Heliyon 9 (2023) e19865

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Economic growth, energy consumption and CO_2 emissions—An empirical study based on the Yangtze River economic belt of China

Rui Zhou

Institute of Regional Modernization, Jiangsu Provincial Academy of Social Sciences, Nanjing, 210004, Jiangsu, China

ARTICLE INFO

Keywords:
Economic growth
energy consumption
CO_2 emissions
Yangtze River economic belt

ABSTRACT

The Yangtze River Economic Belt plays a crucial role in the economic development of China from the perspective of economic growth, as well as from the perspective of the goal of the emission peak and carbon neutrality. In this study, the dynamic and causal relationships among economic growth, energy consumption and CO_2 emissions of the provinces and municipalities along the Yangtze River Economic Belt were analyzed using the panel vector autoregression (PVAR) model. The results revealed that the economic growth and the changes in CO_2 emissions in the current period are significantly influenced by the economic growth and CO_2 emissions in the preceding period, while the energy consumptionin the current period is influenced by the economic growth, energy consumption and CO_2 emissions in the preceding period. The results of the Granger causality test based on panel data suggested that among the three sets of causalities involving economic growth, energy consumption and CO_2 emissions, only economic growth and CO_2 emissions have one-way causality, while the other two sets of causalities are two-way. Further, the results of the impulse response function and variance decomposition showed significantly positive effects and a certain degree of path dependence among economic growth, energy consumption and CO_2 emissions.

1. Introduction

The Yangtze River Economic Belt refers to an economic zone including 9 provinces and 2 municipalities along the Yangtze River that are directly under the central government. It extends from Shanghai, located on the estuary of the Yangtze River, to Yunnan, which sits in the upper reaches of the Yangtze River. It has a share of over 40% in both population and gross economic output nationwide. Due to its easy access to land and water transportation, the Yangtze River Economic Belt houses the majority of the modern industries, such as steel, automobile, electronics and petrochemistry, and a large number of emerging strategic industries in China. In addition, multiple megacities and other major cities are located along this belt, represented by Shanghai and a large number of the top 100 cities and counties in China, which enjoy a leading position in terms of urbanization. However, the provinces and municipalities along the Yangtze River Economic Belt face two significant problems in terms of their development. First, despite having a per capita gross domestic product (GDP) that is slightly higher than the national average, this region has not yet met the economic requirements of China for fulfilling its second Centennial Goal. Further, the levels of economic development in the upper, middle, and lower reaches of the Yangtze River Economic Belt differ significantly. Second, the goal of carbon emissions reduction is yet to be achieved. Since the industries along the belt develop under comparatively high industrial inertia, they have relatively high energy consumption and CO_2 emissions. Consequently, it is difficult for significant changes in emissions to occur in this region over a short period.

E-mail address: zhourui@jsass.org.cn.

https://doi.org/10.1016/j.heliyon.2023.e19865
Received 28 March 2023; Received in revised form 30 August 2023; Accepted 4 September 2023
Available online 6 September 2023
2405-8440/

China has proposed various strategies to address such problems and enhance the economic development of the Yangtze River Economic Belt. Moreover, the principle of "focusing on protection as a whole and avoiding large-scale development" must be followed when implementing development strategies. This principle was proposed to change the conventional production and consumption modes accompanying "large-scale production, large-scale consumption, and large-scale emissions"; this would help advance the transformation of production modes and direct people's lifestyles toward greenness and low carbon. In this manner, the capacity for sustainable development can be enhanced through the conservation and efficient utilization of resources to accelerate modernization, as well as ensure harmony between mankind and nature. For instance, a large amount of energy from coal, oil and other fossil fuels is required for economic growth if the Yangtze River Economic Belt is designed to develop according to the conventional development mode, thus leading to increased CO_2 emissions. However, the dependence of economic growth on traditional sources of energy can be reduced effectively if greater efforts are made to replace traditional energy with clean energy and enhance efficiency, thus achieving the green and low-carbon transformation of the economy.

Despite all this, the provinces and municipalities along the Yangtze River Economic Belt still see rising energy comsumption and CO_2 emissions as a result of development, with several conflicts arising among economic growth, energy consumption and CO_2 emissions. Consequently, the adoption of "power rationing" has emerged in response to the "Total energy consumption Control and energy consumption Intensity Control" policy for national energy management in some regions, exerting negative impacts on regional economic growth. In addition, the launch of projects with "high energy consumption, high pollution but low added values" in some regions for short-term economic growth has also caused energy consumption and CO_2 emissions to rise. Therefore, to identify these mechanisms, the relationships among economic growth, energy consumption and CO_2 emissions of the provinces and municipalities along the Yangtze River Economic Belt need to be explored. This would provide a basis for future research and enable these provinces and municipalities to formulate appropriate policies to achieve their "carbon peaking and carbon neutrality" goals, as planned.

In the past few decades, extensive research has been conducted on the relationship between economic growth, energy consumption and CO2 emissions, resulting in significant findings. In comparison to these studies, it focuses on the Yangtze River Economic Belt, which is the most representative region of China's economic development, instead of commonly studied individual countries or multi-country regions. And the panel data from provinces and municipalities along the Yangtze River Economic Belt are used to construct a panel vector autoregression (PVAR) model, which examines the dynamic and causal relationships between economic growth, energy consumption and CO2 emissions in the region.

The rest of the paper is structured as follows: Section 2 provides a literature review, Section 3 explains the data and presents basic

Table 1
Literature summary.

Method	Author	Region	Time	Conclusion
ARDL model	Ozturk and Acaravci [23]	Turkey	1968–2005	Despite a long-term relationship among the variables, neither an increase in CO_2 emissions nor EC contributes to EG.
	Asongu et al. [24]	24 African countries	1982–2011	Despite a long-term relationship among the variables, no short-term causality is revealed between EC and EG.
	Mirza and Kanwal [25]	Pakistan	1971–2009	A two-way causality exists between EC and CO_2 emissions and between EG and CO_2 emissions.
	Tong et al. [26]	Brazil, India, Indonesia, Mexico, China, Russia and Turkey	1965–2017	The increase of EC in the E7 countries, except Indonesia, is the short-term Granger cause for the increase in CO_2 emissions, while EG is the short-term Granger cause for the increase in CO_2 emissions in Brazil, India, Mexico, and China.
	Nawaz et al. [27]	BRICS and OECD countries	1980–2016	Economic growth is negatively correlated with CO2 emissions, positively correlated with non-renewable energy consumption, and carbon emissions are positively correlated with energy consumption.
	Usman et al. [28]	Pakistan	1990–2017	In the long term, economic growth and the consumption of non-renewable energy lead to an increase in CO2 emissions. In the short term, the consumption of non-renewable energy reduces CO2 emissions. There exists a unidirectional Granger causal relationship between economic growth, non-renewable resource consumption, and CO2 emissions.
PVAR model	Magazzino [29]		1992-2013	No mutual impacts were observed between EG and EC; however, an increase in CO_2 emissions leads to decreased EC.
	Antonakakis et al. [30]	106 countries worldwide	1971–2011	The impacts of different types of EC on EG and CO_2 emissions in different groups of countries are different. Besides, the causality between total EG and EC is two-way.
	Acheampong [31]	116 countries worldwide	1990–2014	Although EG is uncorrelated to an increase in EC, an increase in CO_2 emissions speeds up EG. Significant regional differences were observed in terms of the impacts of EC on EG and CO_2 emissions. However, an increase in CO_2 emissions does not necessarily increase EC.
	Pejović et al. [32]	The European Union and the Western Balkans	2008-2018	Unlike the relationship between EG and CO_2 emissions, the two-way relationship between CO_2 emissions and the consumption of renewable energy is negative. No causality was observed between EG and the consumption of renewable energy. Though EG leads to decreased CO_2 emissions, a decrease in CO_2 emissions contributes to EG.

Source: Arranged by the author.

statistical analysis, Section 4 covers unit root tests and cross-sectional dependency tests, Section 5 estimates the PVAR model, Section 6 analyzes impulse response functions and variance decomposition, and Section 7 presents the main conclusions and limitations.

2. Literature review

In recent years, two major aspects of the relationships among Economic growth (EG), energy consumption (EC) and CO_2 emissions have been explored extensively. First, research has been conducted on the hypothetical environmental Kuznets curve (EKC), which postulates the existence of an inverted U-shaped relationship between environmental pollution and per capita income. However, different conclusions have been drawn in the relevant empirical studies. Although some scholars agree with the existence of an inverted U-shaped relationship [1,2], others argue in favor of a curve that has either an N-shape or some alternative shape [3,4]. In addition, several studies have hypothesized that no relationships exist between environmental pollution and per capita income [5,6]. Second, the existing literature also explores the relationship between EC and EG. Oztuk [7] proposed four kinds of relationships, i.e., the growth hypothesis [8–10], the protection hypothesis [11], the feedback hypothesis [12,13] and the neutrality hypothesis [14].

Regardless of the aspect being studied, numerous controversies exist in the literature. According to Adewuyi and Awodumi [15], the research on the relationship between EC and EG emissions contributes little to the existing literature when CO_2 emissions are not considered. Moreover, EC influences CO_2 emissions directly. Therefore, some scholars investigated the relationships among EG, EC and CO_2 emissions. For instance, Ang [16] discovered long-term causality between EG and the increase of EC and between EG and the increase of pollutant emissions using the co-integration and vector error correction models to analyze the data for France between 1960 and 2000. According to Soytas et al. [17], incomes cause no CO_2 emissions while EC does result in CO_2 emissions in the United States. Further, Zhang and Cheng [18] observed a one-way Granger causality between EG and EC and between EC and CO_2 emissions in China. Salari et al. [19] conducted a study using panel data from 1997 to 2016 across various states in the United States to examine the relationship between CO2 emissions, energy consumption and GDP. They found that energy consumption has a positive impact on CO2 emissions, and there exists an inverted "U" relationship between CO2 emissions and GDP.

With the recent development of modern econometrics, the autoregressive distributed lag (ARDL) model and the panel vector autoregression (PVAR) model have been widely applied in research on the relationships among EG, EC and CO_2 emissions (Table 1). In addition, different methods, such as the panel data-based generalized method of moments (GMM) and the KAYA identical equation by Muhammad [20] and Lai et al. [21] have also been used to explore the relationships among the three variables. Further, Debone et al. [22] reviewed the relevant literature to determine the research progress and dynamic development. The relationship between economic growth, energy consumption, and CO2 emissions is to some extent dependent on the economic development characteristics and institutional environment of the research subjects. Currently, there is a lack of research on regions undergoing rapid industrialization, urbanization, and with a strong government intervention capacity.

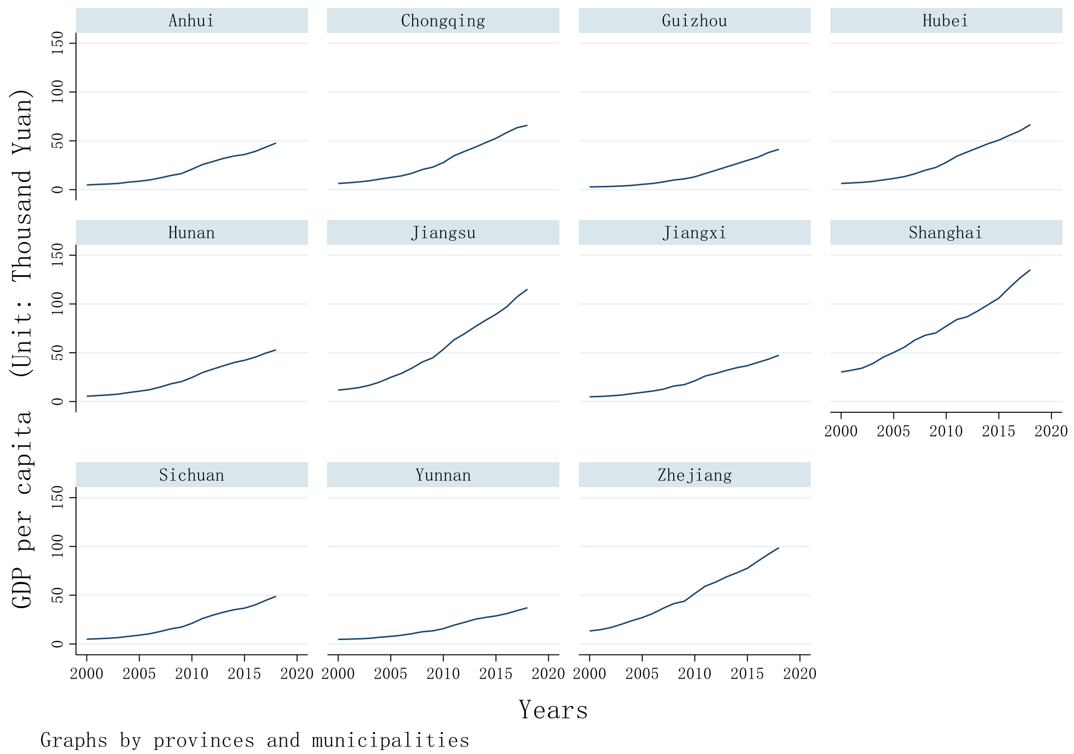

Fig. 1. Changes in GDP per capita for provinces and municipalities along the Yangtze River Economic Belt.

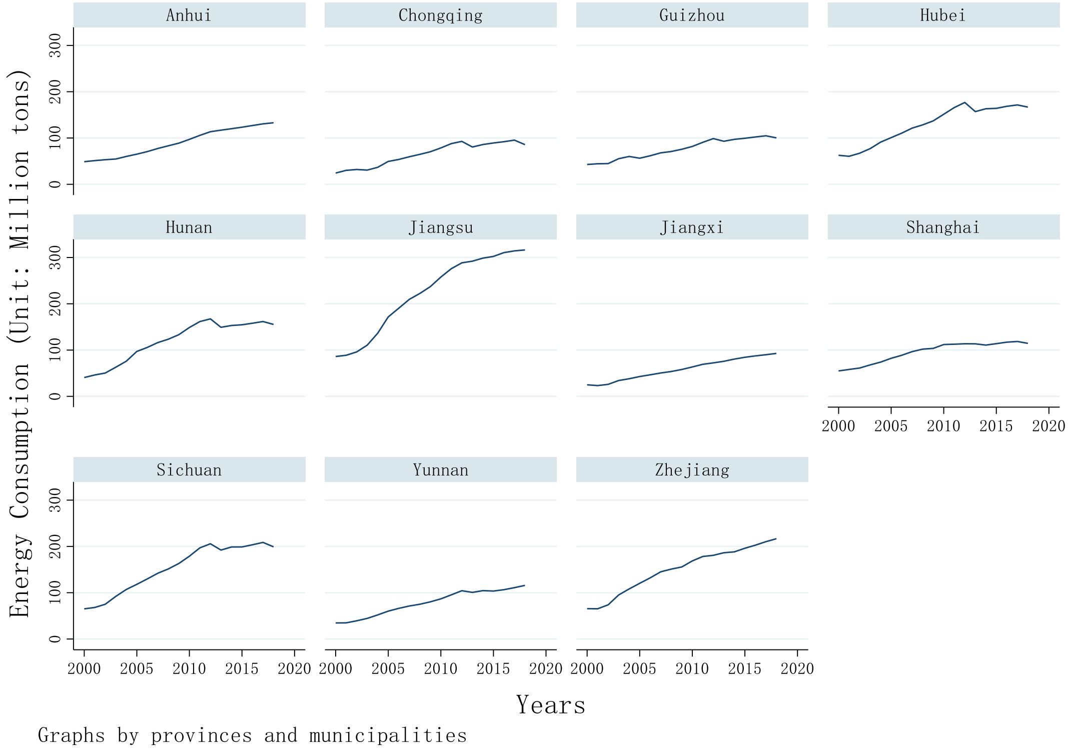

Fig. 2. Changes in energy consumption for provinces and municipalities along the Yangtze River Economic Belt.

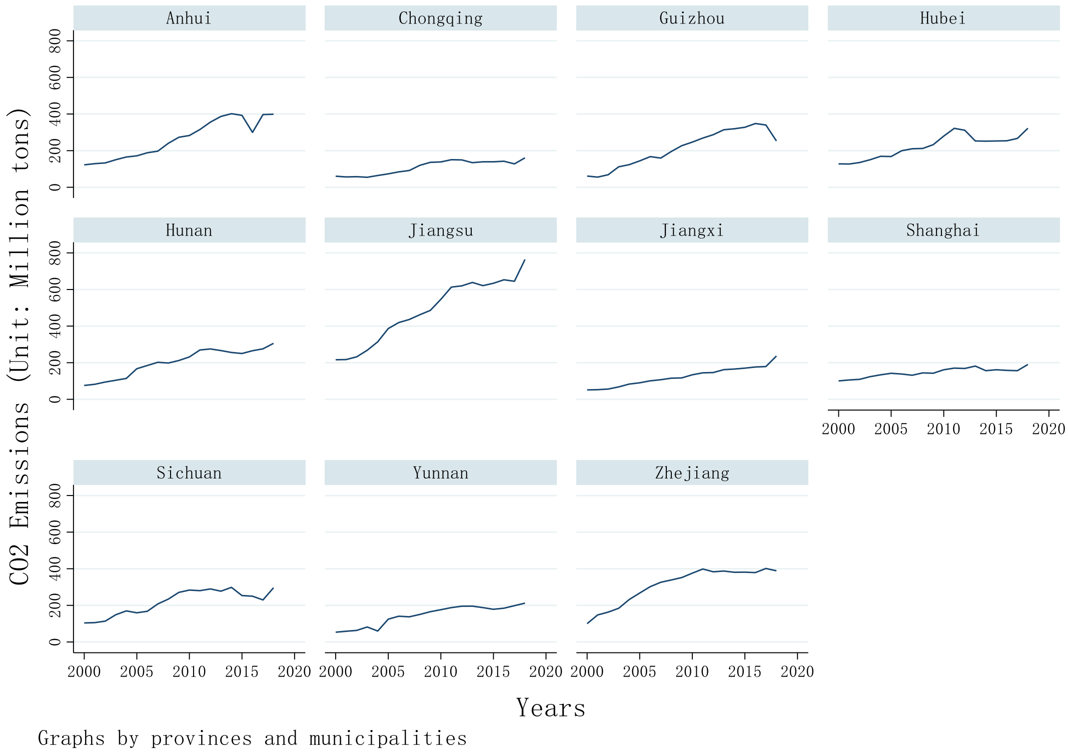

Fig. 3. Changes in CO_2 emissions for provinces and municipalities along the Yangtze River Economic Belt.

Based on the current research findings, firstly, there is no consistent conclusion regarding the relationship between economic growth, energy consumption, and CO2 emissions, which can be attributed to differences in sample selection, research methods, and other factors. In fact, some findings even contradict each other. Secondly, researchers have divided energy consumption into renewable and non-renewable energy sources to examine their relationships with economic growth and CO2 emissions. Thirdly, some scholars have incorporated factors such as tourism development [33], foreign direct investment [34], urbanization [35], and other variables into the study of the relationship between economic growth, energy consumption, and CO2 emissions to explore their impact on CO2 emissions. The controversial nature of research findings and the expansion of research scope not only make the exploration of the relationship between economic growth, energy consumption, and CO2 emissions more intriguing but also contribute to the development of green and inclusive growth policies for specific countries or regions.

3. Data specification and basic statistics

3.1. Data sources and variables

The data samples used in this paper covered all provinces and municipalities located along the Yangtze River Economic Belt, spanning the period from 2000 to 2018. The data included three variables, namely, EG, EC and CO_2 emissions, represented by the change in regional GDP per capita (unit: yuan), total regional consumption (unit: million tons of standard coal), and total regional emissions (unit: million tons), respectively. Data for the first two variables were obtained from the *China Statistical Yearbook (2001–2019)* and the *China Energy Statistical Yearbook (2001–2019)*, respectively. Data for CO_2 emissions were obtained from the Carbon Emission Accounts and Datasets for Emerging Economies (CEADs). The logarithms of EG, EC, and CO_2 emissions were represented by lnEG, lnEC, and $\ln CO_2$, respectively, while $\triangle$lnEG, $\triangle$lnEC, and $\triangle \ln CO_2$ denoted the values of the logarithmic first-order differences of EG, EC, and CO_2 emissions, respectively.

3.2. Basic statistics

Figs. 1–3 depict the trends in GDP per capita, energy consumption, and CO2 emissions in the Yangtze River Economic Belt. All provinces and municipalities show a clear upward trend in GDP per capita, with Jiangsu, Shanghai, and Zhejiang exhibiting the most prominent growth. Energy consumption also displays a noticeable upward trend for all provinces and municipalities. However, provinces such as Hubei, Hunan, and Sichuan experienced a decline in energy consumption after 2013, while Jiangsu had the highest growth rate in energy consumption. In comparison to the changes in GDP per capita and energy consumption, CO2 emissions exhibit greater volatility. Nonetheless, overall, all provinces and municipalities demonstrate an increasing trend in CO2 emissions. Jiangsu still has the highest growth rate in CO2 emissions, while Chongqing and Shanghai experience relatively moderate growth rates in CO2 emissions.

The statistical characteristics of the variables are described in Table 2. The sample variables had a left skew with their values close to zero, as shown in the column of skewness, and thin-tailed distribution with values close to 3, as shown in the column of kurtosis. Therefore, it is evident that the sample variables have the characteristics of a standard normal distribution.

As shown in Table 3, which represents the matrix of paired correlation coefficients among EG, EC and CO_2 emissions, these three variables are closely related to each other. This relationship was especially strong in the case of EC and CO_2 emissions, which had a paired correlation coefficient of 0.914.

4. Testing for non-stationarity and stationarity

Although panel data alleviates the non-stationarity of data and reduces the correlation of variables, there may be trends and intercepts for each variable, leading to the non-stationary of the data, that is, the existence of unit roots, which will result in serious consequences such as false regression. At the same time, in order to meet the condition of the co-integration test of panel data, it is necessary to judge whether there is the same order of integration for each variable through the unit root test. According to whether cross-sectional dependence is assumed, the unit root test of panel data is divided into the first-generation panel unit root test and the second-generation panel unit root test.

4.1. First-generation panel unit root test

Because several available methods for the first-generation panel unit root test can only function under particular conditions,

Table 2
Description of statistical characteristics.

Variable	Number of samples	Average value	Standard deviation	Minimum value	Maximum value	Skewness	Kurtosis
lnEG	209	10.016	.908	7.923	11.813	−.19	2.119
lnEC	209	9.181	.551	7.753	10.362	−.164	2.772
$\ln CO_2$	209	5.237	.581	3.942	6.639	−126	2.769

Source: Author's calculations.

Table 3
Matrix of paired correlation coefficients.

	lnEG	lnEC	$lnCO_2$
lnEG	1		
lnEC	0.742	1	
$lnCO_2$	0.661	0.914	1

Source: Author's calculations.

Table 4
Results of first-generation unit root test based on panel data.

Method	lnEG		lnEC		$lnCO_2$	
	Level	1st difference	Level	1st difference	Level	1st difference
LLC test	2.904 (0.998)	−6.620*** (0.000)	4.114 (1.00)	−4.013*** (0.000)	5.455 (1.000)	−4.802*** (0.000)
Breitung test	3.353 (1.000)	−1.590* (0.056)	3.641 (1.000)	−3.133*** (0.001)	2.276 (0.989)	−6.579*** (0.000)
IPS test	4.413 (1.000)	−2.987*** (0.001)	2.724 (1.000)	−6.871*** (0.000)	1.723 (0.958)	2.759*** (0.003)
DF-Fisher test	2.676 (1.000)	43.630*** (0.004)	10.525 (0.981)	83.903*** (0.000)	9.939 (0.987)	41.495*** (0.007)
PP-Fisher test	1.645 (1.000)	60.722*** (0.000)	0.304 (1.000)	111.707*** (0.000)	29.409 (0.134)	87.471*** (0.000)

Notes: Null hypothesis is that the unit root exists within the panel data. *** and * indicate statistical significance at the 1% and 10% level, respectively. The values in parentheses represent p-values.
Source: Author's calculations.

Table 5
Results of the cross-sectional dependence test.

Test	Statistic	*p*-value
Breusch-Pagan LM	169.105***	0.000

Notes: Null hypothesis is that no cross-sectional dependence exists within the panel data.*** indicates significance at 1% level.
Source: Author's calculations.

Table 6
Results of the second-generation panel unit root tests.

Variables	Level		1st difference	
	Intercept	Intercept and trend	Intercept	Intercept and trend
Pesaran CADF test				
lnEG	−1.685	−1.813	−2.457**	−2.841**
lnEC	−2.061	−2.448	−3.353***	−3.348***
lnCO2	−2.027	−2.230	−2.726***	−3.141***
Pesaran CIPS test				
lnEG	−1.948	−2.079	−2.972***	−3.543***
lnEC	−2.516***	−2.638	−3.934***	−4.158***
lnCO2	−2.565***	−2.367	−3.756***	−4.276***

Notes: Null hypothesis is that variables are not stationary. *** and ** indicate statistical significance at the 1% and 5% level, respectively.
Source: Author's calculations.

Table 7
Results of Pedroni's residual error co-integration test.

Within the group	Test statistic	*p*-value	Among groups	Test statistic	*p*-value
Panel V statistic	2.673***	0.004			
Panel ρ statistics	−5.590***	0.000	Group ρ statistics	−4.587***	0.000
Panel PP statistics	−10.075***	0.000	Group PP statistics	−11.771***	0.000
Panel ADF statistic	−4.504***	0.000	Group ADF statistics	−4.034***	0.000

Note: *** indicates significance at 1% confidence interval.
Source: Author's calculations.

multiple methods are generally applied in empirical studies to avoid potential errors caused by using a single method. In this study, five standard methods, including the LLC test [36], Breitung test [37], IPS test [38], ADF-Fisher test [39] and PP-Fisher test [40], were used

Table 8
Results of Kao's residual error co-integration test.

Residual error	T statistic	*p*-value
ADF	−2.375***	0.009

Note: *** indicates significance at 1% confidence interval.
Source: Author's calculations.

Table 9
Results of Johansen's panel data co-integration test.

Number of co-integrations	Fisher statistic (from trace test)	*p*-value
None	112.7***	0.000
At most 1	50.59***	0.008
At most 2	26.87	0.216

Note: *** indicates significance at 1% confidence interval.
Source: Author's calculations.

to perform this test on the logarithms of EG, total EC and CO_2 emissions. According to the results shown in Table 4, the null hypothesis for all the level values of the variables could not be rejected under the different methods due to the unit root; the null hypothesis could be rejected after the first-order difference equation, thus suggesting that these variables have first-order unit roots.

4.2. Cross-sectional correlation test

Due to the presence of common shocks or unobserved components that can become part of the error term, panel data models may exhibit significant cross-sectional dependence in the errors. Ignoring cross-sectional dependence can lead to severe estimation bias and size distortion [41]. When the time dimension of panel data exceeds the cross-sectional dimension, the Lagrange Multiplier (LM) test can be used [42]. Table 5 presents the results of the LM test for the sample data, and based on the p-values, we reject the null hypothesis, indicating the presence of cross-sectional dependence in the sample data.

4.3. Second-generation panel unit root test

The first-generation panel unit root test assume cross-sectional independence among the panel units. However, applying the first-generation panel unit root test to panel data with significant cross-sectional correlation may lead to significant biases in the conclusions [43,44]. To overcome this issue, second-generation panel unit root tests have been proposed by Phillips and Sul [45], Moon and Perron [46], Choi [47], and Pesaran [48], enhancing the reliability of the conclusions. Considering the presence of cross-sectional dependence in the sample data involved in this study, the Pesaran Cross-sectional Augmented IPS (CIPS) test and Cross-sectional ADF (CADF) test were employed to examine the stationarity of the variables. Table 6 displays the results of the second-generation panel unit root tests. It can be observed that not all variables are stationary at the level. However, after taking first-order difference, the null hypothesis of a unit root can be significantly rejected for all series, indicating that all series are stationary after the first differencing.

5. Estimation of the PVAR model

5.1. Co-integration test of panel data

Co-integration of panel data is generally used to determine whether a PVAR model is subject to spurious regression since it characterizes a long-run equilibrium relationship between or among variables. In this study, the methods used by Pedroni [49], Kao [50] and Johansen [51] were adopted to perform the co-integration test, as shown in Tables 7–9. Co-integration relationships were observed among EG, EC, and CO_2 emissions of the relevant provinces and municipalities, indicating consistent trends of long-term changes in the three variables.

Table 10
Selection of lagged items for the PVAR model.

Lagged item	CD value	J value	J *p*-value	MBIC	MAIC	MQIC
1	0.718	47.331*	0.098	−118.093	−24.669	−62.468
2	0.352	34.486	0.152	−89.582	−19.514	−47.864
3	−3.387	12.547	0.818	−70.165	−23.453	−42.353
4	−253.125	2.983	0.965	−38.373	−15.017	−24.466

Note: * indicates significance at 10% confidence interval.
Source: Author's calculations.

5.2. Selection of the lagged differences

In general, lagged differences must be specified when estimating the PVAR model based on two criteria, namely, the Hansen J statistic [52], and the MMSC-Bayesian information criterion (MBIC), MMSC-Akaike information criterion (MAIC), and MMSC-Hannan and Quinn information criterion (MQIC) proposed by Andrews and Lu [53]. According to the corresponding *p*-value of Hansen J statistics, and the values of MBIC, MAIC (Table 10), and MQIC, the lagged difference of the model was lagged item 1.

5.3. Estimation by the PVAR model

In this paper, the PVAR model, as shown below, was developed to examine the inter-period dynamic relationship of EG, EC and CO_2 emissions of the provinces and municipalities along the Yangtze River Economic Belt.

$$\Delta \ln EG_{it} = \alpha_0 + \alpha_1 \Delta \ln EG_{it-1} + \alpha_2 \Delta \ln EC_{it-1} + \alpha_3 \Delta \ln CO2_{it-1} + f_i + \varepsilon_{it} \tag{1}$$

$$\Delta \ln EC_{it} = \beta_0 + \beta_1 \Delta \ln EG_{it-1} + \beta_2 \Delta \ln EC_{it-1} + \beta_3 \Delta \ln CO2_{it-1} + g_i + \nu_{it} \tag{2}$$

$$\Delta \ln ECO2_{it} = \lambda_0 + \lambda_1 \Delta \ln EG_{it-1} + \lambda_2 \Delta \ln EC_{it-1} + \lambda_3 \Delta \ln CO2_{it-1} + h_i + \varsigma_{it} \tag{3}$$

where, $i = 1, 2, \cdots, N$, $t = 1, 2, \cdots, T$, (f_i, g_i, h_i) denote the fixed effects of region *i*, ε_{it} , ν_{it} and ς_{it} represent random perturbation terms assumed to be zero with the same variance, α_0, β_0 , γ_0 are constant terms, and α_1 , α_2 , α_3 , β_1 , β_2 , β_3 , γ_1 , γ_2 , γ_3 are coefficients to be estimated.

The least-square method has a disadvantage in terms of the consistency of estimators since lagged dependent variables are used as explanatory variables; therefore, individual fixed effects are inevitable in the PVAR model. Therefore, the GMM proposed by Holtz-Eakin et al. [54]was implemented in this study to obtain consistent and asymptotically valid estimators. Furthermore, the GMM estimation does not rely on exact knowledge of the distributional characteristics of the random error term. Rather, it accommodates heteroscedasticity and serial correlation in the error term, and, as long as the model specification is correct, it can always identify a set of moment conditions that the true parameters of the model satisfy. Consequently, the parameter estimates obtained through GMM are more efficient than the fixed effects estimator [55].

To assess the effectiveness of GMM, an overidentification test is conducted to verify if the number of instrumental variables is greater than the number of endogenous variables. By selecting the lagged first-order and second-order differences of $\Delta \ln EG$, $\Delta \ln EC$, and $\Delta \ln CO2$ as instrumental variables and performing the Hensen J test, the results in Table 9 show that the p-value of the Hensen J test is greater than 10%. Thus, we cannot reject the null hypothesis that "all instrumental variables are exogenous," indicating that the model is overidentified and the GMM estimation may be valid and effective.

The GMM estimation results are showed in Table 11, from which four conclusions can be drawn. First, the EG in the provinces and municipalities along the Yangtze River Economic Belt during the preceding period can cause an increase in the EC and CO_2 emissions during the current period, thus indicating that optimistic expectations of EG may boost further investment and consumption and lead to increased EC and CO_2 emissions. Second, the EC in the preceding period can also accelerate the EG and CO_2 emissions in the current period. Generally, energy is a required input element for production in the current period, which may stimulate EG in the same period due to the lagged effect of EC. Consequently, this is likely to affect the EG and CO_2 emissions in the next period. Third, the strengthening relationship between CO_2 emissions in the previous period and EC in the current period reflects the inter-period dynamic relationship between these two variables. Finally, it can be observed that the EG in the previous period has a positive lagged effect. In addition, while the increase of EC in the previous period leads to a further increase in EC in the current period, CO_2 emissions do not follow the same trend and do not have an adverse effect on EG. This is likely related to the intervention of industrial, environmental protection and energy policies implemented by governments at all levels, which not only maintain the EG but also reduce coal consumption by promoting clean energy. Therefore, the increase in CO_2 emissions has a weak effect on the EG and its own growth to the extent that its lagged first-order impact is negligible.

As shown in Table 12, each modulus was less than 1. Therefore, the PVAR model constructed is consistent with the required stability assumptions.

5.4. Granger causality

The Granger causality test was performed on the panel data to further investigate the relationships among EG, EC and CO_2 emissions. To further examine the relationship between EG, EC, and CO2 emissions, a Wald test for Granger causality was conducted on the panel data. Granger [56] proposed a method to analyze the causal relationship in time series data. And then Dumitrescu and Hurlin [57] extended it to test the causal relationship in heterogeneous panel data, This approach allows for varying regression coefficients for each cross-sectional unit, Additionally, through their Monte Carlo simulation, the Wald statistic demonstrates good properties of asymptotic distribution, making it suitable as a statistical measure for hypothesis testing. In empirical study, if the p-value of the Wald test is less than 10%, this shows that one variable granger causes another variable.

According to the results shown in Tables 13 and (1) the increase in EC was the Granger cause of EG, (2) the increase in CO_2 emissions and EG served as the Granger causes for the increase in EC, and (3) EG and the increase in EC were the Granger causes for the increase in CO_2 emissions. There were Granger causalities between all the explanatory and explained variables in the PVAR model.

Table 11
GMM estimation results of the PVAR model.

Model	Equation 1	Equation 2	Equation 3
	△lnEG	△lnEC	△lnCO2
△lnEGt-1	0.692*** (0.000)	0.878*** (0.000)	0.688** (0.017)
△lnECt-1	0.178*** (0.003)	0.251** (0.011)	0.385** (0.042)
△lnCO2t-1	0.020 (0.525)	0.089* (0.059)	−0.060 (0.710)
Hansen's J	12.422 (0.191)		

Notes: *** , ** and * indicate statistical significance at the 1%, 5% and 10% levels, respectively. The values in parentheses represent p-values.
Source: Author's calculations.

Table 12
Stability test of the PVAR model.

Eigenvalue		Modulus
Real part	Imaginary part	
−0.253	0	0.253
0.178	0	0.178
0.070	0	0.070

Source: Author's calculations.

Table 13
Wald test results of Granger causality.

Equation\ exclusion		Chi-square	*p*_value
△lnEG			
	△lnEC	9.393	0.002***
	△lnCO_2	1.488	0.223
	Total	17.825	0.000***
△lnEC			
	△lnEG	21.412	0.000***
	△lnCO_2	3.860	0.049**
	Total	26.474	0.000***
△lnCO_2			
	△lnEG	4.833	0.028**
	△lnEC	4.334	0.037**
	Total	7.589	0.022**

Notes: *** and ** indicate statistical significance at the 1% and 5% levels, respectively. The values in parentheses represent p-values.
Source: Author's calculations.

Moreover, the increase in CO_2 emissions was not the Granger cause of EG, thus signifying that the EG of provinces and municipalities along the Yangtze River Economic Belt is not necessarily accompanied by an increase in CO_2 emissions.

The estimated results of the PVAR model and the Granger causality test of panel data show that no two-way relationship exists between EG and CO_2 emissions of the provinces and municipalities along the Yangtze River Economic Belt. This observation is inconsistent with the findings of Chaabouni and Saidi [58], Dogan and Aslan [59] and Wang et al. [60], who observed a two-way relationship between EG and the increase in CO_2 emissions. The main factors contributing to these changes are twofold. Firstly, there has been a shift in industrial structure. The proportion of the service sector in GDP has been continuously increasing, and the share of high value-added manufacturing in the overall manufacturing sector has also been on the rise. Secondly, there has been a change in the energy consumption structure. The proportion of non-renewable energy sources such as coal and oil in total energy consumption has been consistently decreasing, while renewable energy sources like wind and solar power have been increasingly utilized on a larger scale. Further, an obvious two-way causality between the increase in EC and EG of the provinces and municipalities along the Yangtze River Economic Belt was observed. This contradicts the "neutrality hypothesis", which was previously confirmed by Moutinho and Madaleno [61]. This hypothesis is satisfied if there is no causal relationship between EG and the increase in EC. Indeed, these changes are likely influenced by the developmental stage of the Yangtze River Economic Belt. Overall, the Yangtze River Economic Belt is still undergoing rapid industrialization and urbanization. The process of economic growth in this region requires substantial energy consumption. Simultaneously, the energy consumption process generates new outputs, which will further promote economic growth.

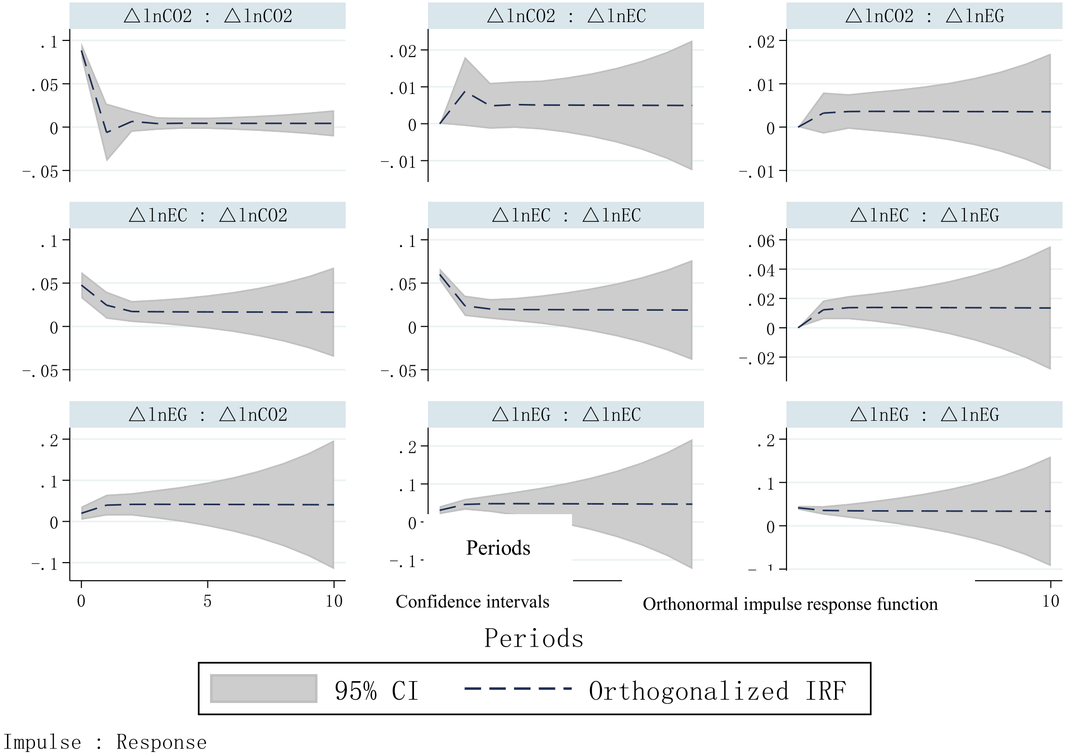

Fig. 4. Impulse response function.

Table 14
Variance decomposition result.

Response variable	Impulse variable		
	△lnEG	△lnEC	△lnCO_2
△lnEG			
1	1	0	0
5	0.895	0.099	0.007
10	0.874	0.118	0.008
	△lnEG	△lnEC	△lnCO_2
△lnEC			
1	0.207	0.793	0
5	0.646	0.344	0.0099
10	0.740	0.250	0.0097
	△lnEG	△lnEC	△lnCO_2
△lnCO_2			
1	0.038	0.217	0.745
5	0.380	0.200	0.421
10	0.543	0.178	0.279

Source: Author's calculations.

6. Impulse response and variance decomposition analysis

6.1. Impulse response analysis

The impulse response function reflects the influence of one endogenous variable on other endogenous variables within the PVAR model. In this study, the impulse response function in Fig. 4 demonstrates that an increase in CO_2 emissions led to a rise in EC and acceleration of EG, which remained at a relatively stable level for a long time. In addition, the increase in EC subsequently resulted in an increase in CO_2 emissions and accelerated EG; however, its impact on CO_2 emissions declined over time while its impact on EG remained stable for a long time. Additionally, EG gave rise to an increase in EC and CO_2 emissions, which were then relatively stable for a long time.

6.2. Variance decomposition

Variance decomposition reflects the contribution of the impact of one variable to the variance of another variable in the system. In general, this method is employed to ascertain the relative importance of dependent variables in explaining the change in independent variables [62]. Additionally, variance decomposition also reveals the transmission channels responsible for the impacts of specific policies [63]. In this study, it was observed that the variance of EG was mainly explained by the change of its lagging term, with approximately 10% attributed to the variance of the increase in EC and less than 1% attributed to the variance of the increase in CO_2 emissions (Table 14). Further, the variance of the increase in EC was initially ascribed largely to the change in its lagging term; however, EG gradually contributed increasingly to the variance of the EC increase, with an approximate contribution of 74% in the tenth period. The increase in CO_2 emissions contributed to a change in variance of less than 1% of the increase in EC. Moreover, the variance of the increase in CO_2 emissions (74.5%) was mainly caused by the initial change in its lagging term. However, the explanatory ability of the change in the lagging term gradually decreased, while the ability of EG to explain the change in the variance of increase in CO_2 emissions began to improve, contributing to 54.3% of this variance in the tenth period.

7. Conclusions and limitations

In this empirical study, the causal and dynamic relationships among EG, EC, and CO_2 emissions of provinces and cities along the Yangtze River Economic Belt were investigated using the PVAR model. The results suggested that the EG and EC in the preceding period promote EG and increase the EC and CO_2 emissions in the current period, while the CO_2 emissions in the preceding period only result in an increase in the EC for the current period. Further, one-way causality was observed between CO_2 emissions and EG, and two-way causalities were observed between CO_2 emissions and EC and between EC and EG. Moreover, the EG, EC and CO_2 emissions tend to rise after positive standard shocks. They fluctuate mainly due to changes in the initial stage and, over time, EG contributes more to the fluctuations in EC and CO_2 emissions.

It fails to achieve “double decoupling” between EG and EC, and between EC and CO_2 emissions in the studied provinces and cities. Further, these variables have obvious positive effects and path dependence on each other. Therefore, these provinces and cities should prioritize ecological conservation, promote green and low-carbon development, enhance green transformation in EG, emphasize clean energy development, realize low-carbon process innovation and digital transformation in traditional carbon-intensive industries, and acknowledge the role of market mechanisms in achieving the goals of peak carbon dioxide emissions and carbon neutrality. This would help achieve these targets as scheduled while maintaining steady and stable EG.

Although this study explores the dynamic and causal relationships between economic growth, energy consumption, and CO2 emissions in the provinces and cities along the Yangtze River Economic Belt, it has several limitations. Firstly, it does not examine the Environmental Kuznets Hypothesis, which means it doesn’t investigate the linear or nonlinear relationship between CO2 emissions and economic growth/energy consumption. Secondly, it only examines the relationship between total energy consumption and economic growth/CO2 emissions, without separately considering the relationship between renewable energy consumption and economic growth/CO2 emissions as well as non-renewable energy consumption and economic growth/CO2 emissions. Thirdly, it does not include factors such as urbanization levels and foreign direct investment in the analysis of the relationship between economic growth, energy consumption, and CO2 emissions. These limitations provide opportunities for further research in the future.

Ethics approval and consent to participate

As this article does not involve animal or human experiments, no ethics approval is required, and it is also unnecessary to obtain the consent of the individual or guardian.

Consent to publish

Not applicable.

Author contribution statement

Rui Zhou: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The author declares that he have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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