



## The relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions: Empirical evidence from China



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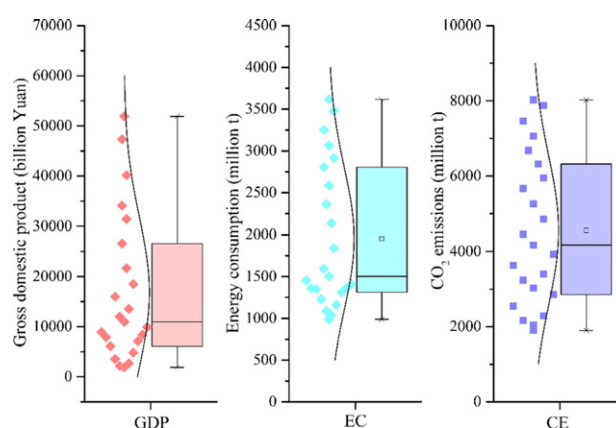
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### HIGHLIGHTS

- The nexus between economic growth, energy use and CO<sub>2</sub> emissions for China examined.
- Cointegration tests suggest presence of long-run relationship among the variables.
- Generalized impulse response due to the external shocks to the system examined.
- Bi-directional causality between economic growth and energy consumption.
- Unidirectional causality from energy consumption to CO<sub>2</sub> emissions.

### GRAPHICAL ABSTRACT



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### ABSTRACT

Following several decades of rapid economic growth, China has become the largest energy consumer and the greatest emitter of CO<sub>2</sub> in the world. Given the complex development situation faced by contemporary China, Chinese policymakers now confront the dual challenge of reducing energy use while continuing to foster economic growth. This study posits that a better understanding of the relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions is necessary, in order for the Chinese government to develop the energy saving and emission reduction strategies for addressing the impacts of climate change. This paper investigates the cointegrating, temporally dynamic, and casual relationships that exist between economic growth, energy consumption, and CO<sub>2</sub> emissions in China, using data for the period 1990–2012. The study develops a comprehensive conceptual framework in order to perform this analysis. The results of cointegration tests suggest the existence of long-run cointegrating relationship among the variables, albeit with short dynamic adjustment mechanisms, indicating that the proportion of disequilibrium errors that can be adjusted in the next period will account for only a fraction of the changes. Further, impulse response analysis (which describes the reaction of any variable as a function of time in response to external shocks) found that the impact of a shock in CO<sub>2</sub> emissions on economic growth or energy consumption was only marginally significant. Finally, Granger casual relationships were found to exist between economic growth, energy consumption, and CO<sub>2</sub> emissions; specifically, a bi-directional causal relationship between economic growth and energy consumption was identified, and a unidirectional causal relationship was found to exist from energy consumption to CO<sub>2</sub> emissions. The findings have

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significant implications for both academics and practitioners, warning of the need to develop and implement long-term energy and economic policies in order to effectively address greenhouse effects in China, thereby setting the nation on a low-carbon growth path.

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## 1. Introduction

Since the Chinese Government's 'Reform and Opening-up' policy was implemented in the late 1980s, the country has witnessed—and in fact continues to witness—rapid economic growth, emerging as the world's largest developing nation (Wang et al., 2014a; Wang et al., 2015b). Gross domestic product (GDP) has increased on average by more than 9% each year since the policy was introduced (Wang et al., 2014a). This growth in turn however poses a number of challenges for the nation, such as how to deal with increasing energy demand, a factor which may lie behind the rapid increases in energy consumption and CO<sub>2</sub> emissions seen in China in the past three decades. The world's largest energy consumer and the world's greatest CO<sub>2</sub> emitter, China has not yet completed the historical tasks of industrialization and urbanization. The country still faces an arduous journey in developing its economy, eliminating poverty, and improving the livelihoods of its population (Wang et al., 2014b). Given this complex development situation, the Chinese government faces a dual challenge: on one hand, it must reduce energy use, while on the other it must actively foster continued economic growth. With a view to these dual challenges, a better understanding of the relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions is required; it is through such understanding that future sustainable development might be achieved (Zhang and Wang, 2013; Zhang et al., 2013; Govindaraju and Tang, 2013; Hu et al., 2014). Despite the critical need for scholarship addressing this relation, most of the existing literature engaged in this task have focused on long-term equilibrium relationships, thereby ignoring temporally dynamic relationships, and the possibilities presented by both vector error correction analysis and impulse response analysis. This deficiency in contemporary research motivates the present study, which aims contribute to precisely such a framing by quantifying the relationship between China's economic growth, energy consumption, and CO<sub>2</sub> emissions accurately and systematically. Exploration of the relationship between these three variables will, importantly, help us to confirm whether or not economic growth does indeed constitute a major factor in the energy consumption increases and CO<sub>2</sub> emissions increases currently witnessed in contemporary China.

Many recent studies have addressed the relationship between energy consumption, CO<sub>2</sub> emissions, and economic growth, and have done so in relation to a number of different countries and regions. In fact, since the pioneering work of Kraft and Kraft (1978), the relationship between energy consumption and economic growth has become a hot topic in environmental science and energy economics. A large volume of empirical research from the last two decades confirms the existence of a strong historical correlation between these two variables, with most empirical results indicating that economic growth can indeed cause increases in energy consumption (Glasure, 2002; Ghali and El-Sakka, 2004; Akinlo, 2008; Apergis and Payne, 2009). Energy consumption, in turn, is now also generally recognized to be the main impact factor in relation to CO<sub>2</sub> emissions. Given all of these findings, the relationship between economic growth and CO<sub>2</sub> emissions has emerged as a key research issue, forming the focus of numerous theoretical explorations, as well as a large number of empirical investigations, in recent years. For example, using an improved STIRPAT model, Wang et al. (2012) found economic growth to be one of the major factors in increases in CO<sub>2</sub> emissions in Beijing City. Similar results were found by Wang et al. (2013) in Guangdong, Paul and Bhattacharya (2004) in India, Elif et al. (2011) in Turkey, Acaravci and Ozturk (2010) in Europe, and Al-mulali et al. (2013) in Latin America and the Caribbean. To test for the existence of a long-run relationship, the cointegration

techniques developed by Engle and Granger (1987) and Pedroni (1997, 1999) were widely used among researchers (see for example, Stern, 2000; Ghali and El-Sakka, 2004, and Squalli, 2007; for some recent studies on developed and developing countries, e.g. Hwang and Yoo, 2014; Yavuz, 2014; Salahuddin and Gow, 2014; Alshehry and Belloumi, 2015, and Joo et al., 2015). These studies predominantly used time series econometric analysis or the dynamic panel data approach in order to establish the presence and degree of cointegrating relationships. Most results indicated that economic growth, energy consumption, and CO<sub>2</sub> emissions were integrated of order 1 (denoted as  $I(1)$ ), and that the three variables were both cross-sectionally dependent and cointegrated.

In comparison to the estimation of the cointegrating relationships, some studies have explored the causal relationships between economic growth, energy consumption, and CO<sub>2</sub> emissions through a multivariate framework using the Granger-causality time series or panel data approaches. *The results of the empirical findings are, however, inconsistent.* The existing literature addressing the causal relationships mainly falls into three categories. *The first category of studies found evidences supporting unidirectional or bidirectional causality.* Taking India as an example, Ghosh and Kanjilal (2014) demonstrated a unidirectional causality running from energy consumption to economic activity. Al-mulali et al. (2013) found that while 60% of Latin American and Caribbean countries maintained a positive bidirectional long-run relationship between energy consumption, CO<sub>2</sub> emissions, and economic growth, the remaining 40% yield mixed results. Using error-correction-based Granger causality models, Acaravci and Ozturk (2010) found a one-way causal relationship to exist between economic growth and energy consumption. The same result was arrived at by Jalil and Mahmud (2009) in their study of China. Results of the study taken by Pao and Tsai (2010) indicated bidirectional strong causality between energy consumption–emissions, and bidirectional long-run causality between energy consumption–output, along with unidirectional causalities between emissions–output and energy consumption–output (both strong and short-run, respectively.). Further, Sari and Soytas (2009) found a long-run relationship between income, energy consumption, and CO<sub>2</sub> emissions in Saudi Arabia, but not in Indonesia, Algeria, Nigeria, and Venezuela. However, Narayan and Popp (2012) revealed a negative causal relationship to exist between energy consumption and economic growth in the G6 countries. *The second category comprises of research that has found no causality existing between the variables.* Soytas et al. (2009) found that income does not maintain a relation of Granger-causality with carbon emissions in the United States in the long run (although energy use does). Soytas and Sari (2003) did not locate a causal relationship between the variables—energy conservation can, in their analysis, help reduce CO<sub>2</sub> emissions without affecting a country's economic growth. Apergis et al. (2010) found that in the short-run renewable energy consumption does not contribute to reductions in emissions. In addition, Hossain (2011) found that there was no evidence of long-run causal relationship from economic growth to CO<sub>2</sub> emissions and from economic growth to energy consumption for the panel of newly industrialized countries from 1971 to 2007. *The third category studies have found that the direction of causality is methods or periods dependent.* For instance, using panel smooth transition regression, Heidari et al. (2015) found that the casual relationship between economic growth, energy consumption and CO<sub>2</sub> emissions is *time instability dependent*. CO<sub>2</sub> emissions increased with GDP growth in the first stage (per capita income below 4686 USD) while the direction

was reversed in the second stage (per capita income above 4686 USD). The study on Malaysia taken by Begum et al. (2015) showed that over the period of 1970–1980, CO<sub>2</sub> emissions decreased with economic growth; however from 1980 to 2009, CO<sub>2</sub> emissions increased sharply with a further increase of GDP. Similar results were also found by Cleveland et al. (2000). Taking China as an example, Wang et al. (2011) demonstrated the existence of short-run and long-run causality running from energy consumption to economic growth using a multivariate causality test. Similar studies were taken in Russia by Zhang (2011), in Switzerland by Baranzini et al. (2013), and in Turkey by Yalta (2011). In addition, Burke et al. (2015) explored the short-run effects of GDP growth on CO<sub>2</sub> emissions for 189 nations taking 1961–2010 into consideration. They found evidence of *delayed effects* between energy–economy causality dialogs: specifically, emissions tend to growth quicker after booms and slower after recessions. Using a meta-analysis of the existing large literature, Kalimeris et al. (2014) did not find a genuine causal effect between energy and GDP in the literature as a whole. Similar results were also found by Bruns et al. (2014) using the same method.

The mixed nature of the empirical findings surveyed above can primarily be attributed to the individual researcher's selection of econometric methods, research periods, and variables. Although these previous studies have certainly enriched our understanding of the relationship between CO<sub>2</sub> emissions, energy consumption, and economic growth (Al Mamun et al., 2014), they have failed to provide reasonable evidence in relation to how variables change in response to external shocks, an important aspect of the relationship. Such change, we note, is possible to investigate using impulse response analysis. In addition, few studies have considered the error correction mechanism when analyzing the long-term equilibrium relationship between the three variables. In order to deal with this deficiency, this paper establishes a comprehensive analysis framework for systematically estimating the nexus between the variables. Building on the previous studies, we firstly calculated CO<sub>2</sub> emissions in China over the period 1990–2012, and then investigated the relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions in China based on time series analysis using a unit root test, cointegration test, vector error correction model, impulse response analysis, and a Granger causality test.

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The remainder of this paper is organized as follows. Section 2 focuses on data and methodology, presenting the steps for establishing the conceptual framework of the study. Section 3 presents the results of the study and discusses the ways in which the models proposed in Section 2 were used to analyze the relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions in China. Section 4 sets out the main conclusions and details a series of policy implications.

## 2. Data and methodology

### 2.1. Estimating CO<sub>2</sub> emissions

Due to the lack of anthropogenic CO<sub>2</sub> emissions statistics in China, we employed the normalized approach recommended by the Intergovernmental Panel on Climate Change (IPCC) in the IPCC Guidelines for assessing China's CO<sub>2</sub> emissions (Du et al., 2012). According to scientific reports, the burning of fossil fuels and industrial production (mainly through the production of cement) are the primary causes of increased anthropogenic CO<sub>2</sub> emissions. These two human sources account for 91% of all anthropogenic CO<sub>2</sub> emissions (Le Quééré et al., 2012). Thus, in order to obtain approximate CO<sub>2</sub> emissions data, we calculated the CO<sub>2</sub> emissions generated from both fossil energy consumption and cement production using coefficients published by the IPCC (2006). The primary energy consumption and cement production statistics from 1990 to 2012 were extracted from the *China Energy Statistical Yearbook* and the *China Statistical Yearbook*. CO<sub>2</sub> emissions were calculating using the formula:

$$CE = \sum_{i=1}^7 FCE_i + CC = \sum_{i=1}^7 EC_i \times E_i + Q \times F \quad (1)$$

where *CE* represents CO<sub>2</sub> emissions from fossil energy consumption and cement production; *i* denotes the different types of fossil fuel (including coal, coke, gasoline, kerosene, diesel, fuel oil, and natural gas); *FCE<sub>i</sub>* represents the consumption of various fossil fuels *i*; and *E<sub>i</sub>* is the CO<sub>2</sub> emissions coefficient of fossil fuels *i* (Table 1); *CC* denotes the CO<sub>2</sub> emissions generated by the cement production process; *Q* represents the quantity of cement production; and *F* is the CO<sub>2</sub> emissions coefficient of cement production process (Table 1).

### 2.2. Data source and pre-analysis

Data on GDP and total energy consumption were taken from the *China Statistical Yearbook* and the *China Energy Statistical Yearbook* respectively. CO<sub>2</sub> emissions data were calculated using Eq. (1). Fig. 1 describes relative changes in emissions, energy consumption, and GDP in China during the period 1990–2012. As shown in Fig. 1, the Chinese economy has undergone spectacular economic development, with an annual growth rate of 16.31% over the past twenty-two years. China's GDP increased from 1866.7 to 51,894.2 billion Yuan between 1990 and 2012. Although China has made remarkable developmental progress, it has not yet completed the historical task of industrialization and its development is unbalanced. Thus, China still faces an arduous task in developing its economy, eliminating poverty, and improving the livelihoods of its population. Economic growth can improve living standards, but it can also lead to increases in energy consumption and CO<sub>2</sub> emissions. While the economy prospered, it is worth bearing in mind that China's total energy consumption jumped from 1311.76 million t in 1990 to 3617.32 million t in 2012 (Fig. 1). According to our calculations, CO<sub>2</sub> emissions increased from 1.89 billion t in 1990 to 8.02 billion t in 2012 (Fig. 1). The upper fitting curve in Fig. 2 shows the correlated relationship between economic growth (the independent variable) and energy consumption (the dependent variable) during the period 1990–2012. The lower curve displays the correlated relationship between economic growth (the independent variable) and CO<sub>2</sub> emissions (the dependent variable) during the same period. As shown in Fig. 2, the three variables are strongly correlated (displaying high R<sup>2</sup> values.)

Fig. 3 displays a scatter plot and distribution overlay of economic growth levels, energy consumption levels, and CO<sub>2</sub> emissions data in the form of a box chart, with the bottom and top of the box representing the 25th and 75th percentiles. From Fig. 3, we find CO<sub>2</sub> emissions to be

**Table 1**  
CO<sub>2</sub> emissions coefficients.  
Source: IPCC (2006).

| Sources                               | Coal  | Coke  | Gasoline | Kerosene | Diesel | Fuel oil | Natural gas | Cement |
|---------------------------------------|-------|-------|----------|----------|--------|----------|-------------|--------|
| CO <sub>2</sub> emissions coefficient | 1.647 | 2.848 | 3.045    | 3.174    | 3.150  | 3.064    | 21.670      | 0.527  |

highly concentrated at 5.26 billion t, and mainly dispersed from 3.33 to 6.68 billion t. Energy consumption is mainly distributed between 1300 and 2500 million t, and is concentrated at 1700 million t (Fig. 3). GDP is distributed from 8440.5 to 26,581.7 billion Yuan, with the most concentrated GDP at 12,033.3 billion Yuan.

2.3. Conceptual framework

China is the largest developing country in the world; its economy has experienced continuous, rapid growth over the past twenty-two years. This growth has, however, been achieved through huge levels of energy consumption, leading to increases in CO<sub>2</sub> emissions. Whilst economic growth has been shown to eliminate poverty and improve peoples' livelihoods, it can also increase energy consumption and, further, generate energy crises. At present, China is in a period of rapid development, wherein rapid urbanization and industrialization processes are leading to increased energy consumption. With this in mind, CO<sub>2</sub> emissions are predicted to rise for many years to come. A better understanding of the relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions is therefore critical in order for the Chinese government to develop effective sustainable development policies. The main goal of this study is to examine the relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions; as such, a new conceptual framework was designed (Fig. 4) which allowed us to address these relations.

The first step in the study was to examine the stationarity of the variables; a unit root test, namely the Augmented Dickey–Fuller (ADF) test, was used for this purpose. If the variables are established as stationary at the first difference through the ADF, a cointegration test and vector error-correction model (VECM) should be used. Impulse response analysis based Vector autoregression (VAR) models can be subsequently used to depict the reaction of a dynamic system in response to an external change. If variables are found to be cointegrated, the Granger causality tests can then be used (in the case of this study, such tests would reveal the Granger causality between economic growth, energy consumption, and CO<sub>2</sub> emissions.)

2.4. Econometric methods

Previous literature indicates that economic growth and energy consumption are major determinants of CO<sub>2</sub> emissions (Wang et al., 2013). To estimate the relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions, the econometric model was employed. Before conducting series tests in order to estimate the relationship, though, the effects of heteroscedasticity must be eliminated from the time series data using the natural logarithm of the variables under investigation. The CO<sub>2</sub> emissions model used is specified as follows:

$$CE_t = \alpha + \beta_1 GDP_t + \beta_2 EC_t + \varepsilon_t \tag{2}$$

where CE is the total CO<sub>2</sub> emissions from fossil energy consumption and cement production (million t); GDP is gross domestic product, measured in billion constant Yuan; EC denotes energy consumption (million t); β<sub>1</sub> and β<sub>2</sub> are the slope coefficients; ε is the residual; t denotes time; and α is the scalar.

2.4.1. Unit root test

The first step was to determine whether all variables are stationary and integrated of the same order. Thus, a unit root test—namely, the ADF unit root test initially introduced by Dickey and Fuller (1979, 1981)—was used. Unit root tests are generally employed in order to identify the variables that belong to a stationary series. The null hypothesis of the test is that the variables have a unit root. To test the unit root hypothesis, the following regression of the ADF test was utilized (Feng et al., 2009):

$$\Delta x_t = (\rho - 1)x_{t-1} + \sum_i \lambda_i \Delta x_{t-i} + \mu_t \tag{3}$$

where x<sub>t</sub> is the variable in period t; Δ denotes the first difference; μ<sub>t</sub> is the disturbance term with a mean 0 and a variance σ<sup>2</sup>. The null hypothesis is H<sub>0</sub>: ρ = 1; when ρ = 1 cannot be rejected, we can identify that the series is non-stationary.

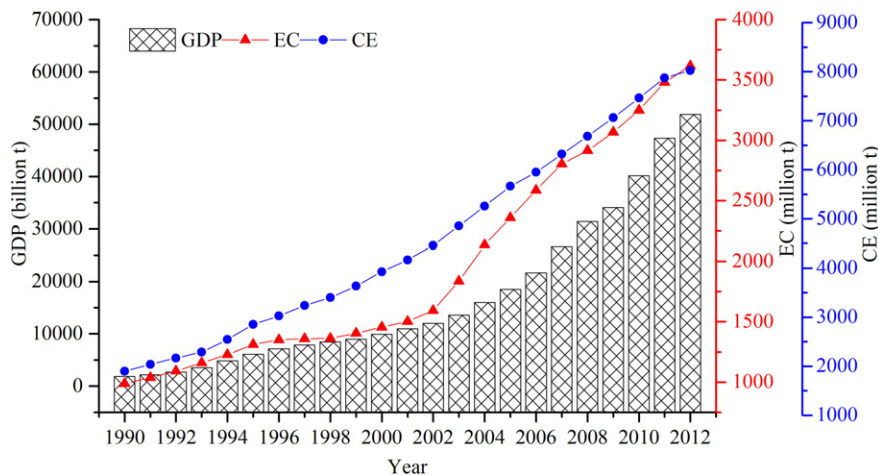


Fig. 1. Trend chart of economic growth, energy consumption, and CO<sub>2</sub> emissions in China from 1990 to 2012.



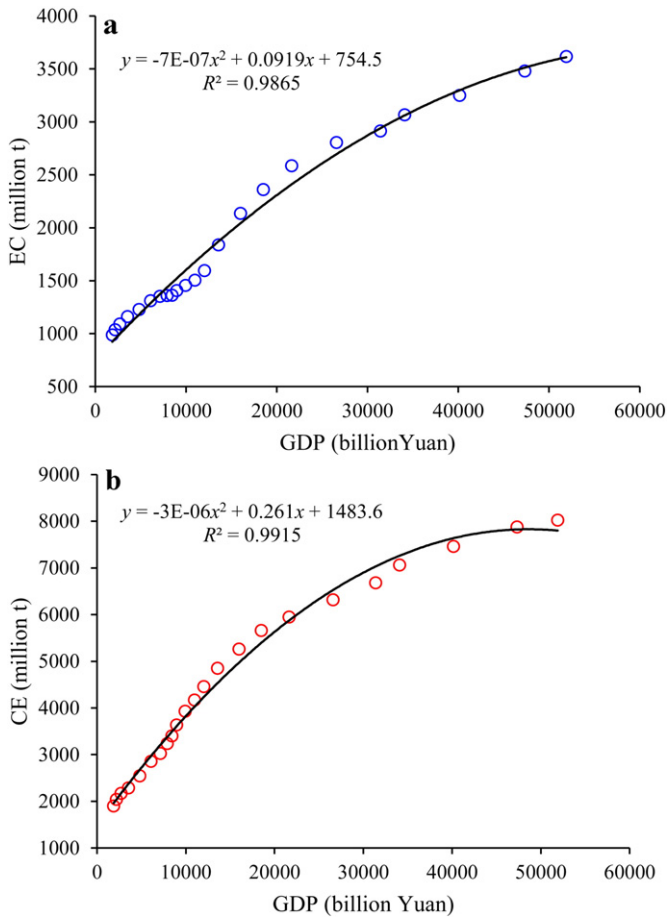


Fig. 2. The fitting curves of economic growth and energy consumption, and economic growth and CO<sub>2</sub> emissions in China from 1990 to 2012.

From a methodological perspective, the ADF test maintains three trend assumptions, namely: no intercept and no trend, intercept, and intercept and trend. The first test model has no intercepts and no trends. The form of the model can be expressed as Eq. (4). Eq. (5) is the form of

the intercept model, which has intercepts but no trends. The third model has both intercepts and trends, as shown at Eq. (6). No intercepts and no trends:

$$\Delta y_t = \delta y_{t-1} + \sum_{i=1}^p \alpha_i \Delta y_{t-i} + \mu_t \tag{4}$$

Intercepts:

$$\Delta y_t = \alpha + \delta y_{t-1} + \sum_{i=1}^p \alpha_i \Delta y_{t-i} + \mu_t \tag{5}$$

Trends and intercepts:

$$\Delta y_t = \alpha + \beta_t + \delta y_{t-1} + \sum_{i=1}^p \alpha_i \Delta y_{t-i} + \mu_t \tag{6}$$

2.4.2. Cointegration analysis and testing method

If a stationary series is integrated of order 1, denoted by  $I(1)$ , this indicates that it must be differenced once in order to become stationary. Thus, if a series is found to be integrated of order  $d$ , written  $I(d)$ , it must be differenced  $d$  times to be made stationary. With respect to cointegration analysis, Engle and Granger (1987) point out that a linear combination of two or more non-stationary series may be stationary. The essence of cointegration is that the linear combination of variables is stable. The stationary linear combination is called the “cointegrating equation” and may be interpreted as demonstrating a long-term equilibrium relationship among the variables.

If series  $x_t$  and  $y_t$  are both integrated of order  $d$ , an ordinary least squares (OLS) significance test can be used to estimate the Eq. (7):

$$y_t = \alpha_0 + \alpha_1 x_t + \mu_t \tag{7}$$

where  $\mu_t$  is random disturbance,  $t$  denotes time.

After the regression, we get the residual  $e_t$ ,

$$\hat{y}_t = \hat{\alpha}_0 + \hat{\alpha}_1 x_t \tag{8}$$

$$e_t = y_t - \hat{y}_t \tag{9}$$

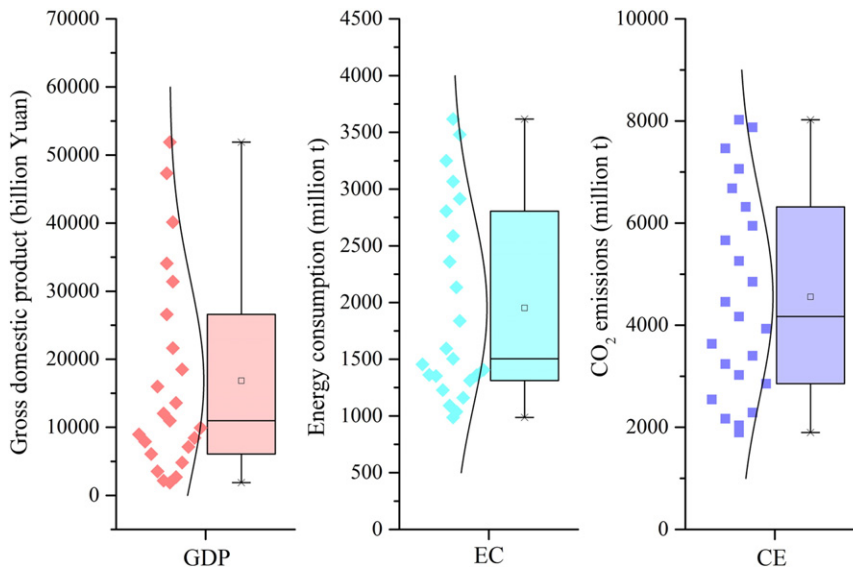


Fig. 3. Description chart of economic growth, energy consumption, and CO<sub>2</sub> emissions in China from 1990 to 2012. Each box plot indicates the 25/50/75 percentiles, whisker caps denote the 5/95 percentiles, the dots represent minimum/maximum values, and the triangles represent mean values.

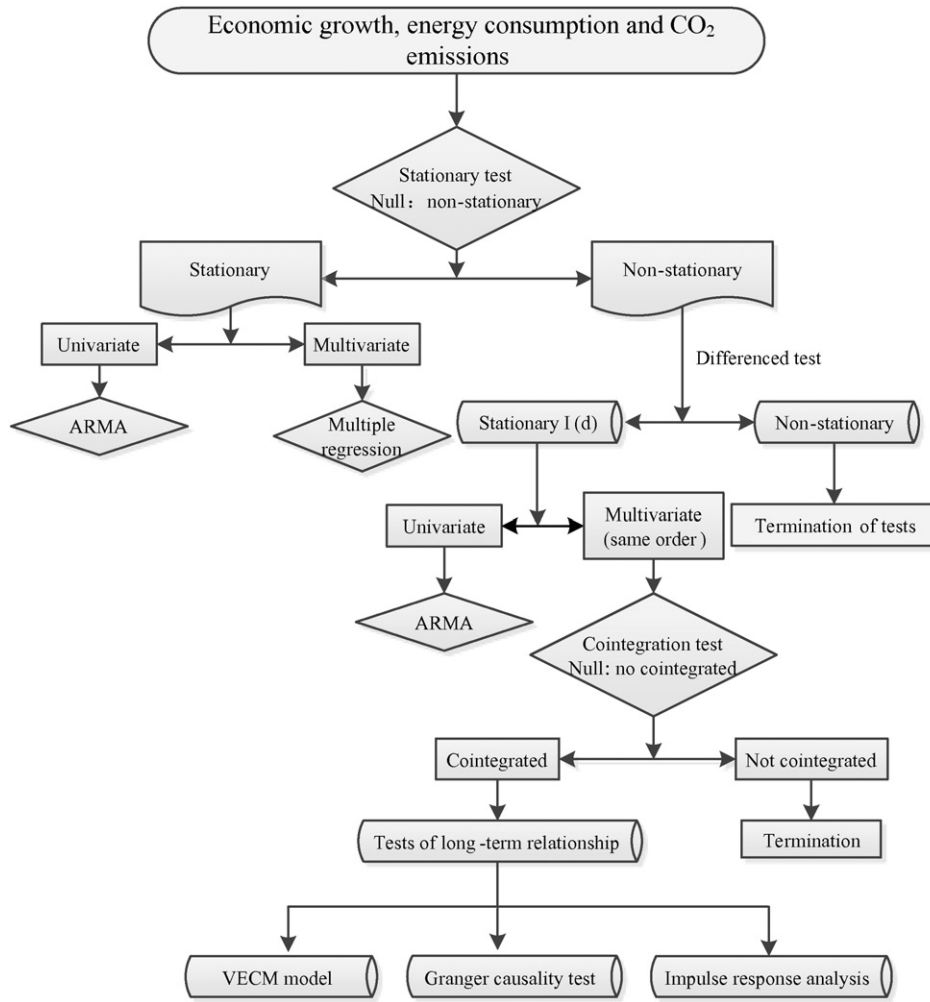


Fig. 4. Framework for analyzing the relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions. Source: Zhao and Wang (2015).

If  $e_t$  is found to be stationary, we can say that  $x_t$  and  $y_t$  are cointegrated; if  $e_t$  does not have the property of being stationary, we say that  $x_t$  and  $y_t$  have no cointegration relationship.

2.4.3. Vector error correction model

With respect to non-stationary series, differenced methods are generally used in order to process the data. However, because differenced methods always neglect important information hidden in the original levels, the regression cannot reveal the long-term equilibrium relationship (Li and Pan, 2010). Vector error correction model (VECM) has been developed in order to deal with this deficiency. VECMs constitute a theory-driven approach that is useful for estimating both the short-term and long-term effects of one time series on another. ECMs are useful models when dealing with cointegrated data, but can also be used with stationary data.

Suppose that variables  $y$  and  $x$  are time series that are related in the long run, noting that some observed variables are not always just on the equilibrium point, but fluctuate around it (Feng et al., 2009). Thus, whilst cointegration equations often reveal the short-term relationship between variables, in order to reveal the long-term relationship between variables and approach the long-term equilibrium relationship, we should consider the series' dynamic non-equilibrium processes when establishing models (VECMs). Autoregressive distributed lag

(ADL) is the basic form of a VECM. The ADL(1,1) model given in this paper is specified as follows:

$$y_t = \beta_0 + \beta_1 x_t + \beta_2 x_{t-1} + \delta y_{t-1} + \mu_t \tag{10}$$

As shown in Eq. (10), changes in  $y_t$  are determined not only by changes in  $x_t$ , but changes in  $x_{t-1}$  and  $y_{t-1}$ . If variables exhibit non-stationarity, the ordinary least square (OLS) regression cannot be directly used. Thus, Eq. (10) should be transformed to:

$$\Delta y_t = \beta_1 \Delta x_t - \lambda (y_{t-1} - \alpha_0 - \alpha_1 x_{t-1}) + \mu_t \tag{11}$$

where  $\lambda = 1 - \delta$ ,  $\alpha_0 = \beta_0 / (1 - \delta)$ ,  $\alpha_1 = (\beta_1 + \beta_2) / (1 - \delta)$ .

2.4.4. Impulse response analysis

Vector autoregression (VAR) is an econometric model used to capture linear interdependencies among multiple variables. VAR models evolve from the univariate autoregression (AR) models by allowing for other variables. A VAR model describes the evolution of a set of  $k$  variables (called endogenous variables) over the same sample period as a linear function of only their past values.

A  $k$ th order VAR, denoted as VAR( $k$ ), is (Li and Pan, 2010):

$$Z_t = \sum_{i=1}^k A_i Z_{t-i} + V_t \tag{12}$$

where  $Z_t$  denotes an n-dimensional column vector of exogenous variables;  $A_i$  is a vector of parameters;  $V_t$  is an n-dimensional column vector of random error terms; and  $V_i$  is the white noise error and  $E(V_i V_j) = 0$  ( $i, j = 1, 2, \dots, n, i \neq j$ ).

With respect to VAR models, impulse response analysis (IFA) is often used in order to describe the reaction of any endogenous variable as a function of time in response to external shocks from other variables. Thus, conducting impulse response analysis reveals the dynamic characteristics of VAR models.

2.4.5. Granger causality tests

Granger causality tests are widely used to investigate causal relationships between variables. The Granger causality test is a statistical hypothesis test for determining whether one variable affects another. Ordinarily, if  $X$  and  $Y$  are two economic time series,  $X$  is said to Granger-cause  $Y$  if it can be shown, usually through a series of t-tests and F-tests on lagged values of  $X$  (and with lagged values of  $Y$  also included), that those  $X$  values provide statistically significant information about future values of  $Y$ . The Granger (1969) model, based on the following bivariate VAR models, is used in this paper to estimate the casual relationship between time series (Feng et al., 2009):

$$y_t = \alpha_0 + \sum_{i=1}^m \alpha_i y_{t-i} + \sum_{i=1}^m \beta_i x_{t-i} + \varepsilon_t \tag{13}$$

$$x_t = \alpha_0 + \sum_{j=1}^n \alpha_j y_{t-j} + \sum_{j=1}^n \beta_j x_{t-j} + \varepsilon_t. \tag{14}$$

The null hypothesis for these tests can be written as Eq. (14), equal to “ $X$  does not Granger-cause  $Y$ ” or “ $Y$  does not Granger-cause  $X$ ”:

$$\begin{aligned} H_0 : \beta_i &= 0, \quad i = 1, 2, \dots, m \\ H_0 : \beta_j &= 0, \quad j = 1, 2, \dots, n. \end{aligned} \tag{15}$$

On the other hand, the alternative hypothesis can be written as follows:

$$\begin{aligned} H_1 : \beta_i &\neq 0, \quad i = 1, 2, \dots, m \\ H_1 : \beta_j &\neq 0, \quad j = 1, 2, \dots, n. \end{aligned} \tag{16}$$

When considering the definitions of causality in Granger (1980), the tests always give us some apparently surprising results. However, some of these questions can be illustrated with a discussion of the potential usefulness of causality tests on control variables. As such, we should add a control variable when conducting the Granger causality tests. Let  $x_t$  be the variable controlled, denoted  $\omega_{t-1} = x_t$ , and is also associated with the time at which it is determined. Supposing that  $y_t$  is

generated by the following equation (Granger, 1988):

$$y_t = \alpha y_{t-1} + c \omega_{t-1} + \mu_t \tag{17}$$

$$\omega_t = -c^{-1} [\alpha y_t - \bar{a}_t] \tag{18}$$

$$y_t = a_{t-1} + u_t \tag{19}$$

where  $x_t = -c^{-1} [\alpha y_{t-1} - a_t]$ .

3. Empirical results

3.1. Results of unit root tests

Prior to conducting the cointegration test to examine the long-run relationship between economic growth (GDP), energy consumption (EC), and CO<sub>2</sub> emissions (CE), it was necessary to test the stationarity of the variables; this is also known as a unit-root test. Under the null hypothesis,  $H_0$ , there is a unit root while the alternative hypothesis  $H_1$  there is no unit root (Feng et al., 2009). From Fig. 5, we find that the three time series are all non-stationary. As shown in Fig. 5, all variables may exhibit an intercept or trend. Thus, the equations used all include trend and intercept. The null hypothesis was that GDP, EC, and CE would all contain a unit root. The unit root tests were carried out with individual trends and intercepts for each variable, and the lag lengths were selected automatically using the Schwarz information criteria (Zhao and Wang, 2015). Table 2 reviews the ADF test results, which clearly show that each variables was not stationary in their level forms.

Ordinarily, with respect to non-stationary time series, differenced methods are further used to identify the stationarity of the variables (Zhao and Wang, 2015).  $\Delta GDP$ ,  $\Delta EC$ , and  $\Delta CE$  denote the variables at their first difference. The sequence changes of the first differenced variables are shown in Fig. 6. From Fig. 6, the first differenced variables are revealed as being stationary: economic growth, energy consumption, and CO<sub>2</sub> emissions as such might be integrated of order 1. The results of the first differenced variables (Table 2) showed that the ADF test statistics for all of the variables were less than the critical values at the 10% level. All the variables were thus revealed as being stationary at the first difference, rejecting the null hypothesis at less than 10% level of significance. This indicated that the variables were integrated of order  $I(1)$ ; there may be one or more cointegration relationships among them.

3.2. Cointegration tests

Since the variables were found to be stationary at the first difference, we were able to proceed with the cointegration test. The cointegration test used in this paper was proposed by Johansen (1988) and Johansen and Juselius (1990). Based on the maximum likelihood

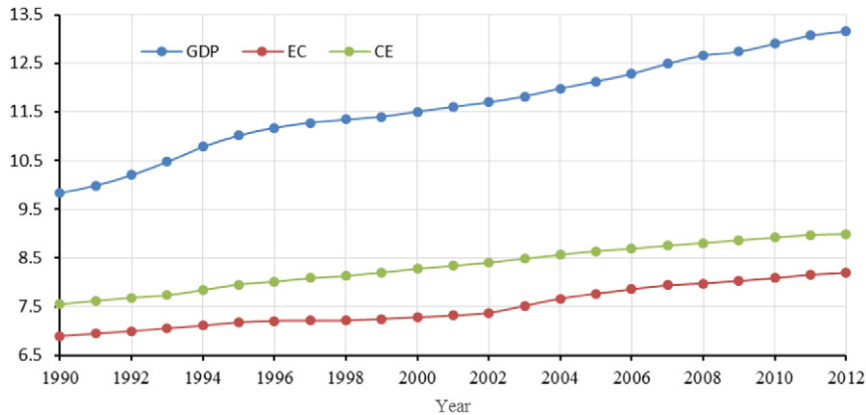


Fig. 5. Sequence chart of economic growth, energy consumption, and CO<sub>2</sub> emissions level data.

**Table 2**  
Unit root tests of urbanization and energy consumption.

| Variable    | ADF unit root test |                     |                      |                |                     |                      |
|-------------|--------------------|---------------------|----------------------|----------------|---------------------|----------------------|
|             | EC                 |                     |                      | CE             |                     |                      |
|             | Level              | Intercept and trend | First difference (Δ) | Level          | Intercept and trend | First difference (Δ) |
| GDP         | Intercept          | Intercept and trend | Intercept            | Level          | Intercept and trend | Intercept and trend  |
| t statistic | -1.3275            | -3.1143             | -4.2234              | -0.6623        | -2.8342             | -3.2745              |
| 10% level   | -2.5712            | -3.4232             | -3.2837              | -2.8741        | -3.3327             | -2.5347              |
| 5% level    | -3.2178            | -3.2287             | -3.4326              | -3.1543        | -3.8638             | -3.6541              |
| 1% level    | -3.3456            | -4.6310             | -4.6736              | -3.8734        | -4.4835             | -3.6431              |
| p value     | -2.5712            | -3.4232             | -3.2837              | 0.7731         | 0.2536              | 0.0512               |
| Results     | Non-stationary     | Non-stationary      | Stationary**         | Non-stationary | Non-stationary      | Stationary**         |

Note: The unit root tests were carried out with individual trends and intercepts for each variable, and the lag lengths were selected automatically using the Schwarz information criteria. Δ denotes the first difference. \*\* Indicates significance at 5% level.

estimator, the Johansen test has the ability to determine whether a cointegrating relationship exists between variables—in this case, economic growth, energy consumption, and CO<sub>2</sub> emissions, using time series covering the years 1990 to 2012. The test results are presented in Table 3. From Table 3, we find that one cointegrating relationship among economic growth, energy consumption, and CO<sub>2</sub> emissions was identified at the 5% significance level; the cointegrating equation is specified as follows (standard error in parentheses):

$$CE = 0.4673GDP + 0.6910EC - 0.9543 \quad (20)$$

(3.6098<sup>\*\*\*</sup>)                      (4.2965<sup>\*</sup>)                      (4.9643<sup>\*\*\*</sup>)

The cointegrating equation indicates that economic growth and energy consumption exert a significant impact on CO<sub>2</sub> emissions in the long-run equilibrium. Assuming that other factors remain constant, a 1% increase in economic growth will thereby lead to a 0.4673% increase in CO<sub>2</sub> emissions, and a 1% increase in energy consumption will produce a corresponding 0.6910% increase in CO<sub>2</sub> emissions. This suggests that to reduce CO<sub>2</sub> emissions in the future, China should reduce fossil energy use. China is currently in the important stage of transforming the mode of economic development and improving the quality of economic development. Economic growth should be derived more from newly emerging industries rather than high-energy-consuming and high-emission industries (Wang et al., 2012).

### 3.3. Vector error correction model

Although economic growth, energy consumption, and CO<sub>2</sub> emissions were found to be cointegrated, according to cointegration theory, different levels of disequilibrium exist (Engle and Granger, 1987). These can be captured by the inclusion of an error-correction term (ECM) in the cointegration relationship. ECMs are important components of vector error correction models (VECM) (Li and Pan, 2010). The establishment of a VECM can allow the researcher to estimate the level of disequilibrium hidden in a long-run relationship, allowing a VECM to capture temporal dynamic changes in explanatory variables. Given this capacity, a VECM was used to assess the co-movement between economic growth, energy consumption, and CO<sub>2</sub> emissions, as well as the possibility that they trend together, finding a long-run equilibrium relationship, then by the Granger representation theorem we may posit the following testing relationships, constituting our vector error-correction model (VECM):

$$\Delta EC_t = -0.068ECM_{t-1} + 0.4657\Delta EC_{t-1} - 0.5342\Delta EC_{t-2} + 0.01473\Delta GDP_{t-1} - 0.427\Delta GDP_{t-2} + 0.0342\Delta EC_{t-1} - 0.5350\Delta EC_{t-2} - 4.611 \quad (21)$$

(0.385<sup>\*\*</sup>)                      (1.5465<sup>\*</sup>)                      (-1.6783<sup>\*</sup>)                      (0.2172<sup>\*</sup>)  
(-2.1685<sup>\*\*</sup>)                      (0.1327<sup>\*\*</sup>)                      -1.6841<sup>\*\*</sup>                      (-4.3126<sup>\*</sup>)

In statistics, the presence of cointegrating relationship among economic growth, energy consumption and CO<sub>2</sub> emissions indicates that a linear combination of non-stationary time series exhibits a stationary linear relationship, thus avoiding the problem of spurious regression (Feng et al., 2009). The error-correction term inserted in the VECM model at Eq. (20) captures the variations associated with adjustment to the long-term relationship. From Eq. (20), we found that the first and second lagged values of both economic growth and energy consumption exerted significant positive and negative impacts, respectively, on CO<sub>2</sub> emissions. In addition, the error-correction term ECM reflects the correction mechanism through which the model adjusts the errors to dynamic equilibrium by itself (Feng et al., 2009).

Considering the control variables, when the short-term dynamics deviate from the long-term relationship and the coefficient of ECM is -1, the errors for the variables (in this case, economic growth, energy consumption, and CO<sub>2</sub> emissions) can be corrected to equilibrium theoretically in the following year. However, in this study the coefficient of ECM was found to be -0.068, indicating that the disequilibrium errors



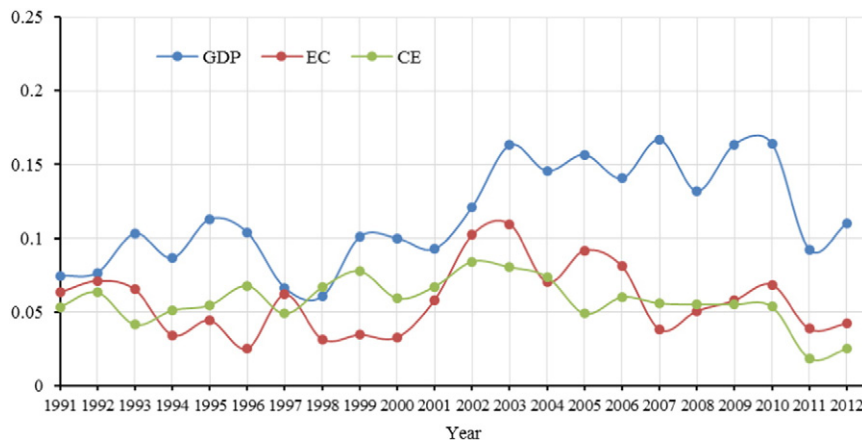


Fig. 6. Sequence chart of first differenced economic growth, energy consumption, and CO<sub>2</sub> emissions data.

that can be adjusted in the next period will only account for only small proportion of the changes evidenced. From the above analysis, we therefore find that although economic growth and energy consumption have an effect on CO<sub>2</sub> emissions, that effect is marginal; changes in CO<sub>2</sub> emissions are also affected by many other factors, such as technology, investment and the transformation of economic development mode.

### 3.4. Impulse response analysis

Impulse response analysis is widely used to describe the reaction of any variable (in this case, economic growth, energy consumption, and CO<sub>2</sub> emissions) as a function of time in response to one external SD shock. Impulse response analysis visualizes the destabilization experienced by variables in response to shocks that arise within other variables. Based on the VAR model, impulse response analysis was here used to reveal the interactive relationship between economic growth, energy consumption, and CO<sub>2</sub> emissions. The results from the impulse response analysis, which was in turn based on a VAR model, are displayed in Fig. 7. The impulse response functions are plotted out to 14 lag lengths after the shock ( $h = 15$ ).

As indicated by the results (Fig. 7), a positive one SD shock within energy consumption was found to lead to a decrease in economic growth from the fourth quarter to the tenth quarter, indicating that reducing energy consumption in China will in fact hinder the nation's economic growth. Further, economic growth demonstrated a general declining pattern in that period, suggesting that energy consumption shocks exert a lagged effect in relation to economic growth. As expected, a positive one SD shock to the CO<sub>2</sub> emissions was found to lead to an increase in economic growth in the last fourteenth quarters. This indicates that increased CO<sub>2</sub> emissions in China will lead to increased economic growth. However, we note that the impact on economic growth of a CO<sub>2</sub> emissions shock is marginal. Economic growth was found to exert a positive influence on energy consumption—in fact, energy consumption was found to begin to increase after the third quarter and to exhibit

the property of stationarity from the eighth quarter. As shown in Fig. 7, energy consumption was thus found to show an insignificant amount of change in response to a shock in CO<sub>2</sub> emissions, indicating that the impact of CO<sub>2</sub> emissions' shocks on energy consumption is marginally significant. Conversely, energy consumption was shown to be a significant factor in accounting for changes in CO<sub>2</sub> emissions. The maximum impact was reached at around the seventh quarter. CO<sub>2</sub> emissions showed a continuous positive response to a positive one SD shock of economic growth, indicating that economic growth exerts a strong influence on CO<sub>2</sub> emissions levels in China.

### 3.5. Granger causality tests

Prior to the Granger causality analysis, we tested the stationarity of the VAR model. From the Fig. 8, we find that all roots are less than 1 and lie inside the unit circle. This indicates that VAR model is stationary. Since the variables were found to be cointegrated, the Granger Causality based on VAR model was utilized in order to examine the causal relationships between variables. Previous studies have asserted that Granger Causality tests are sensitive to the lag length of the variables—as such, different lag lengths were selected to perform the tests (Li and Pan, 2010). If results are the same for different lag lengths, the directions of the casual relationships can be identified. Table 4, below, which introduces the Granger causality test results, clearly shows the existence of causal relationships between economic growth, energy consumption, and CO<sub>2</sub> emissions. From Table 4, we find that when the null hypothesis is “GDP does not Granger cause EC”, the maximum  $p$  value of the tests is 0.0989 which is smaller than 0.1, thus, we can reject the null hypothesis on control variables. This indicates that GDP does Granger-cause energy consumption. According to the same criterion, we further conduct the following tests for estimating the direction of causality between economic growth, energy consumption and CO<sub>2</sub> emissions. Specifically, it demonstrates the existence of a bi-directional causal relationship between economic growth and energy consumption, and a unidirectional causal relationship between energy consumption and CO<sub>2</sub> emissions. Surprisingly, no such causal relation was found to exist between economic growth and CO<sub>2</sub> emissions. These results were supported by studies undertaken in relation to Malaysia by Begum et al. (2015), in Indonesia by Hwang and Yoo (2014), in India by Alam et al. (2011) and in Turkey by Ozturk and Acaravci (2010). According to the existing literature, the direction of the causality between economic growth, energy consumption and CO<sub>2</sub> emissions is both methods and periods dependent. However, our empirical findings have important implications for the government that on the path towards a sustainable society, the effects of economic growth and energy consumption on CO<sub>2</sub> emissions must be taken into consideration.

Table 3  
Results of Johansen's multivariate cointegration tests.

| Hypothesized no. of CE(s) | Eigenvalue | Trace statistic | 0.05 critical value | Prob.** |
|---------------------------|------------|-----------------|---------------------|---------|
| None                      | 0.556478   | 26.72566        | 28.22143            | 0.1543  |
| At most 1                 | 0.445672   | 14.84768        | 14.98476            | 0.0862  |
| At most 2**               | 0.273423   | 4.884365        | 3.766567            | 0.0425  |

Note: Trace test indicates no cointegration at the 0.05 level.

\*\* Denotes rejection of the hypothesis at the 0.05 level.

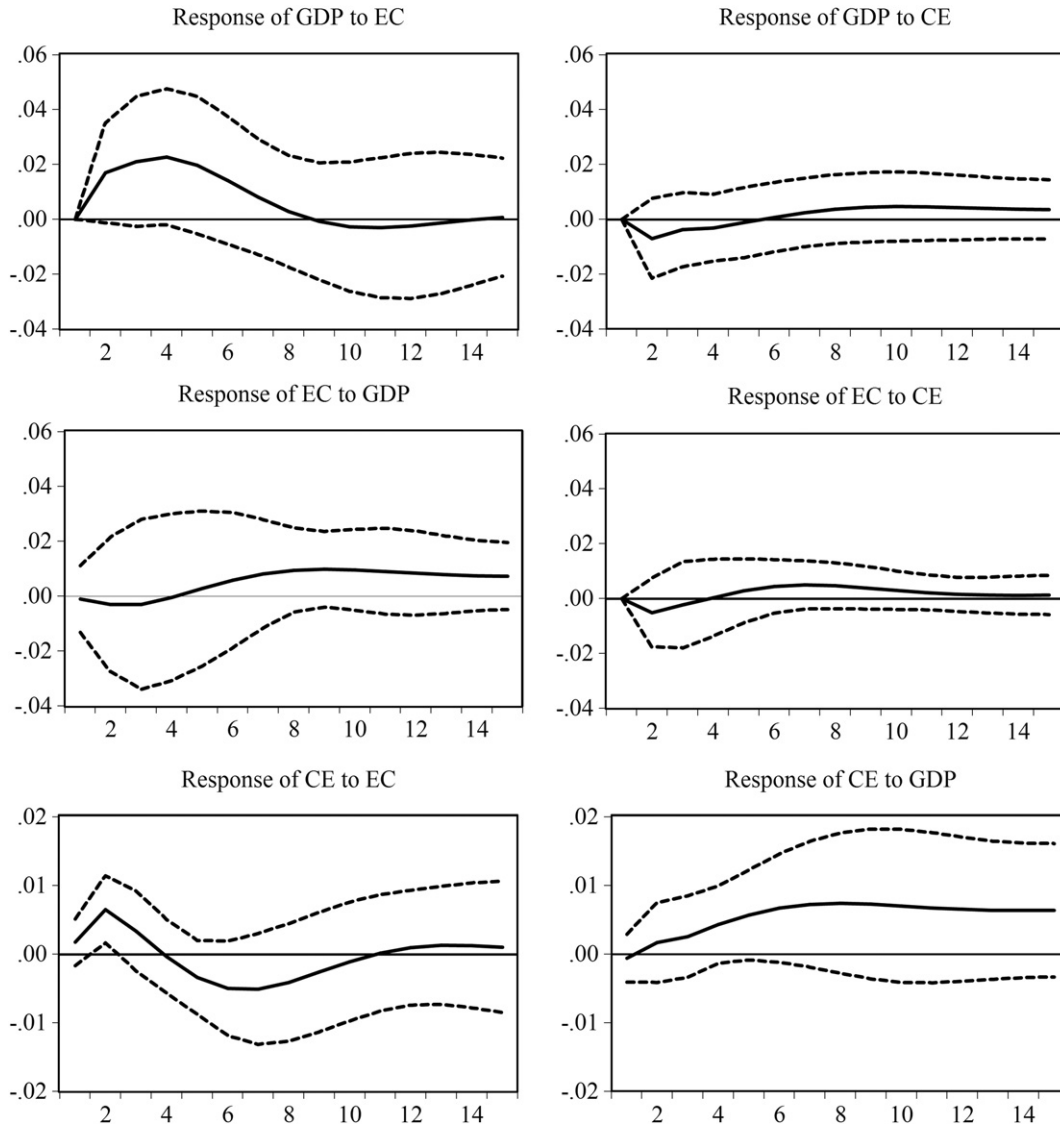
Response to Cholesky One S.D. Innovations  $\pm 2$  S.E.

Fig. 7. The impulse responses of urbanization and energy consumption based on VAR model. Note: The upper and lower dashed lines in each graph denote the 95% confidence interval.

#### 4. Conclusion and policy implications

Over the past three decades, China's economy has evidenced spectacular economic development, with an annual growth rate over 9% (Wang et al., 2014c). However, behind this economic success, like many other new economies in the world, China also faces the challenge of balancing continuously increasing energy use and rapid economic growth with environmental responsibility (Wang et al., 2014a).

This paper investigates the long-run equilibrium relationships, temporal dynamic relationships, and causal relationships between economic growth, energy consumption, and CO<sub>2</sub> emissions in China, using data for the period 1990–2012 and deploying a comprehensive conceptual framework incorporating a unit root test, a cointegration test, a vector error correction model, impulse response analysis, and the Granger causality test. Whilst the ADF test results clearly show that all variables were not stationary at levels, all the variables were found to be stationary at the first difference, thereby rejecting the null hypothesis at the 5% level of significance. Cointegration test results demonstrate that economic growth, energy consumption, and CO<sub>2</sub> emissions are of order one and thus cointegrated. Vector error correction modeling found a corresponding error-correction representation to exist, implying that

changes in economic growth, energy consumption, and CO<sub>2</sub> emissions are a function of the level of disequilibrium in the cointegrating relationship. This relationship in turn is captured by the error-correction term, which in this study was found to be  $-0.006$ , a result which in fact indicates that the disequilibrium errors that can be adjusted in the next period will account for only a little of the changes. CO<sub>2</sub> emissions, as such, have many other determinants and more factors must be taken into account when developing emission reduction policies.

To obtain additional insight into how volatility within economic growth, energy consumption, and CO<sub>2</sub> emissions can extend to the other variables—how, in other words, the three variables can be destabilized by shocks that arise within other variables—we conducted an impulse response analysis. Through that analysis, we found the impact of CO<sub>2</sub> emissions shocks on both economic growth and energy consumption to be only marginally significant. In addition, Granger causal relationships were found to exist between economic growth, energy consumption, and CO<sub>2</sub> emissions; specifically, a bi-directional causal relationship exists between economic growth and energy consumption, and a unidirectional causal relationship from energy consumption to CO<sub>2</sub> emissions was also evident. Surprisingly, no such causal relation was found between economic growth and CO<sub>2</sub> emissions.

Inverse Roots of AR Characteristic Polynomial

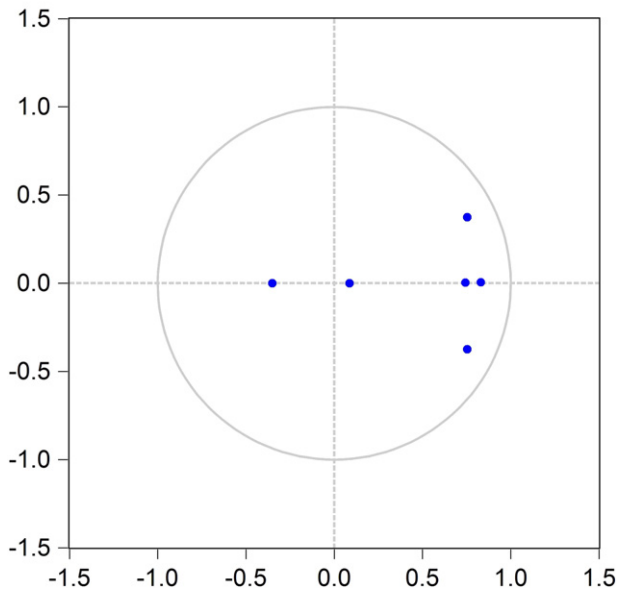


Fig. 8. Results of VAR stability condition check.

Given the demand for designing effective energy conservation and emission reduction policies, the link between economic growth, energy consumption and CO<sub>2</sub> emissions has long attracted attention. The direction of causality between the variables could be a decisive component of this relation. However, despite a large literature studying on this issue, the state of knowledge still remains quite indeterminate and controversial (Kalimeris et al., 2014). Over the past decades, China has made remarkable achievements in terms of its economic development. Yet whilst rapid economic growth can improve living standards, it can also increase energy consumption, thereby producing significant increases in CO<sub>2</sub> emissions (Wang et al., 2015a). To reduce CO<sub>2</sub> emissions in the future, China should reduce fossil fuel-based energy consumption and develop renewable and sustainable energy sources (Wang et al., 2014a). Despite the estimation of the direction of causality between economic growth, energy consumption and CO<sub>2</sub> emissions in China is both methods and periods dependent. The attempt in the present study to examine the relation is meaningful. From our empirical findings it can be concluded that the following policies should be implemented to the new economy to control CO<sub>2</sub> emissions. It is through such policies that a low-carbon growth path might be achieved. The study found the existence of a bi-directional causal relationship between economic growth and energy consumption. Stable economic growth is an inevitable development trend in developing countries

Table 4  
Results of Granger causality tests.

| Null hypothesis               |             | Lag length |         |         |         |
|-------------------------------|-------------|------------|---------|---------|---------|
|                               |             | 2          | 3       | 4       | 5       |
| GDP does not Granger cause EC | F-statistic | 5.87635    | 2.09434 | 6.26578 | 9.67731 |
|                               | p value     | 0.0323     | 0.0356  | 0.0472  | 0.0816  |
| EC does not Granger cause GDP | F-statistic | 4.46373    | 5.45182 | 7.26181 | 6.32364 |
|                               | p value     | 0.0335     | 0.0478  | 0.0132  | 0.0476  |
| GDP does not Granger cause CE | F-statistic | 7.17455    | 4.34539 | 2.29047 | 1.56178 |
|                               | p value     | 0.3284     | 0.1342  | 0.5756  | 0.7189  |
| CE does not Granger cause GDP | F-statistic | 2.85433    | 3.47061 | 7.43546 | 1.16758 |
|                               | p value     | 0.2741     | 0.1043  | 0.3522  | 0.6436  |
| EC does not Granger cause CE  | F-statistic | 7.14134    | 9.88443 | 4.98346 | 3.64157 |
|                               | p value     | 0.0402     | 0.0047  | 0.0254  | 0.0618  |
| CE does not Granger cause EC  | F-statistic | 5.52459    | 4.42574 | 2.8342  | 3.64375 |
|                               | p value     | 0.1021     | 0.3148  | 0.5233  | 0.5314  |

like China, India, where mass migrations have been witnessed from rural to urban areas for better job opportunities. This migration has made major contributions to the nation's economic growth, however, it can also impose tremendous pressure on existing physical and social space and increase energy consumption. So, the sustained economic growth and related environmental degradation (CO<sub>2</sub> emissions) should be an integral part of long-term energy and emission scenario planning (Ghosh and Kanjilal, 2014).

In addition to above measures, China should achieve a circular economy to reduce the environmental pressure. In order to desire a green GDP growth, China should promote energy-saving technology and improve energy efficiency. Over the past decade, China has imported and begun to manufacture domestically many state-of-the-art low-carbon technologies (Guan et al., 2014). The national and local governments can co-ordinate design and implement effective mechanisms to optimize the energy use structure and further realize the transformation of economic development mode. The policy measures to achieve a low-carbon economy would motivate green investments in the field of clean technology, thus preventing further carbonization of the structure of the economy (Zhang et al., 2013). Once the measures are achieved, the economic structure can be gradually decarbonized. From the analysis undertaken in this study, we can conclude that a balance between stable economic growth and the reduction of CO<sub>2</sub> emissions is in fact achievable for China, although a series of sustainability measures are required.

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