Check for
updates

On the nonlinear relationship between energy consumption and economic development in China: new evidence from panel data threshold estimations

Xiao-Ying Dong[1,2,3] · Qiying Ran[6,7] · Yu Hao[1,2,3,4,5]

Abstract

According to China's thirteenth "Five-Year Plan (2016–2020)", the economic and social transition to the sustainable style has become the consensus of the Chinese government and the academic world. Given the important role of energy in China's economic and social development, it is quite important to understand the effects of energy consumption on economic development. Despite a large body of literature in this field, very few studies have investigated the nonlinear relationship between the two. Based on the neoclassical growth model and the Cobb–Douglas production function, the present study uses the panel threshold regression model and provincial panel data covering the period 1985–2014 to investigate whether a nonlinear relationship exists between energy consumption and economic growth. The estimation results indicate that, although there is no evidence for such a nonlinear relationship for the whole nation, a single threshold exists for both eastern and non-eastern regions; however, the elasticity of GDP with respect to energy consumption does not vary significantly either before and after the threshold is reached. Therefore, as China's economy enters the phase of "new normal," with a relatively lower growth rate, sufficient and reliable energy input is still required to maintain reasonable and sustainable economic growth.

Keywords Energy consumption · Economic development · Cobb–Douglas production function · Non-linear relationship · Panel threshold regression

1 Introduction

Since the beginning of reform and opening-up in late 1970s, China's economy has kept growing at a remarkable speed for nearly four decades. Along with China's economic expansion, the country's energy consumption has skyrocketed. However, the surge in the

---

Xiao-Ying Dong and Qiying Ran have contributed equally to this study and share first authorship.

✉ Yu Hao
haoyuking@gmail.com; haoyuking@bit.edu.cn
https://ideas.repec.org/d/cebitcn.html
http://ceep.bit.edu.cn/english/index.htm

Extended author information available on the last page of the article

🍃 Springer

consumption of energy, especially fossil energy, has also caused a series of problems. For instance, China's environmental pollution and emissions of greenhouse gases (GHGs, mainly CO_2) have rapidly increased, and the country's environmental quality has deteriorated remarkably. At present, China is in the process of economic transition and is actively seeking to change its economic development model from the previous excessive style to an inclusive and sustainable one. To achieve this ambitious goal, China's energy policy should be adjusted and formulated in accordance with the changing demands for the development of China's economy and society. In particular, after the Paris Conference on Climate Change in 2015, China's central government formulated relevant energy and environment protection policies to manage global climate changes.

Ever since the reform and opening-up, the Chinese economy has experienced rapid development and a series of far-reaching reforms. Prior to the mid-1980s, the Chinese economy was focused in the rural areas. In the mid- and late 1980s, urban reform became the main driving force of economic and social development. After Deng Xiaoping's "South Tour" in 1992, China speeded up its construction of the market-oriented economy. At the same time, the features and driving forces of economic growth have also constantly changed. For instance, the acceleration of infrastructure construction has, to some extent, caused heavy reliance of China's economy on investment and energy input. After China's entry into the WTO in 2001, foreign trade, especially China's exports, ballooned and gradually became another growth engine for China. Under the tide of financial turmoil that has shrouded the world since 2008, the Chinese government took a series of countermeasures, including "Ten Industries Promotion Plan" and the so-called "Four Trillion" stimulus program, to stabilize the economy.[1,2] Since 2012, China's economy has entered the stage of "new normal," in which China's annual economic growth rate has reduced moderately from double-digit levels in the previous decade.[3] Against the background of the "new normal," the characteristics of China's economic and social development have changed remarkably (Du and Zhang 2018). For instance, China has accelerated the process of upgrading the industrial structure and improvement of the energy mix. In 2014, the State Council of China released the *Energy Development Strategic Action Plan (2014–2020)*, vowing to deepen energy market reform. At the same time, accompanied by the advancement of economic reform, the optimal allocation of resources and energy has become an increasingly urgent issue for China today. In particular, energy has played a key role in

---

[1] At the beginning of 2009, China formulated a comprehensive plan to promote the development of ten major industries that were severely affected by the global financial crisis; these include steel, automobile, shipbuilding, petrochemical, textile, light manufacturing, nonferrous metal, equipment manufacturing, electronic information, and logistics.

[2] On November 9, 2008, the State Council of China announced a stimulus package of four trillion Chinese yuan to shore up China's economy from the negative impact of the global financial crisis. After this program was launched, a series of infrastructural facilities, such as highways and high-speed railways, were built. At the same time, many small-scale industrial factories and plants were set up, many of which were energy- and pollution-intensive. Therefore, some scholars opined that the "Four Trillion" stimulus program should be blamed for the surge in energy consumption and environmental deterioration in recent years (Hao and Wei 2015).

[3] The term of "new normal" was originally raised by China's president Xi Jinping in May 2014. To sum up, there are three important features of "new normal". First of all, China's economic growth would shift gear from the previous high speed to a medium-to-high speed. Second, there would be consistent and continuous improvement and upgradation of economic structure. Third, the growth engine of China's economy would change from input and investment to innovation gradually. For more background information of China's "new normal", one could refer to http://www.chinadaily.com.cn/china/19thcpcnationalcongress/2017-10/05/content_32869258.htm.

China's sustainable development, as it serves as the indispensable material support for industrial production and residents' lives. In 2016, the Chinese President Xi Jinping put forward the energy saving and emission reduction goal in *The Reinforcement of Climate Change Action - Independent Contribution of China* at the Paris Conference on Climate Change and planned to decrease the unit GDP carbon dioxide emission by 60–65% from 2005 to 2030.

Therefore, at different stages of economic development, China's economy has displayed different characteristics. As such, the relationship between energy consumption and economic growth will probably change over time. For instance, when China's secondary industry, especially heavy industry, rapidly developed in the 1990s and early 2000s, the demand for energy skyrocketed, and related environmental pollution surged. However, in recent years, especially since China's economy entered the "new normal" stage, China has paid more attention to environment-friendly sustainable economic development. Therefore, China is in the process of transition, with increasing demands for technological progress and energy saving and conversion. Some recent studies have provided evidence for signs or trends of decoupling of energy consumption and related CO_2 emissions from economic growth in China in recent years (Zhang and Da 2015; Meng et al. 2018).

Thus far, many studies have examined the relationship between energy consumption and economic development in China by using either national or provincial data (e.g., Yuan et al. 2008; Zhang and Xu 2012; Long et al. 2015; Wang et al. 2016a, b; Shan et al. 2016). However, partly due to data limitation, the extant literature has largely ignored the possible change in this relationship, although the characteristics of economic and social development and energy market have changed significantly during the last three decades (Sun et al. 2017; Dong and Hao 2018). In this regard, in the present study, we focus on a very important question: Has the relationship between energy consumption and economic growth undergone a nonlinear shift during China's reform era?

To summarize, compared with previous studies, the contribution of this paper is two-fold. First, this study for the first time quantitatively investigates the nonlinear relationship between energy consumption and economic development in China. Second, the panel threshold regression model is employed to examine provincial panel data for the period of 1985–2014. The relatively long sample period ensures the reasonability and the reliability of the estimation results. Moreover, the use of provincial panel data allows us to account for the remarkable regional gap in economic and social development within China (e.g., Dong and Hao 2018).

The rest of this paper is structured as follows. The second section briefly reviews the relevant studies in this field. The third section explains the theoretical framework of this study and introduces the section containing the variables and data sources. In the fourth section, the estimation results of the panel threshold regression model are interpreted and discussed. Finally, the last section provides conclusions of this study and makes some corresponding policy implications.

2 Literature review

In the field of economics, the correlation among energy factors, economic growth, and other input factors has always been the focus of academia. Kraft and Kraft (1978) conducted a pioneering study that analyzed the relationship between economic development and energy consumption. They found a unilateral causal relationship between GDP and

energy consumption. Subsequently, investigation of such a causal relationship became a hot issue in the field of energy economics (e.g., Huang et al. 2008; Ali et al. 2016; Inglesi-Lotz 2016; Alper and Oguz 2016). Additionally, because energy plays an important role in the promotion of urbanization and industrialization, a series of studies have incorporated urbanization, industrialization, and trade openness into the study of the relationship between energy consumption and economic growth (e.g., Wagner 2008; Alshehry and Belloumi 2015; Begum et al. 2015; Wang et al. 2016a, b). Specifically, the impacts of urbanization and trade openness on energy use and energy structure have been investigated through various forms of multivariate models based on international and Chinese data (e.g., Dhakal 2009; Hossain 2011; Sathaye and Meyers 2013; Kasman and Duman 2015; Tang et al. 2016).

Although most of the previous studies are purely empirical and based on various econometric models (e.g., Dai et al. 2011; Ouyang and Li 2018), a few have a theoretical basis. For instance, the production function is a commonly utilized theoretical foundation for the input–output relationship between energy use and total output (e.g., Kuan et al. 1988; Zhang and Wang 2008). Some scholars have argued that there is evidence for a strong relationship between energy use and other macroeconomic indicators. For instance, based on the Cobb–Douglas production function, Yuan et al. (2009) examined the correlation between energy intensity and technology progress. Their results indicate that the growth of per unit capital and labor factor may lead to an increase in energy intensity, while technological progress leads conclusively to a decline in energy intensity. On the basis of the Cobb–Douglas production function, Fang (2011) found that renewable energy plays an important role in improving economic welfare, including GDP per capita and annual income of rural households. Shahbaz et al. (2013) selected financial development, international trade, and capital as important factors of the production function and confirmed that these inputs have significantly positive influences on economic growth.

Among the studies on the relationship between energy resource factors and economic growth, some scholars have used time series data to examine the long-term correlation between energy consumption and economic development (e.g., Rezitis and Ahammad 2015; Jebli et al. 2016; Chiou-Wei et al. 2016). Some scholars have adopted panel data to perform an in-depth analysis of the relationships between various production factors through the dimensions of time and space (Wang et al. 2011; Zhang and Lin 2012; Wang et al. 2014; Saidi and Hammami 2015). These studies have generally verified the important role of energy factors in economic growth. However, there is no consensus on the causal relationship between the two, and there is controversy over the relative level of the effect of energy input on economic growth. Moreover, because of the complexity of the macroeconomic system, some scholars have also found that the correlation between each production factor and output is nonlinear and asymmetric (e.g., Chiou-Wei et al. 2008; Zhang 2008; Wang and Ye 2017). However, for those studies that have found nonlinear relationship between energy consumption and economic development, there is still a lack of consistent conclusions on the selection of threshold variables and the tests for the nonlinear relationship.

As mentioned previously, despite fruitful results obtained in this field, existing studies have mainly focused on developed countries and used multinational data (e.g., Dergiades et al. 2013; Bölük and Mert 2014; Alper and Oguz 2016). Very few studies have been conducted in the context of China. Besides, most data used in the existent studies are time series data, which do not account for regional differences. Moreover, simple linear regression models were employed in most of the extant studies. In this regard, the present study for the first time investigates the potential nonlinear relationship between energy

consumption and economic development by employing the panel data threshold model. Therefore, this study makes a significant contribution to the existing literature and provides related policy makers with helpful references for the formulation and adjustment of relevant energy and economic development policies.

3 Methodology and data

3.1 Introduction to the theoretical model: single sector Cobb–Douglas production function

Before the 1970s, recognition of the economic circle of production input factors had always remained within the capital, labor, and land factors. Energy factors were usually taken as part of raw materials, which belong to the capital factors. With the release of the book, *The Limit of Growth*, published by The Club of Rome in 1972 (Meadows et al. 1972), academia started to recognize the efficacy of energy resources and surmised that resource exhaustion and unreasonable utilization would become important limitations of economic growth. Since then, separate energy factors have been classified into various production factors together with capital, labor, and other input factors to investigate multiple input factors that will influence economic growth. This study is conducted on the basis of single sector production function. Concretely, the Cobb–Douglas production function is used as the main theoretical framework, and energy is incorporated as an input. The concrete expression of the production function is as follows:

$$Y = A_t L_t^\alpha K_{t-1}^\beta E_t^\gamma \mu \tag{1}$$

where Y represents the overall output of the society; A_t represents comprehensive technical level; L_t represents labor factor input; K_{t-1} represents previous capital stock invested in the current production period; E_t represents energy factor input; α, β, γ represent output elasticity of labor, capital, and resources, respectively; and μ represents impacts of random disturbance terms.

To manage potential heteroscedasticity and transfer the exponential Cobb–Douglas production function into a linear form, the following logarithmic form of the production function is used as the basis for empirical estimations:

$$\ln Y = A_t + \alpha \ln L_t + \beta \ln K_{t-1} + \gamma \ln E_t \tag{2}$$

3.2 Construction of econometrics model: panel threshold regression model

In view of the complexity of the macroeconomic system and the complicated economic transition that has lasted over three decades, the characteristics of Chinese economic development have been changing over time. In this process, the skyrocketing energy demand has played a critical role in the fast economic growth and the development of secondary industry, especially energy- and pollution-intensive industries (e.g., Zhang and Xu 2012; Zhang et al. 2018). Accordingly, the main purpose of this study is to investigate whether there is a nonlinear and asymmetric relationship between energy consumption and economic development in China. If so, how would the nexus of energy consumption and GDP change after the threshold is reached? To examine the existence of the threshold(s), the nonlinear threshold regression model is used. Tong (1978) used the threshold regression

technique for the first time in a study of time series data and interpreted the transition process as jumping beyond the boundary. Hansen (1999) developed the threshold regression method for panel data. After summarizing previous studies, Wang (2015) took one step further and developed a nonlinear regression model and corresponding syntaxes that could be run in software Stata 14.0. This study employs Wang's (2015) method for the empirical estimations.

3.2.1 Threshold regression model with a single threshold

The regression model with a single threshold is shown in the following Eq. (3):

$$y_{it} = \mu_i + \beta_0' x_{1it} + \beta_1' x_{2it} g(q_{it} \leq x) + \beta_2' x_{2it} g(q_{it} > x) + u_{it} \tag{3}$$

where $i = 1, 2 \ldots N$ and $t = 1, 2 \ldots T$ represent province i and time period t, respectively. The dependent variable y_{it} is logarithmic per capital GDP (*ln(Gdp)*), which measures the economic development level. q_{it} is the threshold indicator, which is energy consumption, and energy input factor in this study. x_{1it} is a vector of control variables, which include labor input factor L (*ln(Den)*) and capital input factor K (*ln(Capital)*). x_{2it} is the main explanatory variable—the energy input factor (i.e., energy consumption per capita). β_0', β_1' and β_2' are the coefficients to be estimated. Specifically, β_1' and β_2' measure the relationship between y_{it} and x_{2it} before and after the threshold variable q_{it} exceeds the threshold value of $x \cdot g$ represents the indicator functions. μ_i is the time-invariant cross-section fixed effects. u_{it} represents the random disturbance term.

In this study, the F statistics of the likelihood ratio test for the production function are used to assess the threshold effects of the model. If the corresponding P value of the F statistics is lower than the chosen critical value, the original hypothesis of no threshold effects can be rejected. Therefore, it could be concluded that at least one threshold exists during the sample period.

3.2.2 Threshold regression model with multiple thresholds

In the case of the refusal of the original hypothesis of only single threshold effects, the number of the thresholds should be further examined. For instance, when there are two thresholds, the concrete model could be established as follows.

$$y_{it} = \mu_i + \beta_0' x_{1it} + \beta_1' x_{2it} g(q_{it} \leq x_1) + \beta_2' x_{2it} g(x_1 < q_{it} \leq x_2) + \beta_3' x_{3it} g(x_2 < q_{it}) + u_{it} \tag{4}$$

On the basis of the approach reported in Bai and Perron (1998), the model primarily fixes the estimate value $\hat{x}_1$ in single threshold effects and, secondly, calculates the second threshold value $\hat{x}_2'$ by setting the grid point value to minimize the sum of the squared residuals. Furthermore, through fixing the second threshold value $\hat{x}_2'$, the single threshold estimate value $\hat{x}_1'$ at the minimum of the sum of the squared residuals can be determined.

Similar to the test approach of single threshold effects, F statistics and P value are adopted to testify the significance of dual threshold effects. If the original hypothesis is rejected again, then it could be inferred that there are two threshold values at least. By the same token, additional efforts should be made to expand the model construction for testing until the acceptance of the original hypothesis.

3.3 The explanation of variables

3.3.1 Variable choice and explanations

3.3.1.1 Dependent variable Per capita GDP (*ln(Gdp)*). Taking the year 1978 as the base period, this study measures the economic development level to calculate collective gross output through per capita GDP. If there has been a nonlinear transition relationship that takes per capita energy consumption as the threshold value between each production input factor and economic growth, then the output elasticity of the energy factors for economic growth will change when the per capita energy consumption volume exceeds the threshold value. If the sum of the output elasticities of the input factors is greater than 1, then the regional production will manifest increment characteristics in terms of return to scale. If the sum of output elasticities of the input factors is 1, then the return to scale remains constant. If the sum of output elasticities of the input factors is less than 1, then the provincial production will manifest decrement characteristics in terms of return to scale.

3.3.1.2 Threshold variables Per capita energy consumption volume (*ln(Energy)*). Because of industrial structure optimization and upgrading, constant elevation of urbanization level, continuous enlargement of foreign trade openness, and gradual increase in energy demands in economic activities, the utilization level and energy efficiency have increasingly significant influences on economic growth. Therefore, in this study, the per capita energy consumption is chosen as the threshold variable. In this regard, the main purpose of this research is to investigate whether the contribution of energy factors for society has undergone a nonlinear transformation during the process of the rapid progress and reformation of the economy.

3.3.1.3 Explanatory variables Population density (*ln(Den)*). Labor, in a general sense, refers to the overall population in the society. This study derives the social labor force through provincial population density indicators. Economic growth in China has been dependent on labor-intensive industry for a rather long time. Although the labor force has obtained tremendous liberation and has greatly elevated production efficiency due to the optimization and upgrading of industrial structure, technological innovation, and progress, continuous additional attention should be paid to the contribution of labor factors to economic growth.

Capital stock (*ln(Capital)*). From the perspective of social development, capital stock refers to the overall capital volume available in the society, which could indirectly reflect the present economic development scale and technical development level of the society. Input of capital factors plays an important role in driving economic development and promoting technical innovation. Referring to the calculation approach adopted by Shan (2008) for capital stock, the present study cites the macroeconomic provincial data from 1985 to 2014 to calculate the provincial capital stock in that stage of China.

3.3.1.4 Control variables The secondary industry added value proportion (*Secind*) and the tertiary industry added value proportion (*Service*). Along with the reform and opening-up, the transition of the economic development mode at the end of the 20th century and the entry of China into WTO, the Chinese government has made continuous efforts to attract foreign investment and simultaneously increase the proportion of secondary and tertiary industries to a relatively higher level. With increasing contribution for economic growth, the manufacturing industry and the service industry play a dominant role.

Table 1 Descriptive statistics of the variables used in the empirical study

Variable	Definition	Obs	Mean	SD	Min	Max
ln(Gdp)	Logarithmic GDP per capita	870	7.761	0.997	5.788	10.435
ln(Energy)	Logarithmic energy consumption per capita	870	7.301	0.721	5.069	8.980
Secind	Secondary industry added value proportion	870	0.445	0.085	0.184	0.698
ln(Den)	Logarithmic interaction of population density	870	5.321	1.272	1.730	8.256
ln(Fdi)	Logarithmic direct investment	870	4.606	2.508	− 3.705	8.941
ln(Capital)	Logarithmic capital stock foreign	870	8.342	1.214	5.896	11.359
Service	Tertiary industry added value proportion	870	0.382	0.082	0.179	0.779

The added value data of provincial industry in this study are derived from the annual *Chinese Statistical Yearbook* and the official website of the Chinese Statistics Bureau.

Foreign direct investment (*ln(Fdi)*) refers to the capital input of either foreign economic organizations or foreign individuals in either plants or specific programs. After the execution of the east-oriented regional development strategy in China, provinces in the eastern economic belt have made full use of advantageous economic and geographical conditions, including the identity of special economic zones and the free trade pilot region, and the support of policy to elevate the extent of opening of overseas trade, to boost the economic growth of the eastern coastal region. Foreign direct investment data in the study are derived from the annual *Chinese Statistical Yearbook* and the *Chinese Municipal Yearbook*.

In the absence of data for the Tibet region, this study simply adopts provincial panel data in other Chinese regions from 1985 to 2014. In addition, provincial data in Sichuan and Chongqing are combined for processing in the manner of "Grand Sichuan." For the convenience of description, all provincial-level administrative units are described with the word "province." The data, including GDP, provincial land area, and population density, are mainly from the relevant annual *Chinese Statistical Yearbook* and the Chinese macro-economy database, in order of priority. The data on per capita energy consumption volume are derived from the annual *Chinese Energy Statistical Yearbook* from 1986 to 2015.

3.3.2 Descriptive statistics of data

Prior to the modeling analysis of data, the first thing to do is to make the descriptive statistics. The descriptive statistics are summarized in Table 1.

To further study the relationship between Chinese economic development and energy consumption from 1985 to 2014, the scatterplot for per capita GDP and per capita consumption in this time period is delineated. As shown in Fig. 1, in the last 30 years, the demand for energy is experiencing an upward trend, together with the development of the economy on the whole. Consequently, according to the single sector Cobb–Douglas production function, the question arises regarding whether there exists a nonlinear transformation relationship that takes per capita energy consumption volume as the threshold value among various production input factors within this time period. This paper will conduct a deliberate analysis of and discuss model assessment results in the empirical analysis section.

Fig. 1 Scatter diagram of China's per capita GDP and energy consumption from 1985 to 2014
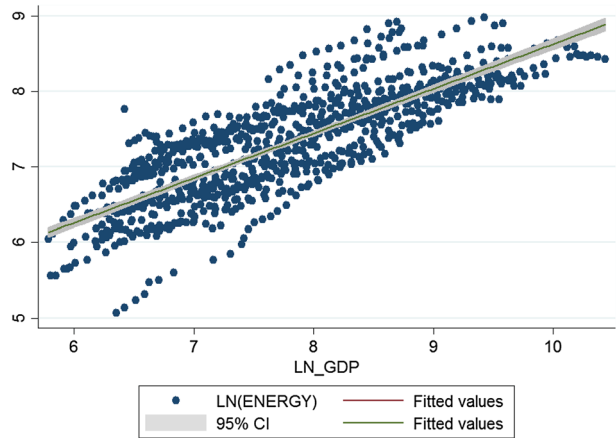
Table 2 Test for unit root in level

Variable	ADF-choi Z-stat	ADF-fisher Chi square	PP-choi Z-stat	PP-fisher Chi square
	(1)	(2)	(3)	(4)
ln(Gdp)	0.551	0.546	0.998	0.998
ln(Energy)	0.982	0.996	1.000	1.000
Secind	0.964	0.894	0.991	0.841
ln(Den)	0.977	0.971	0.995	0.962
ln(Fdi)	0.205	0.136	1.000	0.999
ln(Capital)	0.735	0.636	0.981	0.980
Service	0.829	0.908	0.000***	0.000***

ln(Gdp) stands for the logarithmic GDP per capita. *ln(Energy)* represents the logarithmic energy consumption per capita. *ln(Den)* is the logarithmic interaction of population density. *ln(Capital)* and *ln(Fdi)* represent the logarithmic capital stock foreign and the logarithmic direct investment, respectively. The null hypothesis of this test: Unit root (individual unit root process) exists

***, **, and * represent significance at the 1, 5, and 10% levels, respectively

4 Empirical analysis and results

The software Stata14.0 is applied in data analysis, in combination with the iteration and grid number setting of the model, to derive simulation distribution of panel threshold regression. Unit root tests of panel data show that all variables have unit roots in level. However, the data used in this study are consistent with the characteristics of the first order difference. Therefore, we have conducted a cointegration test. According to the results shown in Tables 2, 3 and 4, all variables follow the I(1) processes, and there is solid evidence for a strong cointegration relationship among all variables. Therefore, the panel threshold regression model could be used in this research.

As presented in the following table, the critical value of energy consumption threshold and the corresponding significance level in the panel threshold regression model can be calculated through model construction and software operation. Pursuant to the significance level, this study can further judge whether there exists a nonlinear transformation

Table 3 Test for unit root in first difference

Variable	ADF-choi Z-stat (1)	ADF-fisher chi square (2)	PP-choi Z-stat (3)	PP-fisher Chi square (4)
ln(Gdp)	0.000***	0.000***	0.000***	0.000***
ln(Energy)	0.000***	0.000***	0.000***	0.000***
Secind	0.000***	0.000***	0.000***	0.000***
ln(Den)	0.000***	0.000***	0.000***	0.000***
ln(Fdi)	0.017**	0.089*	0.007***	0.048**
ln(Capital)	0.000***	0.000***	0.000***	0.000***
Service	0.000***	0.000***	0.000***	0.000***

The definitions of the variables are the same as Table 2

Table 4 Kao Residual Cointegration test for panel data

ADF	t-statistic	Prob.
	−7.041239	0.0000
Residual variance	0.002345	
HAC variance	0.005227	

The null hypothesis of this test: no cointegration

relationship that takes energy consumption as the threshold value between factor input and economic growth under a single sector production function. If any such relationship exists, efforts should be made to determine whether such effects are definite threshold effects or dual threshold effects in nature.

In view of the remarkable differences in economic and social development across Chinese provinces and regions, this study uses the data for the whole nation as well as for two areas: east and inland. As shown in Table 5, there is no evidence for any nonlinear transformation relationship for the nation as a whole. According to the test results for economic growth in the eastern region and the inland region, it can be found that, under the conventional 10% significance level, the input factors simply have significant single threshold effects for the growth of both eastern and inland regions, but there is no evidence for the existence of dual threshold effects. Therefore, the relationships between energy consumption and economic development in both regions are nonlinear. Given that the threshold values in both regions have been surpassed thus far, the two regions have entered the second stage of economic development, which is basically consistent with the conclusion of Chen (2015).

For further testing of the robustness of the data employed in this study, OLS regression is later applied to the data. By conducting a comparative study on the results of OLS regression and panel threshold regression, the conclusion can be derived that the significance level among explanatory variables is basically the same for different regression model calculations. This implies the favorable robustness of the research data. However, because the OLS regression seeks the optimal solution based on the sum of squared residuals, the data with obvious nonlinear characteristics still have certain defects and errors. To summarize, the remaining parts of the study mainly discuss the results of panel threshold regression analysis.

Table 5 Panel threshold existence test results

Area	Threshold	Obs	*P* value	F-stat	bs	RSS
National area (Single threshold effect)	8.63	870	0.39	41.20	300	12.3413
National area (Double threshold effect)	8.47	870	0.97	5.45	300	12.2618
Eastern provinces (Single threshold effect)	8.14	360	0.003	89.80	300	3.5903
Eastern provinces (Double threshold effect)	6.70	360	0.47	26.00	300	3.3281
Inland provinces (Single threshold effect)	8.46	510	0.10	65.27	300	6.0959
Inland provinces (Double threshold effect)	8.56	510	0.76	12.53	300	5.9408

During the implementation period of the Seventh Five-Year Plan (Please refer to the following website for details about the report of the Seventh Five Year Plan of China http://www.npc.gov.cn/wxzl/gongbao/2000-12/06/content_5001763.htm) in China, the Chinese government divided the whole country into three major economic regions according to the regional differences in terms of relative geographical locations, economic development level, infrastructure construction, and practical economic and technical potentials. Among these, Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Guangxi are attached to the eastern regions. Other provinces belong to the inland regions

With regard to the panel threshold regression in the eastern economic region and the inland economic region, there has been a nonlinear transformation relationship that takes per capita energy consumption volume as the threshold value between production factors and economic growth, with concrete manifestation of significant threshold effects. However, for the whole nation, there is no evidence for any significant threshold effects. In other words, regarding the single sector production function nationwide, there is no nonlinear transformation relationship that takes per capita energy consumption volume as the threshold value between production factors and economic growth. To consider the reason for this phenomenon, this study analyzes the calculation results of panel threshold regression analysis. According to Table 6, regarding the provinces in the eastern economic region, the sum of coefficients of production input factors is greater than 1, and the production is characteristic of return to scale features. Moreover, production input factors have significant positive influences on the economic development of the eastern region. Among other factors, the output elasticity of labor is 0.88, the output elasticity of the secondary industry is 1.50, the output elasticity of capital factors is 0.38, the output elasticity of foreign direct investment is 0.04, the output elasticity of the tertiary industry is 1.07, and the initial output elasticity of energy factors for economic growth is 0.37, although the output elasticity of energy factors for economic growth exceeding the threshold value will later become 0.36. Because the coastal provinces in the eastern region have advantageous geographical locations and a high extent of trade openness in the favor of foreign investment, it can be found from the research results that foreign trade has significant impacts on the promotion of economic growth in the eastern region. After exceeding the threshold value of energy consumption, the regression coefficient of energy factors will remain optimistic, but its value will decrease slightly. This implies that the promotional role of energy factors for economic development will diminish slightly along with the gradual transformation of the industrial structure and the constant elevation of energy utilization efficiency in the eastern region. However, it is worth mentioning that such promotional influences remain significant, as

Table 6 Panel threshold regression results

Dep. Var: ln(Gdp)	National area		Eastern provinces		Inland provinces	
	OLS	Panel threshold regression	OLS	Panel threshold regression	OLS	Panel threshold regression
ln(Den)	0.16***	0.64***	0.13***	0.88***	0.17***	0.75***
	(0.01)	(0.07)	(0.02)	(0.08)	(0.01)	(0.10)
Secind	−0.11	−0.10	−0.60**	1.50***	−0.27	−0.91***
	(0.13)	(0.11)	(0.28)	(0.26)	(0.23)	(0.15)
ln(Capital)	0.68***	0.62***	0.49***	0.38***	0.66***	0.70***
	(0.01)	(0.01)	(0.03)	(0.02)	(0.02)	(0.02)
ln(Fdi)			0.12***	0.04***		
			(0.01)	(0.01)		
Service			−0.91***	1.07***		
			(0.31)	(0.27)		
ln(Energy)	0.14***		0.27***		0.23***	
	(0.03)		(0.05)		(0.03)	
0b._cat#c.lnenergy		0.29***		0.37***		0.19***
		(0.03)		(0.04)		(0.04)
1._cat#c.lnenergy		0.29***		0.36***		0.18***
		(0.03)		(0.04)		(0.04)
Constant	0.27***	−2.89***	1.10***	−4.57***	−0.24	−2.71***
	(0.10)	(0.31)	(0.13)	(0.44)	(0.15)	(0.40)
Observations	870	870	360	360	510	510
Number of Province		29		12		17
R-squared	0.94	0.98	0.96	0.99	0.93	0.98

The definitions of the variables are the same as Table 2, and the standard errors are reported in parentheses

usual. Further, together with the constant optimization of the industrial structure, the eastern region has reduced backward industries with outdated capacity and increased investment on the substream and downstream industrial chain, with an emphasis on the extent of contribution of service industry-added value for economic growth. The consequences shown in Table 6 also indicate that the tertiary industry has prominent driving functions for the economic development of the eastern region. The production of the provinces in the middle and eastern economic regions manifests decreasing return to scale features. However, distinct from the eastern region, the output elasticity is a larger negative value, at −0.91. In addition, it is worth noticing that, notwithstanding its rich energy reserves and varieties, the western region still has a significantly lower output elasticity value than the eastern region. The output elasticity of energy factors is 0.19 and 0.18, respectively, prior to and after exceeding the per capita energy consumption threshold value. The reason for this difference lies in the fact that, in pursuit of rapid economic development, the local government and relevant companies fail to pay strong attention to the improvement of resource exploitation technologies and the highly efficient use of resources, leading directly to low energy efficiency. Simultaneously, the massive government input caused by environmental pollution problems triggered by the extensive economic development mode forces secondary industry to have meaningful negative driving impacts on regional economic growth. Shi and Huang (2014) also pointed out the imbalance of infrastructure construction problems among regions in their study. In particular, the western region has been confronted by excessive investment problems in infrastructure construction in recent years. This leads to decreasing returns to scale features in inland production to some extent.

Across the whole country, the sum of the estimated coefficients of all production factors is greater than 1; therefore, the production function has increasing returns to scale features. Moreover, the coefficients of all input factors have significant impacts on the production, suggesting that the inputs of labor, capital, and energy will promote economic growth and lead to production expansion. However, it is still noteworthy that the considerable gap in economic and social development across rich eastern and relatively poor inland provinces might stem from the differences in economic development modes and policies across regions (Sun et al. 2017). It is also notable that the coefficients of the secondary industry are negative in most of the specifications, although the values are relatively small in magnitude. One possible reason for these results is that, during the relatively long sample period of 1985–2014, the industrial structure of the economy changed substantially for not only the whole country but also for different regions. Given the remarkable differences in different industrial structure and economic development styles in different countries, the impact of secondary industry on GDP development might be unclear (Démurger 2001; Liu et al. 2017).

This research concludes that, in previous discussions, there has been a nonlinear transformation relationship that takes energy consumption as the threshold value between production input factors and economic growth. To investigate the regional differences of such a nonlinear transformation relationship, this study conducts a preliminary analysis of whether and when Chinese provinces would exceed the threshold value. As reported in Table 5, the threshold value of single threshold effects in the eastern region is 8.14, and that in the inland region is 8.46. From 2001 to 2013, twelve provinces exceeded the threshold value of energy consumption and realized the nonlinear transformation; these included seven provinces in the eastern economic region, two provinces in the middle economic region, and three provinces in the western economic region. The provinces that exceeded the energy consumption threshold in the eastern region are concentrated mainly in the northern Bohai-Rim Economic Circle and the Yangtze River Economic Circle. The

provinces that exceeded the energy consumption threshold in the inland region are concentrated mainly in several major provinces with considerable energy reserves in the middle and eastern regions. Thus far, energy consumption in China depends mainly on coal. According to statistics in the *China Energy Statistical Yearbook* (2014),[4] coal consumption accounted for 71.3% in the overall energy consumption of China until 2013. Despite having a relatively backward economic growth rate in comparison with provinces in the eastern economic region, provinces such as Shanxi, Inner Mongolia, and Xinjiang in the middle or western economic regions still exceed the energy consumption threshold value because of their rich energy resources, in particular coal resource reserves. This is also in line with the distribution of energy resource structure in China as revealed by The Ministry of Land and Resources.[5] The distribution of energy resources in China is quite unbalanced, with a general incremental trend from east to west and from south to north. In terms of the total coal resources, the northern region accounts for 87% and the western region accounts for 52%. With regard to the recoverable reserves, the northern region accounts for 79% and the western region accounts for 26%. This feature propels partial provinces in middle and western regions to prepare for regional economies based on energy resource advantages.

According to the above-mentioned research conclusions, when the energy consumption volume in a certain province exceeds the threshold level, the association between energy consumption and economic growth in that province will become weaker.

During the implementation of the Tenth Five-Year Plan in China, some provinces successively took the lead in exceeding the threshold value of energy consumption. In 2001, Shanghai became the first to overcome the energy consumption threshold value and realized the nonlinear relationship transformation between economic growth and energy consumption. Up to 2005, four provinces exceeded the energy consumption threshold value. These four provinces were situated in the eastern economic region. Moreover, three of them (Beijing, Tianjin, and Liaoning) were within the Bohai-Rim economic region,[6] and the remaining one (Shanghai) was within the Yangtze River economic region.[7] After the execution of the reform and opening-up policy in 1978, the Chinese government first applied the unbalanced development strategy characteristic of reform and opening-up in the eastern coastal regions. After the determination of the development goal of the socialist market economic system in the 14th Congress of CPC in 1992, the extent of opening of China was elevated rapidly. Subsequently, China became a member state of the WTO in 2001. This, together with the elevation of the extent of opening, enabled the eastern region to make rapid progress. Furthermore, the improvement in import and export trade and the continuous increase in foreign direct investment also encouraged the transformation and

---

[4] Please refer to the following website for details about the *China Energy Statistical Yearbook* (2014) http://tongji.cnki.net/kns55/Navi/result.aspx?id=N2015110114&file=N2015110114000049&floor=1.

[5] Please refer to the following website for details about the portal website of the Ministry of Land and Resources in China www.mlr.gov.cn.

[6] Bohai-Rim Economic Circle: The 14th CPC National Congress report demanded acceleration of the development and opening of the Bohai-rim area and listed this area as one of the key development regions in China. Relevant departments also officially established the concept of the "Bohai-Rim Economic Circle" and made separate regional planning.

[7] Yangtze River Economic Circle usually refers to the urban group in the Yangtze river delta. It is one of the most populous regions with the most vigorous economy, the highest opening degree, and the strongest innovation abilities and absorption abilities. As an important convergence region of "One Belt and One Road" and the Yangtze River Economic Region, the Yangtze River Economic Circle has a dominant strategic status in modernization construction and the overall opening-up pattern.

upgrade of the economic industrial structure, from a secondary industry–oriented industrial structure to a tertiary industry–oriented industrial structure, in the eastern region. The service industry played an increasingly significant role in the economic growth of the eastern region. This further verified the conclusion of Wei and Liefner (2012) that the acceleration of the globalization process and the elevation of the degree of opening of overseas trade would greatly motivate the regional economic growth. The transition of regional strengths enabled some provinces in the eastern economic region to exceed the threshold value of energy consumption at the beginning of the 21st century. Despite insufficient energy reserves in comparison with other internal provinces, the eastern economic region still acted as the pioneer in the national economy by virtue of its advantages. Consistent with the research conclusion of Kangning and Jian (2005), the monetary growth rate in regions with rich resources was usually lower than that in regions with insufficient resources. Then, during the 5 years from 2006 to 2010, another three provinces (Ningxia, Inner Mongolia, and Hebei) exceeded the threshold value of energy consumption. The enactment of the *Western Development Eleventh Five-Year Plan* in December 2006[8] offered western economic progress greater policy support and material guarantees. On the basis of rich mineral resources and a flexible autonomous construction mechanism, the Inner Mongolia Autonomous Region and the Ningxia Hui Autonomous Region seized the favorable opportunity of industrial transfer and became the leading middle and western provinces that exceeded the energy consumption threshold value through optimizing energy utilization efficiency and energy utilization structure. From 2011 to 2015, during the implementation of the Twelfth Five-Year Plan, Jiangsu and Shandong, in the eastern economic region, and Xinjiang, Shanxi, and Qinghai, in the inland economic region, successively exceeded the energy consumption threshold value together with progressive promotion of the regional economic development strategy, constant elevation of the extent of trade opening, optimization of energy development technology, and improvement of energy utilization efficiency. This finding also indicated that the inland economic rise of China had become a new characteristic in the post-financial crisis era, and the regional economic development tendency became increasingly clear. Coupled with the overall development of the Chinese economy, more and more provinces exceeded the energy consumption threshold value and entered the new stage of industrial structure optimization, energy exploitation technology refinement, and energy resource utilization efficiency improvement. However, certain differences in the provinces also existed in terms of the transfer time and adaptation degree. As mentioned by Wu et al. (2014), promoting the adoption of regional economic policy to local government and the coordination among regional policies was the key issue of sustainable development (Table 7, Fig. 2).
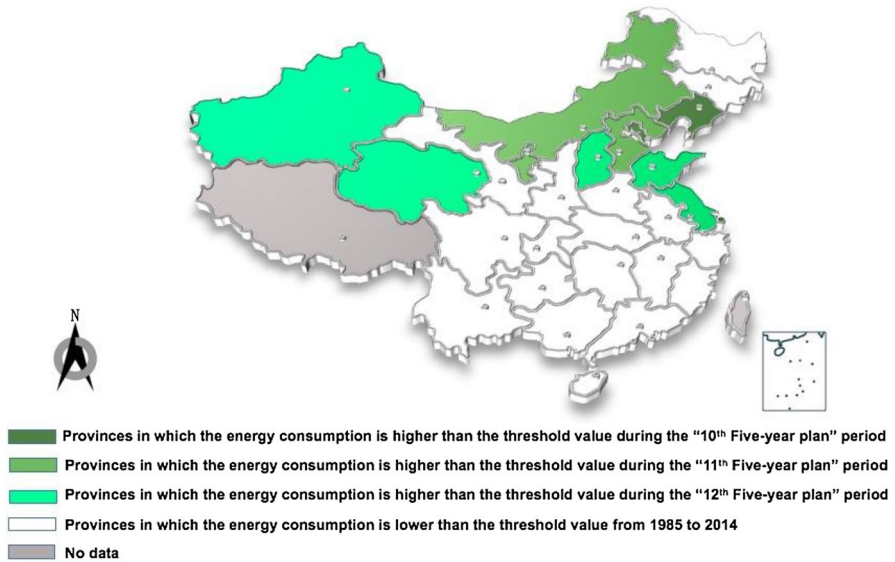
Figure 3 shows the confidence intervals for the single factor single threshold in both the eastern and the inland regions, wherein the threshold value is equal to the per capita energy consumption volume when the likelihood ratio function is larger than 1. With regard to the eastern region, the threshold value of per capita energy consumption is 8.137, and the 95% confidence interval is from 8.1162 to 8.1384. With regard to the inland region data set, the threshold value of per capita energy consumption is 8.4559 (logarithm), and the 95% confidence interval is from 8.4330 to 8.4764, corresponding to the threshold variable fluctuation range covered by the likelihood ratio function under the normal level.

---

[8] Please refer to the following website for details of the *Western Development Eleventh Five-Year Plan* http://www.agri.cn/cszy/BJ/whsh/ncwh/201202/t20120221_2486222.htm.

Table 7 Provinces across the threshold of per capita energy consumption and its span time

Year	Province
2001	Shanghai
2004	Beijing, Tianjin,
2005	Liaoning
2006	Ningxiao, Neimenggu
2008	Hebei
2011	Jiangsu
2012	Xinjiang, Shanxi, Qinghai
2013	Shandong

Provinces in which the energy consumption is higher than the threshold value during the "10th Five-year plan" period

Provinces in which the energy consumption is higher than the threshold value during the "11th Five-year plan" period

Provinces in which the energy consumption is higher than the threshold value during the "12th Five-year plan" period

Provinces in which the energy consumption is lower than the threshold value from 1985 to 2014

No data

Fig. 2 Map for provinces that leap over the threshold of per capita energy consumption in different economic development stages. Note: "10th Five-year plan" period: 2001–2005; "11th Five-year plan" period: 2006–2010; "12th Five-year plan" period: 2011–2015
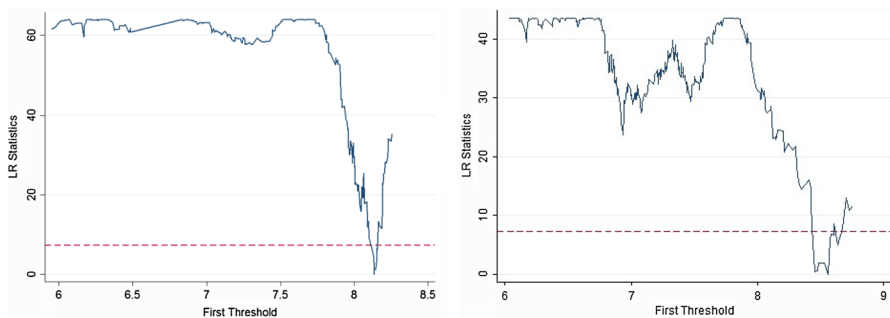
Fig. 3 Confidence interval single sector single threshold in the eastern (left) and non-eastern (right) regions

5 Conclusion and policy suggestions

For a rather long time, the contribution of different production factors of output scale has been the focus of concern of and research by economists. Because energy plays an increasingly important role in both production and life, it can mutually interact and connect with other production factors to operate the entire economic system. In accordance with the single sector Cobb–Douglas production function, this study uses provincial panel data from 1985 to 2014 in China to investigate whether there is a nonlinear transformation relationship that takes per capita energy consumption volume as the threshold values between production factors and economic growth in combination with the nonlinear panel threshold regression mode. The specific research conclusions are as follows.

First, for both the eastern and the inland regions, there exist nonlinear transformation relationships between energy consumption per capita and economic growth. When energy consumption per capita is chosen as the threshold variable, there is a single threshold in each region. However, for the whole nation, there is no evidence for the existence of such a nonlinear relationship. For the eastern region, the threshold value of per capita energy consumption is 8.137 (in logarithmic form), and the contribution elasticities of energy consumption factors of economic growth before and after exceeding the energy consumption threshold value are 0.37 and 0.36, respectively. For the inland region, the threshold value of per capita energy consumption is 8.4559 (in logarithmic form), and the corresponding elasticities of energy consumption with respect to GDP before and after reaching the threshold are 0.19 and 0.18, respectively. These estimation results indicate that, although the single threshold effects are detected in both regions, the changes in the relationship between energy consumption and economic development are essentially not too drastic. In general, the positive associations between energy demand and economic growth before and after the estimated thresholds are reached are statistically positive and do not change remarkably in magnitude. This could also partly explain why there is no solid empirical evidence for the existence of a nonlinear nexus of energy consumption and economic growth for China on the whole.

Second, the production function has increasing returns to scale in the eastern region but decreasing returns to scale in the inland region. The estimation results suggest that the economic development style in the eastern region is relatively more capital- and energy-intensive, while the economic growth in the inland region is comparatively more dependent on the labor input. In this regard, the economic development mode and the energy utilization efficiency in relatively less-developed central and western provinces need to be further improved.

Third, because of a remarkable gap in economic and social development, the relationship between energy consumption and economic growth might differ across provinces. For instance, the estimation results indicate that, since 2001, twelve provinces have successively exceeded the threshold values for energy consumption in the corresponding regions. Specifically, seven of these provinces are from the eastern area, two of them are from the central area, and the other three are from the western area. This finding suggests that a remarkable development gap exists even within the same regions.

On the basis of these main conclusions, several relevant suggestions can be put forward as follows.

First, it is necessary to regulate aggregate energy consumption, accelerate the process of traditional industrial upgrade and reformation, elevate energy utilization efficiency, and optimize energy resource structure allocations. Coal has dominated the energy structure in

China for a long time. Given that China's energy consumption will still increase considerably along with its economic growth in the foreseeable future, the proportion of clean energy, especially renewable energy, such as solar, wind, and geothermal energy, should be promoted sufficiently in the energy mix to meet the need for sustainable development. Moreover, to enhance energy security, the energy import dependence should be reduced from the unreasonably high current level, and the sources of energy import should be further diversified.

Second, it is necessary for government to pay more attention to and encourage the improvement of production efficiency and the optimization of production factor input. Currently, China's economic development is still facing a series of problems, such as excessive supply of industrial products, relatively backward technology, low energy utilization efficiency, and unreasonable factor allocation structure. To foster sustainable development, the Chinese government should focus on the productivity and the distribution of production factors, as the balance between energy supply and demand could be adjusted by regulating energy prices and optimizing resource allocation (Nie and Yang 2016).

Third, it is necessary for the Chinese government to stress the balance of regional development by optimization of the distribution system and making preferential policies for the less developed regions, such as the "Rise of Central China" and the "Western Development" programs. The considerable gap in economic and social development makes it more difficult for the central government to formulate energy policy to effectively control energy consumption. Historically, a favorable development strategy in the eastern region not only propelled rapid regional economic growth but also objectively caused the shift of industries with backward capacity to the middle and western regions, which had already generated giant environmental governance costs and other development problems for the inland regions and provinces. In this regard, by stimulating the western and central regions to grow faster and catch up with the more prosperous eastern region, the national energy consumption as a whole can be held in check, and the environmental quality in both regions can be improved by carefully arranged and coordinated policies.

Although this study contributes to literature by quantitatively investigating the nonlinear relationship between energy consumption and economic development in China over last three decades, there are still some limitations remained, which could also be potential research directions of future follow-up studies. For instance, given the fact that there is still significant differences in economic and social development across cities within a province, more elaborated estimations that fully account for heterogeneity of cities within the same province or region could be conducted when the city-level data are available. Moreover, it is also noteworthy that China's regional gap in development is remarkable. For instance, relatively prosperous eastern and coastal regions benefited a lot from the favorable geological locations and preferable policies that facilitate foreign trade and investment. Therefore, another follow-up research direction is to further explore the impact of trade openness, foreign investment and other possible influential factors on the scale and structure of energy consumption when the regional characteristics are taken into careful consideration.

References

Ali, H.S., Law, S.H., Zannah, T.I.: Dynamic impact of urbanization, economic growth, energy consumption, and trade openness on CO_2 emissions in Nigeria. Environ. Sci. Pollut. Res. **23**(12), 12435–12443 (2016)

Alper, A., Oguz, O.: The role of renewable energy consumption in economic growth: evidence from asymmetric causality. Renew. Sustain. Energy Rev. **60**, 953–959 (2016)

Alshehry, A.S., Belloumi, M.: Energy consumption, carbon dioxide emissions and economic growth: the case of Saudi Arabia. Renew. Sustain. Energy Rev. **41**, 237–247 (2015)

Bai, J., Perron, P.: Estimating and testing linear models with multiple structural changes. Econometrica. **66**(1), 47–78 (1998)

Begum, R.A., Sohag, K., Abdullah, S.M.S., Jaafar, M.: CO_2 emissions, energy consumption, economic and population growth in Malaysia. Renew. Sustain. Energy Rev. **41**, 594–601 (2015)

Bölük, G., Mert, M.: Fossil & renewable energy consumption, GHGs (greenhouse gases) and economic growth: evidence from a panel of EU (European Union) countries. Energy **74**, 439–446 (2014)

Chen, S.: The evaluation indicator of ecological development transition in China's regional economy. Ecol. Ind. **51**, 42–52 (2015)

Chiou-Wei, S.Z., Chen, C.F., Zhu, Z.: Economic growth and energy consumption revisited—evidence from linear and nonlinear Granger causality. Energy Econ. **30**(6), 3063–3076 (2008)

Chiou-Wei, S.Z., Zhu, Z., Chen, S.H., Hsueh, S.P.: Controlling for relevant variables: energy consumption and economic growth nexus revisited in an EGARCH-M (Exponential GARCH-in-Mean) model. Energy **109**, 391–399 (2016)

Dai, H., Masui, T., Matsuoka, Y., Fujimori, S.: Assessment of China's climate commitment and non-fossil energy plan towards 2020 using hybrid AIM/CGE model. Energy Policy **39**(5), 2875–2887 (2011)

Dhakal, S.: Urban energy use and carbon emissions from cities in China and policy implications. Energy Policy **37**(11), 4208–4219 (2009)

Dergiades, T., Martinopoulos, G., Tsoulfidis, L.: Energy consumption and economic growth: parametric and non-parametric causality testing for the case of Greece. Energy economics **36**, 686–697 (2013)

Dong, X.Y., Hao, Y.: Would income inequality affect electricity consumption? Evidence from China. Energy **142**, 215–227 (2018)

Démurger, S.: Infrastructure development and economic growth: an explanation for regional disparities in China? J. Comp. Econ. **29**(1), 95–117 (2001)

Du, J., Zhang, Y.: Does One Belt One Road initiative promote Chinese overseas direct investment? China Econ. Rev. **47**, 189–205 (2018)

Fang, Y.: Economic welfare impacts from renewable energy consumption: the China experience. Renew. Sustain. Energy Rev. **15**(9), 5120–5128 (2011)

Hansen, B.E.: Threshold effects in non-dynamic panels: estimation, testing, and inference. J. Econom. **93**(2), 345–368 (1999)

Hao, Y., Wei, Y.M.: When does the turning point in China's CO_2 emissions occur? Results based on the Green Solow model. Environ. Dev. Econ. **20**(6), 723–745 (2015)

Hossain, M.S.: Panel estimation for CO_2 emissions, energy consumption, economic growth, trade openness and urbanization of newly industrialized countries. Energy Policy **39**(11), 6991–6999 (2011)

Huang, B.N., Hwang, M.J., Yang, C.W.: Causal relationship between energy consumption and GDP growth revisited: a dynamic panel data approach. Ecol. Econ. **67**(1), 41–54 (2008)

Inglesi-Lotz, R.: The impact of renewable energy consumption to economic growth: a panel data application. Energy Econ. **53**, 58–63 (2016)

Jebli, M.B., Youssef, S.B., Ozturk, I.: Testing environmental Kuznets curve hypothesis: the role of renewable and non-renewable energy consumption and trade in OECD countries. Ecol. Ind. **60**, 824–831 (2016)

Kangning, X., Jian, H.: Resource curse effect on regional economy in China: another explanation to regional discrepancy. Economist **6**, 96–102 (2005)

Kasman, A., Duman, Y.S.: CO_2 emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis. Econ. Model. **44**, 97–103 (2015)

Kraft, J., Kraft, A.: On the relationship between energy and GNP. J. Energy Dev. **3**(2), 401–403 (1978)

Kuan, C., Hongchang, W., Yuxin, Z., Jefferson, G.H., Rawski, T.G.: Productivity change in Chinese industry: 1953–1985. J. Comp. Econ. **12**(4), 570–591 (1988)

Liu, Y., Hao, Y., Gao, Y.: The environmental consequences of domestic and foreign investment: evidence from China. Energy Policy **108**, 271–280 (2017)

Long, X., Naminse, E.Y., Du, J., Zhuang, J.: Nonrenewable energy, renewable energy, carbon dioxide emissions and economic growth in China from 1952 to 2012. Renew. Sustain. Energy Rev. **52**, 680–688 (2015)

Meadows, D.H., Meadows, D.H., Randers, J., Behrens III, W.W.: The Limits to Growth: A Report to the Club of Rome (1972). Universe Books, New York (1972)

Meng, M., Fu, Y., Wang, X.: Decoupling, decomposition and forecasting analysis of China's fossil energy consumption from industrial output. J. Clean. Prod. **177**, 752–759 (2018)

Nie, P.Y., Yang, Y.C.: Effects of energy price fluctuations on industries with energy inputs: an application to China. Appl. Energy **165**, 329–334 (2016)

Ouyang, Y., Li, P.: On the nexus of financial development, economic growth, and energy consumption in China: new perspective from a GMM panel VAR approach. Energy Econ. **71**, 238–252 (2018)

Rezitis, A.N., Ahammad, S.M.: The relationship between energy consumption and economic growth in South and Southeast Asian countries: a panel VAR approach and causality analysis (2015)

Saidi, K., Hammami, S.: The impact of CO_2 emissions and economic growth on energy consumption in 58 countries. Energy Rep. **1**, 62–70 (2015)

Sathaye, J.A., Meyers, S.: Greenhouse Gas Mitigation Assessment: A Guidebook, vol. 6. Springer, Berlin (2013)

Shahbaz, M., Khan, S., Tahir, M.I.: The dynamic links between energy consumption, economic growth, financial development and trade in China: fresh evidence from multivariate framework analysis. Energy Econ. **40**, 8–21 (2013)

Shan, H.J.: Estimation of China's capital stock K: from 1952 to 2006. J. Quant. Tech. Econ. **25**(10), 17–31 (2008). **(In Chinese)**

Shan, Y., Liu, J., Liu, Z., Xu, X., Shao, S., Wang, P., Guan, D.: New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors. Appl. Energy **184**, 742–750 (2016)

Shi, H., Huang, S.: How much infrastructure is too much? A new approach and evidence from China. World Dev. **56**, 272–286 (2014)

Sun, Z., Chang, C.P., Hao, Y.: Fiscal decentralization and China's provincial economic growth: a panel data analysis for China's tax sharing system. Qual. Quant. **51**(5), 2267–2289 (2017)

Tang, C.F., Tan, B.W., Ozturk, I.: Energy consumption and economic growth in Vietnam. Renew. Sustain. Energy Rev. **54**, 1506–1514 (2016)

Tong, H.: On a Threshold Model, vol. 29, pp. 575–586. Sijthoff & Noordhoff, Amsterdam (1978)

Wagner, M.: The carbon Kuznets curve: a cloudy picture emitted by bad econometrics? Resour. Energy Econ. **30**(3), 388–408 (2008)

Wang, Q., Zeng, Y.E., Wu, B.W.: Exploring the relationship between urbanization, energy consumption, and CO_2 emissions in different provinces of China. Renew. Sustain. Energy Rev. **54**, 1563–1579 (2016a)

Wang, Q.: Fixed-effect panel threshold model using Stata. Stata J. **15**(1), 121–134 (2015)

Wei, Y.D., Liefner, I.: Globalization, industrial restructuring, and regional development in China. Appl. Geogr. **32**(1), 102–105 (2012)

Wang, S., Fang, C., Guan, X., Pang, B., Ma, H.: Urbanisation, energy consumption, and carbon dioxide emissions in China: a panel data analysis of China's provinces. Appl. Energy **136**, 738–749 (2014)

Wang, S.S., Zhou, D.Q., Zhou, P., Wang, Q.W.: CO_2 emissions, energy consumption and economic growth in China: a panel data analysis. Energy Policy **39**(9), 4870–4875 (2011)

Wang, S., Li, Q., Fang, C., Zhou, C.: The relationship between economic growth, energy consumption, and CO_2 emissions: empirical evidence from China. Sci. Total Environ. **542**, 360–371 (2016b)

Wang, Z.X., Ye, D.J.: Forecasting Chinese carbon emissions from fossil energy consumption using nonlinear grey multivariable models. J. Clean. Prod. **142**, 600–612 (2017)

Wu, H.Q., Shi, Y., Xia, Q., Zhu, W.D.: Effectiveness of the policy of circular economy in China: a DEA-based analysis for the period of 11th five-year-plan. Resour. Conserv. Recycl. **83**, 163–175 (2014)

Yuan, C., Liu, S., Wu, J.: Research on energy-saving effect of technological progress based on Cobb–Douglas production function. Energy Policy **37**(8), 2842–2846 (2009)

Yuan, J.H., Kang, J.G., Zhao, C.H., Hu, Z.G.: Energy consumption and economic growth: evidence from China at both aggregated and disaggregated levels. Energy Econ. **30**(6), 3077–3094 (2008)

Zhang, C., Lin, Y.: Panel estimation for urbanization, energy consumption and CO 2 emissions: a regional analysis in China. Energy Policy **49**, 488–498 (2012)

Zhang, D.: Oil shock and economic growth in Japan: a nonlinear approach. Energy Econ. **30**(5), 2374–2390 (2008)

Zhang, Y.J., Da, Y.B.: The decomposition of energy-related carbon emission and its decoupling with economic growth in China. Renew. Sustain. Energy Rev. **41**, 1255–1266 (2015)

Zhang, J., Wang, G.: Energy saving technologies and productive efficiency in the Chinese iron and steel sector. Energy **33**(4), 525–537 (2008)

Zhang, C., Xu, J.: Retesting the causality between energy consumption and GDP in China: evidence from sectoral and regional analyses using dynamic panel data. Energy Economics **34**(6), 1782–1789 (2012)

Zhang, Q., Liao, H., Hao, Y.: Does one path fit all? An empirical study on the relationship between energy consumption and economic development for individual Chinese provinces. Energy **150**, 527–543 (2018)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Affiliations

Xiao-Ying Dong[1,2,3] · Qiying Ran[6,7] · Yu Hao[1,2,3,4,5]

Xiao-Ying Dong
18813005982@163.com

Qiying Ran
ranqy@aliyun.com

[1] School of Management and Economics, Beijing Institute of Technology, 5 Zhongguancun South Street, Haidian District, Beijing 100081, China

[2] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China

[3] Sustainable Development Research Institute for Economy and Society of Beijing, Beijing 100081, China

[4] Beijing Key Lab of Energy Economics and Environmental Management, Beijing 100081, China

[5] Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing 100081, China

[6] Center for Innovation Management, Xinjiang University, Urumqi 830047, China

[7] College of Economics and Management, Xinjiang University, Urumqi 830047, China