where  $k$  and  $f$  indicate the time and frequency, respectively. “The main role of the  $k$  is to define a wavelet’s particular location in time by exchanging the wavelet while  $f$  controls the distended wavelet for localizing various frequencies” (Kirikkaleli and Sowah 2020). Equation 6 presents the modified  $p(t)$  with the  $\psi$  coefficient.

$$p(t) = \frac{1}{C_\psi} \int_0^\infty \left[ \int_{-\infty}^{\infty} |W_p(a, b)|^2 da \right] \frac{db}{b^2}. \quad (6)$$

The present study employed the wavelet power spectrum (WPS) to obtain information about the vulnerability of economic growth and CO<sub>2</sub> emissions in China. Therefore, WPS allows us to capture the vulnerable periods and frequencies of the time series variables.

$$WPS_p(k, f) = |W_p(k, f)|^2. \quad (7)$$

As mentioned, the advantage of the wavelet coherence approach against traditional correlation and causality tests is that the approach brings out any correlation or causality between the economic growth and CO<sub>2</sub> emissions in combined time-frequency based causalities. As Kirikkaleli et al. (2020) stated, the squared wavelet coherence equation is constructed as shown below:

$$R^2(k, f) = \frac{|C(f^{-1}W_{pq}(k, f))|^2}{C(f^{-1}|W_p(k, f)|^2)C(f^{-1}|W_q(k, f)|^2)} \quad (8)$$

where  $C$  denotes time and the smoothing process over time, with  $0 \leq R^2(k, f) \leq 1$ . Whenever the value of  $R^2(k, f)$  approaches to one indicates a correlation among the time series variables. In the figures, correlated areas are surrounded by a black line and depicted in red color. However, whenever the value gets close to 0, this indicates no correlation between the time series variables and is pictured by blue color. Obtaining  $R^2(k, f)$  does not give us a chance to discuss the relationship’s sign. To deal with this, Torrence and Compo (1998) postulated a means by which I can detect “the wavelet coherence differences through indications of deferrals in the wavering of two-time series. The equation of the wavelet coherence difference phase is constructed as follows”:

$$\phi_{pq}(k, f) = \tan^{-1} \left( \frac{L\{C(f^{-1}W_{pq}(k, f))\}}{O\{C(f^{-1}W_{pq}(k, f))\}} \right), \quad (9)$$

where  $L$  and  $O$  denote an imaginary operator and a real part operator, respectively.

The present study uses Toda-Yamamoto causality (proposed by Toda and Yamamoto (1995)), Fourier Toda-Yamamoto causality (proposed by Nazlioglu et al. 2016), and nonparametric Granger causality (proposed by Diks and Panchenko (2006)) tests as robust causality tests.

## Empirical findings

Even though the immeasurable numbers of studies have explored the nexus between economic growth and CO<sub>2</sub> emissions, no study has been conducted to capture time-frequency dependency of economic growth and CO<sub>2</sub> emissions in China using a wavelet coherence approach. Therefore, as an initial step, the orders of integration of economic growth and CO<sub>2</sub> emissions variables are investigated using the DF-GLS unit root test and Zivot-Andrews unit root test with a single structural break. Table 3 reports the outcomes of the DF-GLS and Zivot-Andrews unit root tests. For the EG variable, the integration of order zero,  $I(0)$ , is not detected since the calculated  $T$ -stats of  $-1.053$  in the DF-GLS unit root test and  $-1.488$  in the Zivot-Andrews unit root test are greater than the 5% critical values of the unit root tests, respectively. However, at the first difference, the null hypothesis that the EG variable has a unit root can be rejected, meaning that the EG variable is integrated of order one,  $I(1)$ . Moreover, Table 3 also reports that the CO<sub>2</sub> variable does not seem stationary at levels but stationary at the first difference. It can be concluded that the integration of the order of the CO<sub>2</sub> and EG variables is one.

Table 4 reports the Maki cointegration test outcomes with regression models of (1) Regime Shift and (2) Regime Shift and Trend. The majority of the models up to five structural breaks prove the existence of a cointegrating relationship between the CO<sub>2</sub> and EG variables at Regime Shift and Regime Shift and Trend models. This outcome approves a cointegrating linkage between the time series variables in the presence of structural breaks. These cointegration findings, in some form, are supported by earlier studies like Jalil and Mahmud (2009) and Saboori et al. (2012).

A wavelet power spectrum for the variables of GDP per capita and CO<sub>2</sub> emissions per capita in China is reported in Figs. 2 and 3. In the present study, a scale of 23 periods has been determined, since the dataset covers the period from 1950 to 2016 (67 observations). The white cone-shaped curve indicates the cone of influence, representing an edge below where the wavelet power is affected by discontinuity, while the thick black shape presents a 5% significance level determined by Monte Carlo simulations. Although the GDP per capita variable exhibits low power between 1950 and 2001, the variable between 2002 and 2015 appears highly

**Table 3** Unit root tests

Variables	DF-GLS unit root test			Zivot-Andrews unit root test			
	T-stat	Critical value		T-stat	SB	Critical value	
		5%	10%			5%	10%
EG	-1.053	-1.946	-1.613	-2.785	2000**	-4.93	-4.58
Δ EG	-7.934**	-1.946	-1.613	-4.802**	1964	-4.93	-4.58
CO <sub>2</sub>	0.944	-1.946	-1.613	-4.125	2003**	-4.93	-4.58
Δ CO <sub>2</sub>	-3.166**	-1.946	-1.613	-4.996**	2002**	-4.93	-4.58

\*\* and \* indicate the significance levels at 5% and 10%. SB denotes structural break, while Δ presents the first difference of the time series variables

vulnerable at very high frequency (at 3–6 scale periods) in Fig. 2, meaning that economic growth had a significant volatility for the period 2001–2015 in the short-run. As seen in Fig. 3, a high variation occurs for CO<sub>2</sub> emissions per capita in China at 4 and 6 scale periods from 1955 to 1965. Moreover, a significant high volatility is noted in CO<sub>2</sub> emissions per capita in China, as seen in Fig. 3 between 2000 and 2015 at different frequencies.

To capture the signs of and causal relationship between economic growth and CO<sub>2</sub> emissions in China, a continuous

wavelet coherence approach is applied in the present study, and the outcomes from this approach are pictured in Figs. 4. The cold (blue) colors represent no dependency between economic growth and CO<sub>2</sub> emissions in China in Fig. 4, whereas warmer color areas denote the significant correlation or causality between the time series variables. In the continuous wavelet coherence approach, the direction of the significant causality is represented by arrows surrounded by the thick black line. “While arrows pointing to the left indicate negative correlation among the variables, arrows point to the right

**Table 4** Maki cointegration test

Model	T-stats	Critical values		Break years
		5% Level	10% Level	
<b>Regime Shift and Trend</b>				
CO <sub>2</sub> = f(EG)	-5.569**	-5.541	-5.281	1971
CO <sub>2</sub> = f(EG)	-6.146**	-6.100	-5.845	1971, 1965
CO <sub>2</sub> = f(EG)	-7.131**	-6.524	-6.267	1971, 1965, 1955
CO <sub>2</sub> = f(EG)	-7.131**	-7.009	-6.712	1971, 1965, 1955, 1963
CO <sub>2</sub> = f(EG)	-7.374*	-7.414	-7.110	1971, 1965, 1955, 1963, 1959
EG = f(CO <sub>2</sub> )	-4.164	-5.541	-5.281	1997
EG = f(CO <sub>2</sub> )	-4.164	-6.100	-5.845	1997, 2009
EG = f(CO <sub>2</sub> )	-5.346	-6.524	-6.267	1997, 2009, 1980
EG = f(CO <sub>2</sub> )	-7.362**	-7.009	-6.712	1997, 2009, 1980, 1968
EG = f(CO <sub>2</sub> )	-8.125**	-7.414	-7.110	1997, 2009, 1980, 1968, 2006
<b>Regime Shift</b>				
CO <sub>2</sub> = f(EG)	-5.121**	-4.895	-4.626	1955
CO <sub>2</sub> = f(EG)	-5.324*	-5.363	-5.070	1955, 1981
CO <sub>2</sub> = f(EG)	-7.298**	-5.703	-5.402	1955, 1981, 1960
CO <sub>2</sub> = f(EG)	-7.298**	-6.011	-5.723	1955, 1981, 1960, 1971
CO <sub>2</sub> = f(EG)	-7.298**	-6.357	-6.057	1955, 1981, 1960, 1971, 1977
EG = f(CO <sub>2</sub> )	-5.568**	-4.895	-4.626	1976
EG = f(CO <sub>2</sub> )	-7.089**	-5.363	-5.070	1976, 1966
EG = f(CO <sub>2</sub> )	-7.834**	-5.703	-5.402	1976, 1966, 1991
EG = f(CO <sub>2</sub> )	-8.121**	-6.011	-5.723	1976, 1966, 1991, 1956
EG = f(CO <sub>2</sub> )	-8.414**	-6.357	-6.057	1976, 1966, 1991, 1956, 1953

\*\* and \* indicate the significance levels at 5% and 10%

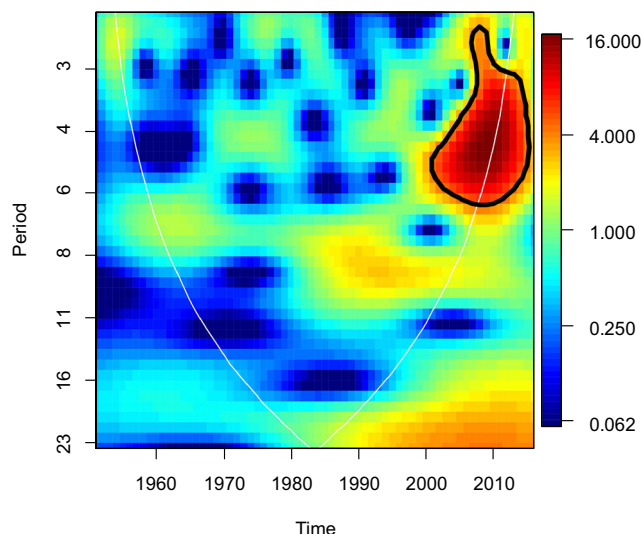


Fig. 2 The wavelet power spectrum for GDP per capita

represent the positive correlation.” Besides, arrows pointing up, right-up, or left-down show that CO<sub>2</sub> emissions cause economic growth in China, whereas arrows pointing down, right-down, or left-up indicate that changes in the economic growth variable significantly lead to changes in the CO<sub>2</sub> emissions’ variable. As clearly demonstrated in Fig. 4, arrows point right down at the thick black shape at 6, 8, and 11 scales, implying that economic growth leads to CO<sub>2</sub> emissions in the medium-term. This result clearly shows that economic growth was an important predictor of CO<sub>2</sub> emissions in China. Moreover, detecting rightward arrows between 1970 and 1990 reveal that economic growth and CO<sub>2</sub> emissions are in phase at 3 and 4 scales—at high frequency. In other words, there is a significant positive correlation between economic growth and CO<sub>2</sub> emissions in China in the short-term.

As robust tests for the outcomes of continuous wavelet coherence technique, Toda-Yamamoto causality, Fourier

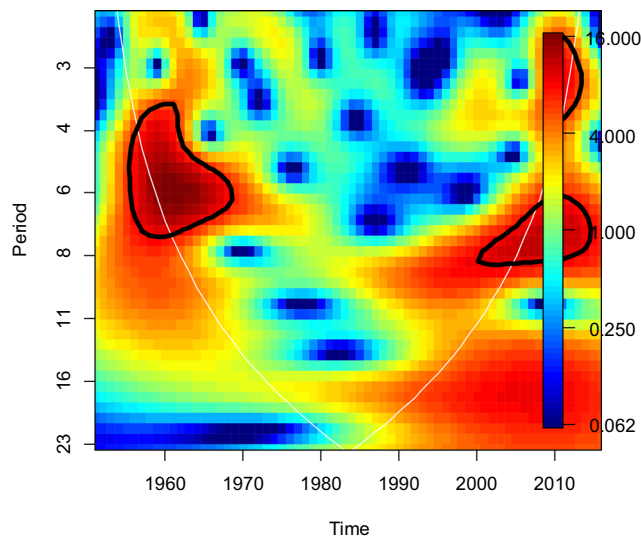


Fig. 3 The wavelet power spectrum for CO<sub>2</sub> emissions per capita

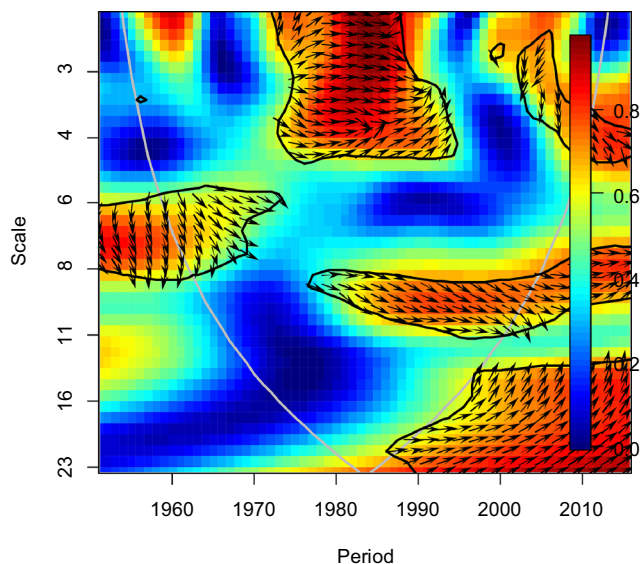


Fig. 4 Wavelet coherence between GDP per capita and CO<sub>2</sub> emissions per capita

Toda-Yamamoto causality, and nonparametric Granger causality tests are applied to investigate the causal relationship between economic growth and CO<sub>2</sub> emissions in China. The findings from these tests are reported in Table 5, proving that the null hypothesis that economic growth does not cause CO<sub>2</sub> emission can be rejected at a 5% significance level. In other words, there is a unilateral causality running from economic growth to CO<sub>2</sub> emissions in China. This finding is rational and inline with the studies of Wasti and Zaidi (2020), Aydoğan and Vardar (2020), Riti et al. (2017), Shahbaz et al. (2015) and Jafari et al. (2015) which underline growth-led CO<sub>2</sub> emissions hypothesis in their studies. It is worth mentioning that the outcomes of more Fourier Toda-Yamamoto causality and nonparametric Granger causality tests are in line

Table 5 Robustness causality test results

Toda-Yamamoto causality test			
Direction of causality	Lag	MWALD	Prob.
EG → CO <sub>2</sub>	2	8.611**	0.013
CO <sub>2</sub> → EG	2	3.540	0.170
Fourier Toda-Yamamoto causality test			
Direction of causality	Lag	F-Stat	Prob.
EG → CO <sub>2</sub>	2	7.442**	0.024
CO <sub>2</sub> → EG	2	2.554	0.278
Nonparametric Granger causality test			
Direction of causality	Lag	T-stat	Prob.
EG → CO <sub>2</sub>	2	1.435*	0.075
CO <sub>2</sub> → EG	2	1.062	0.144

→ stands for the direction of the causality. \*, \*\*, and \*\*\* denote the statistical significance at 10%, 5%, and 1% levels



with the outcomes of the continuous wavelet coherence approach which is pictured in Fig. 4.

## Conclusion

Since the four decades, economic growth has become a vital policy indicator for the Chinese government to measure environment crises. Current studies on China's economic growth mainly discuss the typical cases of economic growth mode concerning specific stimuli, while few researches deal with the efficiency trend of macro-economy from the regional perspective, along with great many studies on the impact of CO<sub>2</sub> emissions in both the developed and developing countries. Previous researches have also explored the determinants of CO<sub>2</sub> emissions using panel and time series based models in the literature. However, up to date, no previous studies have explicitly examined time-frequency dependency of economic growth and CO<sub>2</sub> emissions in China, precisely by using a continuous wavelet coherence approach. The wavelet coherence technique allows the present study to investigate the short-term and long-term relationships between economic growth and CO<sub>2</sub> emissions in China. Apart from the continuous wavelet coherence approach, the present study also employs the Maki cointegration test to capture the long-run linkage between economic growth and CO<sub>2</sub> emissions in China. Furthermore, the robust causality approaches of Toda-Yamamoto causality, Fourier Toda-Yamamoto causality, and nonparametric Granger causality tests were implemented respectively. The outcomes of the present study underline that (i) there is a significant vulnerability in economic growth and CO<sub>2</sub> emissions throughout the 2000s in the short-term and medium-term; (ii) there is a long-run cointegration linkage between economic growth and CO<sub>2</sub> emissions in China; (iii) economic growth in China has an important power for predicting CO<sub>2</sub> emissions over the selected time period, especially short-term and medium-term; and (iv) in the short-term, it is also observed that there is a positive correlation between economic growth during the 1980s and 1990s.

Based on these findings, the present study makes several unique and substantial contributions to the literature, which is significant for future sustainable development in the case of China. In addition, since China is the largest carbon emitter in the world and has signed the COP21 agreement to hold the rising global average temperature below 2 °C and the target will be 1.5 °C, governors and investors in China should invest in environmentally friendly and renewable energy sources to enhance expected economic growth while continuously reducing the CO<sub>2</sub> intensity of GDP. Besides, China should intensively substitute fossil fuel with new and renewable energy sources to reduce CO<sub>2</sub> emissions based on the main target of COP21, which is to reach peak emissions earlier than the current Paris target of 2030. Although the present study

provides valuable contribution and robust empirical findings, further studies should include other time series macroeconomic variables to deepen these findings, and the regional comparative study on the nexus between economic growth and CO<sub>2</sub> emissions could offer a remarkable contribution for emerging markets.

## References

- Acheampong AO (2018) Economic growth, CO<sub>2</sub> emissions, and energy consumption: what causes what and where? *Energy Econ* 74:677–692
- Adeyoyin FF, Gumede MI, Bekun FV, Etokakpan MU, Balsalobre-lorente D (2020) Modeling coal rent, economic growth, and CO<sub>2</sub> emissions: does regulatory quality matter in BRICS economies? *Sci Total Environ* 710:136284
- Ahmad, M., Hengyi, H., Rahman, Z. U., Khan, Z. U., Khan, S., & Khan, Z. (2018). Carbon emissions, energy use, gross domestic product, and the total population in China. *Ekonomia i Środowisko*
- Ahmad M, Zhao ZY, Irfan M, Mukeshimana MC, Rehman A, Jabeen G, Li H (2020) Modeling heterogeneous dynamic interactions among energy investment, SO<sub>2</sub> emissions, and economic performance in regional China. *Environ Sci Pollut Res* 27(3):2730–2744
- Alam MJ, Begum IA, Buysse J, Van Huylenbroeck G (2012) Energy consumption, carbon emissions, and economic growth nexus in Bangladesh: cointegration and dynamic causality analysis. *Energy Policy* 45:217–225
- Al-Mulali U, Che Sab CNB (2018) Electricity consumption, CO<sub>2</sub> emission, and economic growth in the Middle East. *Energy Sour, Part B: Econ Plan Policy* 13(5):257–263
- Aydoğan B, Vardar G (2020) Evaluating the role of renewable energy, economic growth, and agriculture on CO<sub>2</sub> emission in E7 countries. *Int J Sustain Energ* 39(4):335–348
- Bakirtas I, Cetin MA (2017) Revisiting the environmental Kuznets curve and pollution haven hypotheses: MIKTA sample. *Environ Sci Pollut Res* 24(22):18273–18283
- Bekhet HA, Matar A, Yasmin T (2017) CO<sub>2</sub> emissions, energy consumption, economic growth, and financial development in GCC countries: dynamic simultaneous equation models. *Renew Sustain Energ Rev* 70:117–132
- Chontanawat J (2020) Relationship between energy consumption, CO<sub>2</sub> emission, and economic growth in ASEAN: cointegration and causality model. *Energy Rep* 6:660–665
- Diks C, Panchenko V (2006) A new statistic and practical guidelines for nonparametric Granger causality testing. *J Econ Dyn Control* 30(9–10):1647–1669
- Elliott G, Rothenberg TJ, James H (1996) Stock, 1996, “Efficient tests for an autoregressive unit root”. *Econometrica* 64(4):813–836
- Gallagher KS, Zhang F, Orvis R, Rissman J, Liu Q (2019) Assessing the policy gaps for achieving China's climate targets in the Paris agreement. *Nat Commun* 10(1):1–10
- Gökmenoğlu K, Taspınar N (2016) The relationship between CO<sub>2</sub> emissions, energy consumption, economic growth, and FDI in Turkey's case. *J Int Trade Econ Develop* 25(5):706–723
- Gorus MS, Aydin M (2019) The relationship between energy consumption, economic growth, and CO<sub>2</sub> emission in MENA countries: causality analysis in the frequency domain. *Energy* 168:815–822
- Goupillaud P, Grossmann A, Morlet J (1984) Cycle-octave and related transforms in seismic signal analysis. *Geoexploration* 23(1):85–102

- Han J, Du T, Zhang C, Qian X (2018) Correlation analysis of CO<sub>2</sub> emissions, material stocks, and economic growth nexus: evidence from Chinese provinces. *J Clean Prod* 180:395–406
- Jafari Y, Ismail MA, Othman J, Mawar MY (2015) Energy consumption, emissions, and economic growth in Bahrain. *Chin J Populat Resour Environ* 13(4):297–308
- Jalil A, Mahmud SF (2009) Environment Kuznets curve for CO<sub>2</sub> emissions: a cointegration analysis for China. *Energy Policy* 37(12):5167–5172
- Joo YJ, Kim CS, Yoo SH (2015) Energy consumption, CO<sub>2</sub> emission, and economic growth: evidence from Chile. *Int J Green Energy* 12(5):543–550
- Khan Z, Hussain M, Shahbaz M, Yang S, Jiao Z (2020) Natural resource abundance, technological innovation, and human capital nexus with financial development: China's case study. *Res Policy* 65:101585
- Kirikaleli D, Adedoyin FF, Bekun FV (2020) Nuclear energy consumption and economic growth in the UK: evidence from the wavelet coherence approach. *Journal of Public Affairs*
- Kirikaleli D, Sowah JK Jr (2020) A wavelet coherence analysis: nexus between urbanization and environmental sustainability. *Environ Sci Pollut Res Int*
- Liu H, Lei M, Zhang N, Du G (2019) The causal nexus between energy consumption, carbon emissions, and economic growth: new evidence from China, India, and G7 countries using convergent cross-mapping. *PLoS One* 14(5)
- Maki D (2012) Tests for cointegration allowing for an unknown number of breaks. *Econ Model* 29(5):2011–2015
- Mardani A, Streimikiene D, Cavallaro F, Loganathan N, Khoshnoudi M (2019) Carbon dioxide (CO<sub>2</sub>) emissions and economic growth: a systematic review of two decades of research from 1995 to 2017. *Sci Total Environ* 649:31–49
- Mirza FM, Kanwal A (2017) Energy consumption, carbon emissions, and economic growth in Pakistan: dynamic causality analysis. *Renew Sust Energy Rev* 72:1233–1240
- Munir Q, Lean HH, Smyth R (2020) CO<sub>2</sub> emissions, energy consumption, and economic growth in the ASEAN-5 countries: a cross-sectional dependence approach. *Energy Econ* 85:104571
- Nazlioglu S, Gormus NA, Soytaş U (2016) Oil prices and real estate investment trusts (REITs): gradual-shift causality and volatility transmission analysis. *Energy Econ* 60:168–175
- Omri A, Nguyen DK, Rault C (2014) Causal interactions between CO<sub>2</sub> emissions, FDI, and economic growth: evidence from dynamic simultaneous-equation models. *Econ Model* 42:382–389
- 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
- Pablo-Romero MDP, De Jesús J (2016) Economic growth and energy consumption: the energy-environmental Kuznets curve for Latin America and the Caribbean. *Renew Sust Energy Rev* 60:1343–1350
- Racine J, Li Q (2004) Nonparametric estimation of regression functions with both categorical and continuous data. *J Econ* 119(1):99–130
- Rhodes CJ (2016) The 2015 Paris climate change conference: COP21. *Sci Prog* 99(1):97–104
- Riti JS, Song D, Shu Y, Kamah M (2017) Decoupling CO<sub>2</sub> emission and economic growth in China: is there consistency in estimation results in analyzing the environmental Kuznets curve? *J Clean Prod* 166:1448–1461
- Saboori B, Sulaiman J, Mohd S (2012) Economic growth and CO<sub>2</sub> emissions in Malaysia: a cointegration analysis of the environmental Kuznets curve. *Energy Policy* 51:184–191
- Saint Akadiri S, Alola AA, Olasehinde-Williams G, Etokakpan MU (2020) The role of electricity consumption, globalization, and economic growth in carbon dioxide emissions and its implications for environmental sustainability targets. *Sci Total Environ* 708:134653
- Shahbaz M, Solarin SA, Sbia R, Bibi S (2015) Does energy intensity contribute to CO<sub>2</sub> emissions? A trivariate analysis in selected African countries. *Ecol Indic* 50:215–224
- Shahbaz M, Jam FA, Bibi S, Loganathan N (2016a) Multivariate granger causality between CO<sub>2</sub> emissions, energy intensity, and economic growth in Portugal: evidence from cointegration and causality analysis. *Technol Econ Dev Econ* 22(1):47–74
- Shahbaz M, Mahalik MK, Shah SH, Sato JR (2016b) Time-varying analysis of CO<sub>2</sub> emissions, energy consumption, and economic growth nexus: statistical experience in next 11 countries. *Energy Policy* 98:33–48
- Shahbaz M, Shafiullah M, Papavassiliou VG, Hammoudeh S (2017) The CO<sub>2</sub>–growth nexus revisited: a nonparametric analysis for the G7 economies over nearly two centuries. *Energy Econ* 65:183–193
- Toda HY, Yamamoto T (1995) Statistical inference in vector autoregressions with possibly integrated processes. *J Econ* 66(1–2):225–250
- Tong T, Ortiz J, Xu C, Li F (2020) Economic growth, energy consumption, and carbon dioxide emissions in the E7 countries: a bootstrap ARDL bound test. *Energy Sustain Soc* 10:1–17
- Torrence C, Compo GP (1998) A practical guide to wavelet analysis. *Bull Am Meteorol Soc* 79(1):61–78
- Wang S, Li Q, Fang C, Zhou C (2016a) The relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions: empirical evidence from China. *Sci Total Environ* 542:360–371
- Wang K, Zhu B, Wang P, Wei YM (2016b) Examining the links among economic growth, energy consumption, and CO<sub>2</sub> emission with linear and nonlinear causality tests. *Nat Hazards* 81(2):1147–1159
- Wang D, He W, Shi R (2019a) How to achieve the dual-control targets of China's CO<sub>2</sub> emission reduction in 2030? Future trends and prospective decomposition. *J Clean Prod* 213:1251–1263
- Wang H, Lu X, Deng Y, Sun Y, Nielsen CP, Liu Y, Zhu G, Bu M, Bi J, McElroy MB (2019b) China's CO<sub>2</sub> peak before 2030 implied from characteristics and growth of cities. *Nat Sustain* 2(8):748–754
- Wang L, Vo XV, Shahbaz M, Ak A (2020) Globalization and carbon emissions: is there any role of agriculture value-added, financial development, and natural resource rent in the aftermath of COP21? *J Environ Manag* 268:110712
- Wasti SKA, Zaidi SW (2020) An empirical investigation between CO<sub>2</sub> emission, energy consumption, trade liberalization, and economic growth: a case of Kuwait. *J Build Eng* 28:101104
- Zivot E, Andrews DWK (2002) Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. *J Bus Econ Stat* 20(1):25–44

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