Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Forecasting China’s energy demand post-COVID-19 pandemic: Insights from energy type differences and regional differences

Qiang Wang a,b,*, Fuyu Zhang a,b, Rongrong Li a,b,**, Lejia Li a,b

a School of Economics and Management, China University of Petroleum (East China), Qingdao, 266580, People’s Republic of China
b Institute for Energy Economics and Policy, China University of Petroleum (East China), Qingdao, 266580, People’s Republic of China

ARTICLE INFO

Keywords:
Energy consumption
Economic growth
China
Regional differences
Panel data

ABSTRACT

As the first country to restart the economy after the COVID-19 pandemic, China’s fast-growing energy consumption has brought huge challenges to the energy system. In this context, ensuring a stable energy supply requires accurate estimates of energy consumption for China’s post-Covid-19 pandemic economic recovery. To this end, this study uses multiple panel regression model to explore the relationship between energy consumption and economic growth from the perspective of energy sources (total energy, coal, oil, natural gas) and regional difference. The data from 30 provinces in China from 2000 to 2017 were selected. Our findings indicate that China economic growth has led to the largest increase for oil consumption, followed by natural gas consumption, and finally coal consumption. That is, China economic growth has led to the largest increase for oil consumption, followed by natural gas consumption, and finally coal consumption. In addition, the coefficients of regional energy consumption equations are heterogeneous. Among them, energy consumption growth in provinces with high energy consumption is most affected by economic growth, followed by provinces with low energy consumption, and finally provinces with middle energy consumption.

1. Introduction

The Coronavirus disease 2019 (COVID-19) pandemic jeopardizes the safety of public life [1–3]. Many countries have adopted measures such as lockdowns, travel bans and social distancing to control the spread of the virus [4]. These measures have halted the spread of the virus but have also resulted in heavy financial costs [5]. The GDP fell by 3–6% in most countries and by 15% in some service-oriented countries [6,7]. Moreover, these measures also affect the energy sector. For example, closures of offices, factories, bars, restaurants and theaters reduce energy consumption by an average of 10% in some European countries [8]. Energy consumption in the early stage of the epidemic is reduced by more than 1.5 million barrels per day. Oil consumption, in particular, is as the lowest point in 30 year [9]. The lower oil consumption leads to a drop in prices [10,11], which makes the epidemic bring unprecedented challenges to the energy industry.

As the first country to effectively control the epidemic, China takes the lead in entering a period of economic recovery [12]. On February 3, 2020, the Chinese government proposed policies to help various production enterprises resume work and production. Consequently, rapid recovery in industrial production has led to a substantial increase in energy consumption. In the first half of 2021, China’s electricity consumption, coal consumption and natural gas market demand increases by 16.2%, 10.7% and 21.2% year-on-year, respectively [13]. In December 2020, Zhejiang, Hunan, Jiangxi, and Inner Mongolia autonomous regions successively issued notices of orderly electricity consumption or power curtailment to deal with the shortage of electricity and coal. Among them, Zhejiang Province, which uses the most electricity, has the most severe power cuts. Besides, some factories produce alternatively at the request of the government. The combinations of power cut and alternative production threaten small and medium-sized enterprises struggling to survive after the epidemic and hinder the economic recovery to a certain extent.

The economic recovery following the lifting of China’s COVID-19 lockdown has led to short-term fluctuations in energy consumption. To ensure the balance of energy supply and demand, it is necessary to accurately explore the energy consumption of China’s economic recovery of post-Covid-19. The relationship between economic growth and energy consumption has always been a research hotspot [14,15]. In general, the relationship between these two variables is related to the

* Corresponding author. School of Economics and Management, China University of Petroleum (East China), Qingdao, 266580, People’s Republic of China.
** Corresponding author. School of Economics and Management, China University of Petroleum (East China), Qingdao, 266580, People’s Republic of China.
E-mail addresses: wangqiang7@upc.edu.cn (Q. Wang), lirr@upc.edu.cn (R. Li).

https://doi.org/10.1016/j.esr.2022.100881
Received 5 September 2021; Received in revised form 6 May 2022; Accepted 29 May 2022
Available online 10 June 2022
2211-467X © 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
economic structure and development stage [16]. In particular, due to the different levels of industrialization and urbanization in different provinces in China, the impact of economic recovery on energy demand varies [17]. In addition, various energy sources have their own demand elasticity, which lead to differences in consumption of coal, oil, and natural gas [18]. In this regard, this study investigates the relationship of economic growth and energy consumption from two perspectives: regional differences and sources differences. The energy consumption of China’s economic recovery of post-Covid-19 pandemic was reflected through the historical relationship between economic growth and energy consumption. The conclusions answer the questions “Which regions of China will experience the greatest increase in energy consumption demand?” and “For coal, oil and gas, which energy consumption is most affected by economic growth?”, which are of great importance for the development of China’s energy planning in the post-epidemic era.

The rest of the study is organized as follows: Section 2 describes the relevant literature review; Section 3 shows the methods and data used in the calculations; Section 4 shows the empirical results and analyses; Section 5 provides an in-depth discussion of the results; Section 6 gives conclusions and policy implications.

2. Literature review

Existing research has deeply explored the relationship between economic growth and energy consumption from multiple perspectives through different methods [19–21]. The conclusions in this field can be attributed to four hypotheses [22,23]: The first is the feedback hypothesis that economic growth and energy consumption are causal to each other [24]; The second is to support the conservative hypothesis that economic growth promotes energy consumption in one direction [25]; The third is the growth hypothesis that energy consumption promotes economic growth in a single direction [26,27]; The fourth is the neutral hypothesis that there is no causal relationship between economic growth and energy consumption [28]. Due to the differences in the research objects and periods, the relationship between the two has not yet reached a consensus [29]. Below we conduct a literature review from two perspectives.

2.1. Based on the regional perspective

From the perspective of measurement model, studies can be divided into two categories: time-series data and panel data [30]. The research object of time series data is mainly a single region. Taking India as an example, this study used the Engel-Granger cointegration method to test data from 1950 to 1996 and found that there is a two-way causal relationship between China’s oil consumption and economic growth [31]. For Turkey, income is determined by energy consumption and foreign trade [32]. Dividing renewable and non-renewable energy consumption, this study focuses on the time-varying causal relationship between energy consumption and economic growth [31]. For India, the study found that GDP is a positive factor affecting electricity consumption through a multivariate regression model [34]. In addition, the interaction mechanism between energy consumption and economic growth in the Yangtze River Delta of China has been investigated. Evidence shows that coal consumption has played a positive role in accelerating economic development [35]. From the perspective of panel data, research is usually carried out on a global or national scale. At the international level, PerrySadorsky’s results show that for 18 emerging economies including China, economic growth has created opportunities for the growth of renewable energy consumption in these countries [36]. On the contrary, a study of 27 EU countries did not find a causal relationship between economic growth and energy consumption [37]. For 11 major industrialized countries at the same level of development, the results show that, except for the case of Britain, Germany, and Sweden, there is a neutral hypothesis among the remaining countries. Besides, Canada, Belgium, the Netherlands, and Switzerland have a one-way causal relationship from energy consumption to GDP [38]. In the panel vector error correction model of six Central American countries, the results show that there is a two-way causal relationship between energy consumption and actual output [39]. At the national level, this study based on 29 provinces in China found that energy consumption is the Granger cause of GDP and financial development is not the Granger cause of GDP [40]. Panel data models have been established in 50 states in the United States to study the complex and controversial relationship between energy consumption and GDP. The results of the Dumitrescu-Hering causality test indicate that there is mixed evidence for the direction of the causal relationship between energy consumption and GDP in the short term [41]. In short, different regions support different conclusions regarding the impact of economic growth on energy consumption. Therefore, the following research must fully consider the regional heterogeneity between regions.

2.2. Based on the energy sources perspective

With the deepening of study, energy consumption is divided into different sub-energy sources. As the main primary energy source, coal has attracted many scholars to investigate it. A study confirms that coal consumption may make a positive contribution to economic growth through the autoregressive distribution lag limit test method, which is called the growth hypothesis [42]. In this case, economic development can easily become dependent on coal energy, especially in developing countries. The energy-saving hypothesis supports that there may be a one-way Granger causality from economic growth to coal consumption [43]. Moreover, some studies provide support for the two-way causality between coal consumption and economic growth [44]. The empirical results of OECD countries prove the neutral hypothesis that a causal relationship cannot be established between coal consumption and economic growth [45]. Oil is the world’s main commercial energy source and acts as an engine of economic development [46]. In addition to coal, Zheng et al. thoroughly explored the relationship between China’s industrial structure and their respective oil consumption growth paths. The results suggest that the long-term elasticity between oil consumption and the output value of the tertiary industry is the largest, followed by the secondary industry. The output value of the primary industry has a negative impact on oil consumption [47]. Zou et al. investigated the equilibrium relationship between China’s oil consumption and economic growth. The cointegration test shows that these two variables tend to move together in the long run. Furthermore, the Granger causality test indicates that oil consumption may be a useful factor for predicting short-term and long-term economic changes [48]. This may be because the massive consumption of oil in industries and other fields may directly promote the economy. In the four emerging economies of Russia, China, South Korea, and India, three-quarters of the countries have feedback effects between oil consumption and economic growth. The results of Johansen’s cointegration indicate that rising oil prices have an adverse effect on the growth of emerging economies [49].

In China’s “13th Five-Year Plan”, natural gas has been listed as a vigorously developed energy due to its low carbon emissions. Corresponding study has also increased. Li et al. found a positive correlation between China’s natural gas consumption and economic growth, which means that promoting natural gas consumption can improve the economy [50]. The work of Zheng et al. also reached the same conclusion [47]. When Germany and Japan are undergoing major energy reforms, natural gas consumption accounts for an increasing share of their energy supply. The empirical results show that there is a two-way causal relationship between these variables in Germany and Japan, which is consistent with the “feedback hypothesis”. The study of Magazzino et al. claims that the supply of natural gas should be further strengthened to
gradually replace the most polluting fuels (oil and coal), ensuring a viable transition to the path to renewable energy [51]. In conclusion, although the economy and energy have a close relationship, due to the differences in the characteristics of energy, the consumption of various energy sub-types plays specific roles in economic growth. Therefore, there are differences in the dependence of economic growth on various energy sources, which is very important in the study of energy economics.

To advance research on this issue, this study focuses on the energy sources and regional differences of energy consumption affected by economic growth. Regional difference is examined by re-dividing 30 provinces into three regions (high energy consumption region, medium energy consumption region, and low energy consumption region) according to the level of energy consumption; Energy sources difference is achieved by subdividing the total energy consumption into coal, oil, and natural gas energy consumption. To this end, regional model and source model for energy consumption were constructed, and the relationship between multiple energy consumption and economic growth in 30 provinces in China was analyzed. In addition, the impact of industrial structure and trade openness on energy consumption is also included in the model. Conclusions are particularly important for China to ensure energy security during the economic recovery period in the post-epidemic era.

3. Data description and model construction

3.1. Variable selection and data description

This study uses data samples from 30 provinces (including provinces, districts and municipalities directly under the Central Government, hereinafter collectively referred to as provinces) in China from 2000 to 2017 (excluding Tibet, Hong Kong, Macao, and Taiwan). According to the 2017 energy consumption statistics of various regions in the China Energy Yearbook, ten provinces with total energy consumption higher than 190 million tons of standard coal are called high energy consumption region (Guangdong, Hebei, Henan, Liaoning, Inner Mongolia, Shandong, Shanxi, Sichuan, Zhejiang). Ten provinces with total energy consumption between 100 and 190 million tons of standard coal are called middle energy consumption region (Anhui, Fujian, Guangxi, Guizhou, Heilongjiang, Hunan, Shaanxi, Shanghai, Xinjiang, Yunnan). Ten provinces with total energy consumption less than 100 million tons of standard coal are called low energy consumption regions (Hainan, Qinghai, Hubei, Ningxia, Beijing, Gansu, Tianjin, Jilin, Jiangxi, Chongqing) (as shown in Fig. 1).

The study selected variables such as total energy consumption, coal consumption, oil consumption, natural gas consumption, economic growth, industrial structure, and regional openness to construct energy consumption functions to explore the impact of economic growth on energy consumption. The construction of each variable selection is explained as follows. The relevant data comes from the “China Statistical Yearbook”, “China Energy Statistical Yearbook” and the provincial statistical yearbooks over the years:

(1) The explained variable

Total energy consumption (TEC): Total energy consumption measures the level of energy consumption. Total energy consumption refers to the sum of various energy consumed by various industries and households in the national economy, and is divided into three parts, namely, terminal energy consumption, energy processing and conversion losses, and losses. To further investigate the impact of the difference of economic recovery on the consumption of different types of energy, the annual consumption of coal (COAL), oil (OIL), and natural gas (GAS) in each province was selected and used as the regression equation of the difference test stage.

(2) Core explanatory variables

Economic growth (GDP): Energy demand is linked to economic growth. To ensure the balance of energy supply and demand during the economic recovery period, it is necessary to quantitatively analyze the relationship between the two. This study uses the GDP of each province to measure the level of economic growth. Regional GDP can measure the economic conditions of the entire region and is a comprehensive indicator of economic performance. In this study, the price of each province in 1978 was used as the base price, and the price index was used to eliminate the impact of price level changes.

(3) Other control variables

Industrial Structure (IS): As different industries have specific demands for energy, structural changes are one of the factors that affect energy consumption. This study reflects the industrial structure based on the proportion of the output value of the secondary industry in each

![Fig. 1. The division of energy consumption levels in China’s 30 provinces.](image-url)
province in China in the total output value. The secondary industry includes mining, manufacturing, electricity, heat, gas and water production and supply, and construction.

Regional openness (OPEN): On the one hand, regional openness has led to the expansion of energy consumption. On the other hand, technological progress brought about by trade opening may improve energy efficiency. This study reflects the degree of regional openness based on the total import and export volume of each province in my country (by domestic destination and source of goods).

To reduce the errors caused by heteroscedasticity and avoid spurious regression, each variable is in logarithmic form. The descriptive statistics of the variables are shown in Table 1.

### 3.2. Measurement model

To quantitatively analyze the impact of China’s economic growth on energy consumption, this introduces panel data to build a model, as shown in Eq (1):

$$\ln TEC_{it} = a_0 \ln GDP_{it} + \beta X_{it} + \delta_t + \epsilon_i + \mu_{it}$$  

(1)

Among them, \(n\) represents the cross-sectional unit of provinces, and the benchmark model includes 30 provinces in China \(n = 1, 2, \ldots, 30\); \(t\) represents time, \(t = 2000, 2001, \ldots, 2017\); \(\ln TEC_{it}\) represents the logarithm of the total energy consumption; \(\ln GDP_{it}\) represents the logarithm of the GDP of each province, reflecting the economic growth of each province; \(\delta_t\) represents the time non-observation effect, which reflects the influence of non-time-varying factors other than the main variable, such as changes in policy and technology; \(\delta_t\) represents the regional non-observation effect, which reflects the persistent differences between provinces, such as different carbon emission patterns, differences in regulations, and differences in preferences due to differences in resource endowments. \(\mu_{it}\) is a random error term that has nothing to do with time and region. \(X_{it}\) is other control variables, including industrial structure, regional openness, etc. Equation (1) is a benchmark econometric regression model. To deeply explore the specific impact of economic growth on various subdivisions of energy, total coal consumption, natural gas consumption \(\ln COAL_{it}, \ln OIL_{it}, \ln GAS_{it}\), are respectively regressed as explained variables.

### 3.3. Estimation techniques

First, we use the panel unit root test to test the stability of each variable. Second, we use the panel cointegration test to determine the long-term cointegration relationship between variables. Next, the fixed-effect OLS and FMOLS cointegration estimates are used to analyze the long-term cointegration relationship between variables.

#### 3.3.1. Cross-sectional dependency (CSD) tests

To solve the cross-sectional dependency problem, we choose the Breusch-Pagan LM test proposed by Ref. [52], the Pesaran scaled LM test and the Pesaran CD test proposed by Ref. [53] to check the data cross-sectional dependence. Among them, the test of [52] is more suitable for small sample panels, and the formula is as Eq (2):

$$LM = \frac{1}{B(B-1)} \sum_{i=1}^{n} \sum_{m=1}^{M} A_{nm} \hat{\beta}_{m}^2 - 1 \sim B(0,1)$$  

(2)

Pesaran scaled LM test is suitable for large samples, and the formula is as Eq (3):

$$LM = \frac{1}{B(B-1)} \sum_{i=1}^{n} \sum_{m=1}^{M} A_{nm} \hat{\beta}_{m}^2 \sim B(0,1)$$  

(3)

A and B respectively represent the time dimension and the cross-sectional dimension. In this study, A = 18 and B = 30. \(\hat{\beta}_{m}\) is the error-related parameter. The LM test is based on the average of the residuals over the squares of the relevant parameters of the sample. The null hypothesis of the test is as follows: \(H_0: \hat{\beta}_{m} = 0, n \neq m\), which means that there is no cross-sectional correlation. \(H_1: \hat{\beta}_{m} \neq 0, n \neq m\), which means that there is cross-sectional correlation. But when \(n \rightarrow \infty\), the LM test may fail. The CD test proposed in Ref. [53] solves this problem, and the formula is as Eq (4):

$$CD = \frac{2}{B(B-1)} \sum_{i=1}^{n} \sum_{m=1}^{M} A_{nm} \hat{\beta}_{m}^2 \sim B(0,1)$$  

(4)

Among them, \(\hat{\beta}_{m}\) is the residual related statistics. A and B respectively represent the time dimension and the cross-sectional dimension.

#### 3.3.2. Panel unit root tests

The four unit root tests (LLC, IPS, Fisher-ADF and Fisher-PP) used in this study include the same root test and the different root test. If the result shows that the null hypothesis is accepted, that is to say, the null hypothesis exists, the variable is not stationary, and the result rejects the null hypothesis, the variable is stable.

Among them, the formula of LLC test is as Eq (5) [54]:

$$ \Delta Q_{df} = a_0 Y_{df,1} + \sum_{L=1}^{m} b_L a_0 Y_{df,-L} + c_0 d_{df} + e_{df}, \quad p = 1, 2, 3$$  

(5)

where \(a_0, b_L, c_0, d_{df}, e_{df}\) represent the autoregression coefficients, the corresponding vectors of the regression coefficients, and the corresponding vectors of the regression parameters are \(p = 1,2,3\). The principle of IPS testing is similar to that of LLC testing [55]. Besides, The different root test Fisher-PP was developed by Phillips and Perron [56]. The expressions are as Eq (6) and Eq (7):

$$FisherADF = - 2 \sum_{m} \log(Mq) \rightarrow P$$  

(6)

$$ChoiADF = \frac{1}{\sqrt{T-n}} \sum_{i=1}^{n} \theta^{-1}(Mq) \rightarrow K(0,1)$$  

(7)

where \(m, \theta^{-1}\) denotes the reciprocal of the normal distribution function, \(Mq\) denotes the P-value of the ADF unit root test. The null hypothesis is \(a_0 = 0\) there is a unit root; if \(a_0 < 0\) there is no unit root.

### Table 1

| Variable | Description | Unit | Mean | Standard Deviation | Maximum | Minimum |
|----------|-------------|------|------|--------------------|---------|---------|
| TEC      | Total energy consumption | 10,000 tons of standard coal | 11058.1651 | 7839.3337 | 38899 | 480 |
| COAL     | Coal consumption | Ten thousand tons | 10918.9578 | 9007.9454 | 42942.29 | 192 |
| OIL      | Oil consumption | Ten thousand tons | 1401.5720 | 1341.4886 | 7000.91 | 0.01 |
| GAS      | Natural gas consumption | One hundred million cubic meters | 37.1180 | 39.8312 | 237.69 | 0.01 |
| GDP      | Economic Growth | 100 million yuan | 2229.5138 | 2256.7408 | 14376.2714 | 60.7558 |
| IS       | Industrial structure | % | 0.4423 | 0.0787 | 0.5932 | 0.1901 |
| OPEN     | Regional openness | Ten thousand U.S. dollars | 802.0532 | 1725.3177 | 12812 | 1.6069 |
3.3.3. Panel cointegration tests

In this study, the panel Pedroni test [57] and Kao test [58] are selected. Cointegration test is used to investigate whether there is a cointegration relationship between variables. Pedroni’s cointegration test includes two important hypotheses: panel statistical test and outlier statistical test. Details as Eqs. (8)-(12):

$$F(\sqrt{PQ} \rightarrow F) \equiv F\sqrt{P}\left(\sum_{a=1}^{P} \sum_{b=1}^{Q} (L^{-2} \Delta_{a,b} - \theta_{a,b})\right)^{-1} \sum_{a=1}^{P} \sum_{b=1}^{Q} (L^{-2} \Delta_{a,b} - \theta_{a,b})$$

B. Panel- $\beta$

$$Q_{\Delta\beta}^{(p)} \equiv \left(\sum_{a=1}^{p} \sum_{b=1}^{q} (L^{-2} \Delta_{a,b} - \theta_{a,b})\right)^{-1} \sum_{a=1}^{p} \sum_{b=1}^{q} (L^{-2} \Delta_{a,b} - \theta_{a,b})$$

C. Group-$\beta$

$$FQ_{\Delta\beta}^{(p)} \equiv P^{-1} \sum_{a=1}^{P} \sum_{b=1}^{Q} (L^{-2} \Delta_{a,b} - \theta_{a,b})$$

D. Group- $\beta$

$$P^{-1} Q_{\Delta\beta}^{(p)} \equiv P^{-1} \sum_{a=1}^{P} \sum_{b=1}^{Q} (L^{-2} \Delta_{a,b} - \theta_{a,b})$$

where

$$\hat{\theta}_{a,b} = \frac{1}{2} (\hat{\mu}_{a,b} - \hat{\omega}_{a,b}), \quad \hat{\mu}_{a,b} = \frac{1}{P} \sum_{a=1}^{P} \hat{\mu}_{a,b}$$

3.3.4. Panel cointegration estimates

The cointegration test is followed by regression estimation. Ordinary Least Squares (OLS) and Fully Modified Least Squares (FMLS) are adopted. FMOLS is widely used in regression [59]. Compared with OLS estimation, FMOLS estimation can correct sequence correlation and prevent the occurrence of spurious regression. It is a more effective panel econometric technique. The equation proposed by Pedroni is as Eq. (13) [60]:

$$Y_{mt} = l_{mt} + m_{mt} + \sum_{p=1}^{P} \hat{\rho}_{mp} \Delta X_{mp} + \theta_{mt}$$

Define $\hat{\rho}_{mp} = (\hat{\rho}_{mp}, \Delta X_{mp})$, $\delta_{m} = \lim_{n \rightarrow \infty} E\left[\sum_{t=1}^{n} \frac{1}{n} \left(Y_{mt} - \bar{Y}_{m} - \bar{\Delta} X_{mp}ight)\right]$, $\delta_{m}$ is the long-term covariance. In this equation, $x$ and $Y_{mt}$ have a cointegration relationship. The long-term covariance can be decomposed into $\delta_{m} = \delta_{m}^{0} + \omega_{m} = \omega_{m}^{0}$, where $\omega_{m}^{0}$ is the weighted sum of the covariance, $\omega_{m}$ is the automatic covariance and $\omega_{m}$. The FMOLS criteria are as Eq. (14):

$$\hat{\alpha}_{\text{FMOLS}} = \frac{1}{Q} \sum_{a=1}^{P} \left[\frac{1}{Q} \sum_{t=1}^{Q} \frac{1}{Q} \sum_{m=1}^{Q} \left(Y_{mt} - \bar{Y}_{m} - \bar{\Delta} X_{mp}ight)\right]$$

where

$$\bar{Y}_{m} = Y_{mt} - (\hat{\delta}_{2,1,1} \bar{X}_{2,1,1}) / \hat{\omega}_{2,2,1,1}$$

(3.3.5. Panel granger causality test)

In this section, we used Engel and Granger’s multivariate panel-based Granger causality test to test for causality between variables [61]. Although it fails to adequately address the endogeneity problem, the method can be effectively implemented to examine the relationship between energy consumption and economic growth in a multivariate setting, rather than a bivariate setting [52]. This method is divided into two steps. The first step uses the OLS regression to estimate the residual according to the long-term parameters, and the residual is used as the right variable. The second step uses the right variable to estimate the short-term error correction model. The Granger causality test formula is as Eqs. (15)-(17):

$$\Delta TEC_{mn} = \gamma_{1m} + \sum_{i} \gamma_{12m} \Delta TEC_{mn-1} + \sum_{i} \gamma_{13m} \Delta GDP_{mn-1} + \sum_{i} \gamma_{14m} \Delta X_{mn-1} + \alpha_{1m} \Delta ECT_{mn-1} + \beta_{1m}$$

$$\Delta GDP_{mn} = \gamma_{2m} + \sum_{i} \gamma_{21m} \Delta TEC_{mn-1} + \sum_{i} \gamma_{22m} \Delta GDP_{mn-1} + \sum_{i} \gamma_{23m} \Delta X_{mn-1} + \alpha_{2m} \Delta ECT_{mn-1} + \beta_{2m}$$

$$\Delta X_{mn} = \gamma_{3m} + \sum_{i} \gamma_{31m} \Delta TEC_{mn-1} + \sum_{i} \gamma_{32m} \Delta GDP_{mn-1} + \sum_{i} \gamma_{33m} \Delta X_{mn-1} + \alpha_{3m} \Delta ECT_{mn-1} + \beta_{3m}$$

where $\Delta X_{mn}$ denotes the error correction term, hysteresis length and first-order difference of the variable respectively. In this study, the Akaike information standard is used to determine the optimal lag length.

4. Empirical results

4.1. Cross-sectional dependency (CSD) test results

Table A1 (in Appendix) shows the results of three cross-section dependence tests. According to the parameters obtained from the results, we find that all variables reject the null hypothesis at the 1% significance level, that is, reject the assumption of cross-section independence. In other words, all variables of the panel model in this study have cross-sectional dependence. For this phenomenon, we conduct a panel unit root test.

4.2. Unit root test results

According to the results in Table 2, the unit root test results support those 7 variables have unit roots in the levels, that is, the levels are non-stationary. After the first-order difference, all variables reject the null hypothesis, which means that all variables are stable after the first-order difference. Therefore, it can be considered that the variables selected in this study are first-order integration. This result supports our next long-term cointegration test.

4.3. Cointegration test results

To further investigate whether there is a long-term cointegration relationship between each group of variables, we adopted the Pedroni and Kao cointegration test. The results of the cointegration test for each group are shown in Table A2 and Table A3 (in Appendix). When exploring the impact of economic growth on the difference of energy consumption based on energy sources, the selected three sub-energy sources (coal, oil, and natural gas) are respectively used as the explained variables for regression, so the cointegration test should also be performed separately. Similarly, the high energy consumption region, middle energy consumption region, and the low energy consumption region are also tested for cointegration respectively. The Pedroni cointegration test provides seven statistics, most of which show rejection of the null hypothesis. The Kao test result also rejects the null hypothesis, so the results support a cointegration relationship between variables. Each group of variables will be cointegrated estimation in the next step.

4.4. Regression estimation results

According to the results of the cointegration test, there is a long-term cointegration relationship between total energy consumption, coal
consistent, which proves that our results are robust. We focus on differences. Industrial structure and trade openness are also included in energy consumption from the perspective of energy sources and regional differences. Our results support that energy consumption, and the structure effect on energy consumption through cointegration regression.

Note: ***, **, and * indicate that can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.

This work examines the relationship between economic growth and energy consumption from the perspective of energy sources and regional differences. Industrial structure and trade openness are also included in the equation as control variables. The results at the national level are shown in Table 3. The results of OLS regression and FMOLS regression show that the directions of the elastic coefficients of each variable are consistent, which proves that our results are robust. We focus on explaining the results of the panel FMOLS. It is not difficult to find that economic growth, industrial structure and regional openness are all significantly correlated with the explained variables at the 1% statistical level. This implies that regional GDP, industrial structure and trade openness have a close influence on total energy consumption. Specifically, the regression coefficient of lnGDP is 0.6993, that is to say, an increase in 1% of regional GDP can bring about a 0.6993% increase in energy consumption, which shows that China’s overall economic growth is still highly dependent on energy consumption. The regression coefficient between the industrial structure and the explained variable is 0.2162, which means that for every 1% increase in the output value of the secondary industry in GDP, energy consumption increases by 0.2162%. The secondary industry includes various industries and manufacturing industries, and its development inevitably needs to consume a large amount of fossil energy resources. Compared with the primary and tertiary industries, the secondary industry is highly dependent on energy resources [63]. The regression coefficient of trade openness is 0.0736, which means that the increase in trade openness can promote energy consumption. The degree of regional openness is positively correlated with total energy consumption. For China, the increase in total imports and exports has a positive effect on energy consumption. Trade has many ways of acting on energy consumption, including scale effect, structural effect, and technology effect [64]. Among them, the scale effect increases energy consumption, the technology effect reduces energy consumption, and the structure effect on energy consumption depends on specific regional conditions [65]. Our results support that the increase in the degree of regional openness in China’s provinces promotes energy consumption, which means that the sum of the technology and structural effects brought about by trade cannot offset the scale effect. Finally, the regression coefficient of lnGDP is much higher than that of lnIS (0.2162) and lnOPEN (0.0736). Compared with the industrial structure and regional openness, economic growth is the main driving force for energy consumption.

At the inter-provincial level, the results are shown in Table 4. The total energy consumption is selected as the dividing standard because existing studies have shown that the relationship between economic growth and energy consumption has non-linear characteristics [66,67]. Comparing the results of the three groups, lnGDP and lnTEC are both significantly correlated at a statistical level of 1%, which shows that regardless of the level of total energy consumption, economic growth is closely related to energy consumption growth. The difference is that the regression coefficients of lnGDP in the three groups. Specifically, for the high energy consumption region whose total energy consumption is higher than 190 million tons of standard coal, economic growth has a promotion effect of 0.6193 on the total energy consumption, which is the largest among the three groups; Next is the low energy consumption region with total energy consumption less than 100 million tons of standard coal. Economic growth has a promotion effect of 0.5815 on total energy consumption; The promotion effect for the middle energy consumption region between 100 and 190 million tons of standard coal is 0.4216, which is the weakest among the three groups. This result shows that the impact of economic growth on energy consumption is heterogeneous in energy consumption levels. The growth of energy consumption demand is more sensitive to economic changes in provinces with higher energy consumption, followed by provinces with the lowest energy consumption. The least sensitive are the provinces with medium energy consumption.

### Table 2
Unit root test results.

| Variables | LLC | IPS | ADF | PP-Fisher |
|-----------|-----|-----|-----|-----------|
| lnTEC (I(0)) | 1.0367 | 8.1139 | 34.4291 | 29.645 |
| lnCOAL (I(0)) | 4.4399 | 8.7338 | 18.9081 | 10.5975 |
| lnOIL (I(1)) | -3.2933*** | 0.0582 | 56.544 | 69.339 |
| lnGAS (I(0)) | -0.7111 | -0.5455 | 77.6073** | 167.3300*** |
| lnGDP | 3.1513 | 6.9294 | 27.0282 | 6.0355 |
| lnIS | -0.8201 | 0.3292 | 63.1201 | 46.8741 |
| lnOPEN (I(1)) | -2.1690** | 4.0686 | 36.0776 | 21.3132 |

#### Table 3
Regression results of national economic growth and total energy consumption.

| Variable | OLS | FMOLS |
|----------|-----|-------|
| lnGDP (Coefficient) | 0.5685*** | 0.6993*** |
| lnCOAL | 0.2701*** | 0.0545*** |
| lnGDP | 4.4150*** | 4.2402*** |

#### Table 4
Regression results of OLS and FMOLS.

| Coefficient | T value | P value | Coefficient | T value | P value |
|-------------|---------|---------|-------------|---------|---------|
| lnGDP | 21.8430 | 0.0000 | 12.9652 | 0.0000 |
| lnCOAL | 6.6582 | 0.0000 | 4.8028 | 0.0000 |
| lnGDP | 3.0210 | 0.0026 | 0.0736*** | 5.4936 | 0.0000 |
| lnIS | 33.0776 | 0.0000 | 21.3132*** | 272.3120*** |
| lnOPEN | 4.2402*** | 0.0000 | 307.4720*** | 110.8540*** |

Note: ***, **, and * indicate that can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.
Table 4
Regression results of economic growth and total energy consumption at the provincial level.

| Variable | High energy consumption region | Middle energy consumption region | Low energy consumption region |
|----------|--------------------------------|----------------------------------|-------------------------------|
|          | OLS | FMOLS | Statistics | P value | OLS | FMOLS | Statistics | P value | OLS | FMOLS | Statistics | P value |
| lnGDP    | 0.6621*** | 0.0000 | 0.6193*** | 0.0000 | 0.4393*** | 0.0000 | 0.4216*** | 0.0000 | 0.6061*** | 0.0000 | 0.5815*** | 0.0000 |
| lnIS     | 0.5207*** | 0.0000 | 0.4476*** | 0.0000 | 0.1516*  | 0.0598 | 0.0865*  | 0.0706 | 0.6101*** | 0.0000 | 0.5920*** | 0.0001 |
| lnOPEN   | 0.0039 (0.1327) | 0.8946 (1.7102) | 0.0320* (17.6447) | 0.0892 | 0.1602** | 0.0000 | 0.1752** | 0.0000 | -0.0079 (21.6984) | 0.8040 (10.6223) | 0.0312 (2.3045) | 0.2291 |
| C        | 4.7974*** (25.1390) | 0.0000 | 3.6258*** (16.6727) | 0.0000 |

Note: ***, **, and * indicate that can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.

Table 5
Regression results of economic growth and different sources of energy consumption.

| Variable | lnCOAL | lnOIL | lnGAS |
|----------|--------|-------|-------|
|          | OLS | FMOLS | Statistics | P value | OLS | FMOLS | Statistics | P value | OLS | FMOLS | Statistics | P value |
| lnGDP    | 0.47701*** (10.411) | 0.0000 | 0.4736*** (10.036) | 0.0000 | 0.1111 (11.124) | 0.4841 | 1.5581*** (32.3830) | 0.0000 | 1.8362*** (10.822) | 0.0000 | 0.8191*** (16.6727) | 0.0000 |
| lnIS     | 0.8809*** (8.4346) | 0.0000 | 0.3883*** (7.0307) | 0.0000 | 0.6803* (1.6716) | 0.0952 | 1.8463*** (32.3609) | 0.0000 | 0.5566 (1.9326) | 0.1644 | 2.4669*** (42.2149) | 0.0000 |
| lnOPEN   | 0.0656*** (2.0662) | 0.0393 (2.7538) | 0.1802*** (5.7609) | 0.0062 | 0.5167*** (17.6447) | 0.0000 | 1.5453*** (22.3867) | 0.0000 | -0.1339 (14.2415) | 0.2591 | -0.5610*** (8.3862) | 0.0000 |
| C        | 5.2339*** (22.2775) | 0.0000 | -1.3105 (21.6984) | 0.0000 | 0.1124 (15.994) | 0.0000 | -8.1676*** (17.2135) | 0.0000 | -8.3219 (19.4648) | 0.0000 |

Note: ***, **, and * indicate that can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.

Table 6
Granger causality results of different types of energy consumption and economic growth in China.

| Null Hypothesis | F-Statistic | Prob. |
|-----------------|-------------|-------|
| lnGDP does not Granger Cause lnTEC | 6.6550*** | 0.0002 |
| lnTEC does not Granger Cause lnGDP | 7.5463*** | 0.0006 |
| lnOPEN does not Granger Cause lnTEC | 2.5806* | 0.0768 |
| lnTEC does not Granger Cause lnOPEN | 9.7175*** | 0.0001 |
| lnIS does not Granger Cause lnTEC | 6.4075*** | 0.0018 |
| lnTEC does not Granger Cause lnIS | 19.4557*** | 0.0000 |
| lnGDP does not Granger Cause lnCOAL | 24.1625*** | 0.0000 |
| lnCOAL does not Granger Cause lnGDP | 4.6238*** | 0.0103 |
| lnOPEN does not Granger Cause lnCOAL | 12.5296*** | 0.0000 |
| lnCOAL does not Granger Cause lnOPEN | 5.9593*** | 0.0040 |
| lnIS does not Granger Cause lnCOAL | 11.6859*** | 0.0000 |
| lnCOAL does not Granger Cause lnIS | 7.7984*** | 0.0005 |
| lnGDP does not Granger Cause lnOIL | 1.7229 | 0.1798 |
| lnOIL does not Granger Cause lnGDP | 0.7673 | 0.4649 |
| lnOPEN does not Granger Cause lnOIL | 2.0571 | 0.1291 |
| lnIS does not Granger Cause lnOIL | 1.6721 | 0.1891 |
| lnIS does not Granger Cause lnIS | 0.2504 | 0.7786 |
| lnIS does not Granger Cause lnGDP | 3.5980*** | 0.0282 |
| lnGDP does not Granger Cause lnGAS | 6.9807*** | 0.0010 |
| lnGAS does not Granger Cause lnGDP | 12.4659*** | 0.0000 |
| lnIS does not Granger Cause lnOPEN | 11.4698*** | 0.0000 |
| lnGAS does not Granger Cause lnIS | 2.8869* | 0.0568 |
| lnIS does not Granger Cause lnGAS | 0.5877 | 0.5561 |
| lnGAS does not Granger Cause lnIS | 0.0614*** | 0.0000 |
| lnOPEN does not Granger Cause lnGDP | 2.8785* | 0.6572 |
| lnIS does not Granger Cause lnIS | 18.0967*** | 0.0000 |
| lnIS does not Granger Cause lnGDP | 1.9574 | 0.1424 |
| lnIS does not Granger Cause lnGAS | 21.0017*** | 0.0000 |
| lnGAS does not Granger Cause lnOPEN | 10.6223*** | 0.0000 |
| lnIS does not Granger Cause lnIS | 13.9547*** | 0.0000 |

Note: ***, **, and * indicate that can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.

From Table 6 and Fig. 2, bidirectional Granger causality from economic growth to energy consumption, coal consumption, and gas consumption was found at the national level. This validates the Feedback causality for the case of China. In addition, there is a bidirectional Granger causality running from energy consumption, coal consumption, gas consumption and trade openness. The results also indicate short-run unidirectional panel causality running from gas consumption and oil consumption toward industrial structure. Table 7 shows the results of Granger causality at the regional level. Among them, the Granger causality is the most complex in the high energy consumption region, followed by the low energy consumption region, and the simplest in the middle energy consumption region. Specifically, high energy consumption region shows a bidirectional Granger causality between economic growth and energy consumption. However, there is a unidirectional Granger causality between economic growth and energy consumption in low energy consumption region. Furthermore, energy consumption and trade openness show a bidirectional Granger causality in high energy consumption region and a unidirectional Granger causality in middle energy consumption region. Between energy consumption and industrial structure, all regions show a unidirectional Granger causality between energy consumption and industrial structure.

5. Discussion of energy consumption of China’s economic recovery of post-Covid-19

5.1. Insights from energy sources

Table 5 shows the regression results of economic growth and different sources of energy consumption. Among fossil energy sources, China’s economic recovery has the greatest driving effect on oil.
For every 1% increase in GDP, the consumption of coal increases by 0.4736%. According to data from the National Bureau of Statistics of China, as the world’s largest coal consumer, China’s coal consumption has increased for the fourth consecutive year in 2020 [77]. In 2020, coal consumption accounted for 56.8% of total energy consumption, a decrease of 0.9% points from the previous year. Under the direction of green development and low-carbon development of China’s energy revolution, relevant departments in various regions are also promoting continuous innovation in the coal industry [78]. In recent years, the proportion of coal in energy consumption has continued to decline in China. This may be the reason why the elasticity coefficient of coal energy and the economy is smaller than that of oil and natural gas. However, due to the abundant coal resources in China and the relatively large proportion of thermal power generation, coal still holds a strong position as the main energy source. Therefore, coal consumption still has a significant positive correlation with China’s economic growth.

5.2. Insights from regional different

Fig. 3 illustrates the spatial distribution of the relationship between energy consumption and economic growth in China 30 provinces. For high energy consumption region, the elasticity coefficient of GDP to energy consumption is the largest. High energy consumption region includes Shandong, Guangdong, Jiangsu, Hebei, Henan, Liaoning, Hubei, Jiangsu, Sichuan, Shanxi, and Inner Mongolia. Among them, Jiangsu and Zhejiang belong to the Yangtze River Delta region of China. As China’s economic center, the terminal energy consumption is the largest, but it is energy-scarce areas. Due to the high dependence on inputs from outside, energy supply is facing tremendous pressure. Guangdong Province belongs to the Pearl River Delta region and is the frontier of China’s reform and opening up. Like the Yangtze River Delta region, the Pearl River Delta region is an energy importing region [79]. However, Liaoning and Shanxi used to be China’s important industrial and energy supply bases and typical energy output regions, with huge coal production [80]. During the recovery period of China’s economy, as the region where energy consumption is most affected by economic growth, high energy consumption region first faced huge energy consumption demand. Zhejiang, Inner Mongolia, and Guangdong all implemented power curtailment policies. For low energy consumption region, Beijing has entered a post-industrial development stage, and Tianjin has basically completed industrialization. The rapid development of social economy has brought about a continuous increase in the total energy consumption [81], which has intensified the degree of external dependence on regional energy supply. The overall situation of energy shortage is present. In addition, Ningxia and Chongqing are important bases for China’s “West-to-East coal transportation”, “West-to-East gas transmission” and “West-to-East power transmission”, and are important cornerstones for ensuring energy security [82]. The energy consumption brought about by economic growth in the eastern region has finally been implemented in these resource-based provinces. Therefore, in the context of rapid economic growth, the energy consumption of the low energy consumption region is second only to the high energy consumption region.

6. Conclusions and policy implications

This study uses the data of 30 provinces in China from 2000 to 2017 to analyze the relationship between economic growth and energy consumption through the energy consumption functions. The conclusions are as follows: First, the total energy consumption is positively affected by economic growth, industrial structure, and trade openness. Economic

### Table 7

Granger causality results of energy consumption and economic growth in different regions.

| Null Hypothesis | High energy consumption region | Middle energy consumption region | Low energy consumption region |
|-----------------|-------------------------------|---------------------------------|-------------------------------|
| lnGDP does not Granger Cause lnTEC | F-Statistic 7.9765*** | F-Statistic 2.3111 | F-Statistic 3.5349** |
| lnTEC does not Granger Cause lnGDP | 9.1872*** | 1.0809 | 0.4046 |
| lnIS does not Granger Cause lnOPEN | 2.5188* | 0.1395 | 1.5150 |
| lnIS does not Granger Cause lnTEC | 4.1131** | 6.5622*** | 2.1680 |
| lnOPEN does not Granger Cause lnTEC | 1.9170 | 1.4601 | 2.1938 |
| lnTEC does not Granger Cause lnIS | 11.3852*** | 10.9663*** | 4.9932*** |
| lnOPEN does not Granger Cause lnGDP | 0.7841 | 6.1202*** | 1.4358 |
| lnGDP does not Granger Cause lnIS | 3.0494* | 7.7562*** | 10.1951*** |
| lnIS does not Granger Cause lnGDP | 1.0063 | 0.4061 | 0.7839 |
| lnIS does not Granger Cause lnTEC | 9.0099*** | 10.5939*** | 8.1922*** |
| lnIS does not Granger Cause lnOPEN | 0.6602 | 5.9434*** | 5.5242*** |
| lnOPEN does not Granger Cause lnIS | 4.2876*** | 3.6509** | 9.0304*** |

Note: ***, **, and * indicate that can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.

consumption.

The 1% economic recovery has driven the demand for gas consumption to increase by 0.8191%, second only to oil consumption. Actually, natural gas has become an important transitional energy in the process of China’s energy transition due to its higher combustion efficiency and lower carbon emissions [75]. Over the past two decades, China’s natural gas market has been in short supply, with consumption growth exceeding 10% in most years. Even in 2020, which is affected by the epidemic, relatively rapid growth has been achieved. In the future, China’s policy of accelerating natural gas exploration and development will not change [76]. Therefore, in the context of China’s rapid economic recovery in the post-epidemic era, the demand for natural gas energy has also grown significantly.
growth has the greatest impact on total energy consumption, which is 0.6993. Second, for various fossil energy, the consumption of oil is most driven by economic growth, at 1.5581, followed by natural gas consumption at 0.8191, and coal consumption at 0.4736. Third, the relationship between energy consumption and economic growth in each province has a regional difference. The promotion of economic growth on energy consumption is strongest in provinces with high energy consumption, followed by provinces with low energy consumption, and the weakest in provinces with middle energy consumption.

An energy security reserve system must be established to ensure the security of energy supply in the post-Covid-19 stage and four measures can be taken. First, the scale of strategic oil reserves needs to be expanded. The conclusion shows that China’s economic recovery after COVID-19 increases oil consumption demand dramatically. However, China’s domestic oil supply cannot meet the demand and the current dependence on foreign oil exceeds 70%. To prevent the scale of strategic

Fig. 2. Schematic diagram of Granger causality test at national and regional level.

Fig. 3. The spatial distribution of the relationship between economic growth and total energy consumption in China 30 provinces.
oil reserves from being unable to meet the needs of national strategic
security, the Chinese government may consider expanding the scale of
strategic oil reserves by taking advantage of the short-term oil price
situation. Second, the rupture of the natural gas industry chain must be
avoided and relevant measures must be implemented to make the nat-
ural gas market stable and guide the development of the industry. Third,
the National Energy Administration and coal production enterprises
need to work together to ensure a stable supply of coal. As China’s basic
energy source, a stable supply of coal must be ensured. In the early days
of the epidemic, the failure of production recovery resulted in a tight
coal supply side. The imbalance between supply and demand in the coal
market will continue in the short term. Under this condition, the Na-
tional Energy Administration should strengthen the information
communication between coal transfer places and improve the tripartite
connection among production, transportation and demand to ensure
that the national thermal coal reserve is at a reasonable level. At the
meantime, coal production enterprises should adhere to scientific pro-
duction, storage and transportation infrastructure. For the old industrial
districts such as Shanxi, Jilin, Heilongjiang, Liaoning and energy-rich
regions such as Xinjiang, Ningxia, and Inner Mongolia, the energy
resource potential must be fully utilized to guarantee the national en-
ergy security supply. With the large regional differences shown above,
both the regional resource potential and the status quo of energy system
should be considered to promote the cross-regional energy cooperation.

Further research can be carried out from the following aspects.
Firstly, a forecasting model can be added if further quarterly data is
available. The regional economic growth rate in the late stage of COVID-
19 can be obtained through the prediction model, and then combined
with the cointegration model in this study, the prediction of future en-
ergy consumption can be achieved [83]. Secondly, with the change of
China’s energy structure, the status of renewable energy cannot be
ignored. Therefore, renewable energy can be further included in the
energy consumption function if renewable energy consumption data can
be obtained. Third, categorizing regions based on energy consumption
levels alone does not fully address the issue of heterogeneity. Further
exploration of heterogeneity based on the structural fracture hypothesis
can be performed if nonlinear panel regression techniques can be
employed.

Author contribution statement
Qiang Wang: Conceptualization, Methodology, Software, Data
curation, Writing – original draft preparation, Supervision, Writing-
Reviewing and Editing. Fuyu Zhang: Methodology, Software, Data
curation, Investigation Writing – original draft, Writing- Reviewing
and Editing. Rongrong Li: Conceptualization, Methodology, Software,
Methodology, Data curation, Investigation Writing – original draft,
Writing- Reviewing. Lejia Li, Methodology, Software, Methodology,
Data curation, Investigation.

Declaration of competing interest
The authors declare that they have no known competing financial
interests or personal relationships that could have appeared to influ-
ence the work reported in this paper.

Acknowledgement
The authors would like to thank the editor and these five anonymous
reviewers for their helpful and constructive comments during the four
rounds of review, which greatly contributed to improving the final
version of the manuscript.

Appendix A

Table A1 Cross-sectional dependence tests results.

| Variables | Breusch-Pagan LM test | Pesaran scaled LM test | Pesaran CD test |
|-----------|-----------------------|-----------------------|----------------|
|           | Statistic             | P-value               | Statistic      | P-value | Statistic | P-value |
| lnTEC     | 7237.5170***         | 0.0000                | 230.6269***    | 0.0000  | 84.8822*** | 0.0000  |
| lnCOAL    | 5906.9630***         | 0.0000                | 185.3135***    | 0.0000  | 69.8754*** | 0.0000  |
| lnGAS     | 3209.7940***         | 0.0000                | 94.0743***     | 0.0000  | 45.5230*** | 0.0000  |
| lnGDP     | 4718.0620***         | 0.0000                | 145.2094***    | 0.0000  | 65.4208*** | 0.0000  |
| lnIS      | 7714.1750***         | 0.0000                | 246.7874***    | 0.0000  | 87.6274*** | 0.0000  |
| lnOPEN    | 3313.2940***         | 0.0000                | 97.5833***     | 0.0000  | 43.7949*** | 0.0000  |

Note: ***, **, and * indicate that can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.

Table A2 Cointegration test results of different types of energy consumption and economic growth

| Explained variable | Total energy consumption | Coal consumption | Oil consumption | Natural gas consumption |
|--------------------|--------------------------|------------------|----------------|------------------------|
| Pedroni Cointegration Test | Statistics | P value | Statistics | P value | Statistics | P value | Statistics | P value |
| Panel v-Statistic   | 40.5625***               | 0.0000           | -1.0336        | 0.8493                | 1.9030**        | 0.0285      | 0.5022         | 0.3078       |
| Panel rho-statistic | 3.7157                   | 0.9999           | 2.8536         | 0.9978                | 0.4664         | 0.6795       | 0.4260         | 0.6650       |
| Panel PP-statistic  | 0.4090                   | 0.6587           | -4.3305***     | 0.0000                | -3.5285***     | 0.0002       | -4.2808***    | 0.0000       |
| Panel ADF-statistic | -2.3217**                | 0.0101           | -4.2904***     | 0.0000                | -4.5770***     | 0.0000       | -4.5338***    | 0.0000       |
| Group rho-statistic | 5.0084                   | 1.0000           | 4.8608         | 1.0000                | 2.2374         | 0.9874       | 2.4359         | 0.9926       |

(continued on next page)
Table A2 (continued)

| Pedroni Cointegration Test | Total energy consumption | Coal consumption | Oil consumption | Natural gas consumption |
|----------------------------|--------------------------|------------------|-----------------|-------------------------|
| Group PP-statistic         | –3.1322***               | –4.1215***       | –6.2266***      | –8.5190***              |
| Group ADF-statistic        | –2.6831***               | –5.5972***       | –6.7703***      | –7.5637***              |

| Kao Cointegration Test | Statistics | P value | Statistics | P value | Statistics | P value | Statistics | P value |
|-----------------------|------------|---------|------------|---------|------------|---------|------------|---------|
| ADF                   | –3.2901*** | 0.0005  | 1.7327*    | 0.0416  | –4.8174*** | 0.0000  | –5.4623*** | 0.0000  |
| Residual variance     | 0.0055     | 0.0095  | 0.0086     |         | 0.0078     |         | 0.0078     |         |
| HAC variance          | 0.0078     | 0.0140  | 0.0130     |         | 0.0114     |         |           |         |

Note: ***, **, and * indicate that can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.

Table A3

| Region                  | High energy consumption region | Middle energy consumption region | Low energy consumption region |
|-------------------------|--------------------------------|----------------------------------|-----------------------------|
| Pedroni Cointegration Test | Statistics | P value | Statistics | P value | Statistics | P value |
| Panel v-Statistic       | –0.6375 | 0.7381 | 10.9828*** | 0.0000 | 5.9558*** | 0.0000 |
| Panel PP-statistic      | –1.8800** | 0.0301 | –2.6417*** | 0.0041 | –7.2421*** | 0.0000 |
| Panel ADF-statistic     | –2.7421*** | 0.0031 | –3.0420 | 0.0012 | –8.9484*** | 0.0000 |
| Group rho-statistic     | 1.8353 | 0.9668 | 2.3201 | 0.9988 | 1.5649 | 0.9390 |
| Group PP-statistic      | –3.8153*** | 0.0001 | –5.0638*** | 0.0000 | –9.8837*** | 0.0000 |
| Group ADF-statistic     | –3.6534*** | 0.0001 | –4.7324*** | 0.0000 | –8.2984*** | 0.0000 |

| Kao Cointegration Test | Statistics | P value | Statistics | P value | Statistics | P value |
|-----------------------|------------|---------|------------|---------|------------|---------|
| ADF                   | –5.5238*** | 0.0000 | 1.9781** | 0.0240 | –1.4868* | 0.0685 |
| Residual variance     | 0.0034     | 0.0015  | 0.0025     |         | 0.0020     |         |
| HAC variance          | 0.0039     |         |           |         |           |         |

Note: ***, **, and * indicate that can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.

References

[1] A. Atkinson, What will be the economic impact of covid-19 in the us? Rough estimates of disease scenarios, Labor. Demographics & Economics of the Family Journal (2020).
[2] Y. Qiu, X. Chen, W. Shi, Impacts of Social and Economic Factors on the Transmission of Coronavirus Disease 2019 (COVID-19) in China, medRxiv, 2020.
[3] C. de Waal, J. de Waal, F. Halicioglu, An econometric study of CO2 emissions, energy consumption, and GDP in Greece, Energy 137 (2017) 518–526.
[4] J. Sakti, S. Hammami, The impact of energy consumption and CO2 emissions on economic growth: fresh evidence from dynamic simultaneous-equations models, Energy Sources 42 (2020) 1785–1795.
[5] U. Soytas, R. Sari, Energy consumption and GDP: causality relationship in G-7 countries and emerging markets, Energy Econ. 25 (2003) 33–37.
[6] D. Dogan, D. Balsalobre-Lorente, M.A. Naser, European commitment to COP21 and the role of energy consumption, FDI, trade and economic complexity in sustaining economic growth, J. Environ. Manag. 273 (2020), 111146.
[7] B. Dogan, D. Balsalobre-Lorente, M.A. Nasir, European commitment to COP21 and the role of energy consumption, FDI, trade and economic complexity in sustaining economic growth, J. Environ. Manag. 273 (2020), 111146.
[8] E. Yu, B.-K. Kwang, The relationship between energy and GDP: further results, Energy Econ. 6 (1984) 186–190.
[9] A. Akcara, T.V. Long, Energy and employment: a time-series analysis of the causal relationship, Resour. Energy 2 (1979) 151–162.
[10] F. Fallahi, Causal relationship between energy consumption (EC) and GDP: a Markov-switching (MS) causality, Energy 36 (2011) 4165–4170.
[11] F. Emirmahmutoglu, Z. Denaux, M. Topcu, Time-varying causality between energy consumption and economic growth, Energy 321 (2019) 180–188.
[12] F. Fallahi, Causal relationship between energy consumption (EC) and GDP: a Markov-switching (MS) causality, Energy 36 (2011) 4165–4170.
[13] M. Soares, S. Anvar, Causal relationship between trade openness, economic growth and energy consumption: a panel data analysis of Asian countries, Energy Pol. 69 (2014) 82–91.
[14] N. Bowden, J.E. Payne, The causal relationship between U.S. energy consumption and real output: a disaggregated analysis, J. Pol. Model. 31 (2009) 180–188.
[15] S. Nair, S. Anvar, Causal relationship between trade openness, economic growth and energy consumption: a panel data analysis of Asian countries, Energy Pol. 69 (2014) 82–91.
[16] S.S. Akadiri, A.A. Alola, O. Usman, Energy mix outlook and the EKC hypothesis in BRICS countries: a perspective of economic freedom vs. economic growth, Environ. Sci. Pollut. Control Ser. 28 (2021) 8922–8926.
[17] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[18] P.F. Rupani, M. Nilashi, R.A. Abumalloh, S. Asadi, S.A. Samad, S. Wang, G. Feng, H. Yang, Q. Gong, C.-p. Chang, What is the exchange rate volatility based on the effective management of energy consumption during the COVID-19 pandemic: the response to COVID-19 and government interventions? Econ. Anal. Pol. 69 (2021).
[19] C. de Waal, J. de Waal, F. Halicioglu, An econometric study of CO2 emissions, energy consumption, and GDP in Greece, Energy 137 (2017) 518–526.
[20] T. Goh, Y. Jin, M. Tvaronavičienė, M. Cienienu, M. Raudeliūnienė, T. Veinys, F. Esmail, O. Iškutis, L. Lukšienė, J. Raudeliūnienė, T. Veinys, S. Asadi, S.A. Samad, S. Wang, G. Feng, H. Yang, Q. Gong, C.-p. Chang, What is the exchange rate volatility based on the effective management of energy consumption during the COVID-19 pandemic: the response to COVID-19 and government interventions? Econ. Anal. Pol. 69 (2021).
[21] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[22] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[23] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[24] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[25] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[26] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[27] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[28] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[29] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[30] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
[31] N. Fernandes, Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy, IBESE Business Working Paper Series, 2020.
empirical analysis of China’s Yangtze River Delta Region, Ecol. Complex. 44 (2020), 100701.

[36] P. Sadorsky, Renewable energy consumption and income in emerging economies, Energy Pol. 37 (2009) 4021–4028.

[37] A.N. Menegaki, Growth and renewable energy in Europe: a random effect model with evidence for neutrality hypothesis, Energy Econ. 33 (2011) 257–263.

[38] C.-C. Lee, The causality relationship between energy consumption and GDP in G-11 countries revisited, Energy Pol. 34 (2006) 1086–1093.

[39] N. Apergis, J.E. Payne, CO2 emissions, energy usage, and output in Central America, Energy Pol. 37 (2009) 3282–3286.

[40] Y. Hao, L.-G. Wang, C.-C. Lee, Financial development, energy consumption and China’s economic growth: new evidence from provincial panel data, Int. Rev. Econ. Finance 69 (2020) 1132–1151.

[41] M. Saldivia, W. Kristjanpoller, J.E. Olson, Energy consumption and GDP revisited: a new panel data approach with wavelet decomposition, Appl. Energy 272 (2020), 115207.

[42] M. Bhattacharya, S. Rafiq, S. Bhattacharya, The role of technology on the dynamics of coal consumption-economic growth: new evidence from China, Appl. Energy 154 (2015) 686–695.

[43] R. Li, G.C.K. Leung, Coal consumption and economic growth in China, Energy Pol. 40 (2012) 438–442.

[44] M.E. Bildirici, T. Bakirtas, The relationship among oil, natural gas and coal consumption and economic growth in BRICs (Brazil, Russian, India, China, Turkey and South Africa) countries, Energy 65 (2014) 134–144.

[45] T. Jin, J.-S. Kim, Coal consumption and economic growth: panel cointegration and causality evidence from OECD and non-OECD countries, Sustainability 10 (2018) 660.

[46] Q. Wang, S. Li, M. Zhang, R. Li, Impact of COVID-19 pandemic on oil consumption in the United States: a new estimation approach, Energy 239 (2022), 122280.

[47] Y. Zheng, D. Luo, Industrial structure and oil consumption growth path of China: empirical evidence, Energy 57 (2013) 336–343.

[48] G. Zhou, K.W. Chau, Short- and long-run effects between oil consumption and economic growth in China, Energy Pol. 34 (2006) 3644–3655.

[49] H. Nazer, Analysing the long-run relationship among oil market, nuclear energy consumption, and economic growth: an evidence from emerging economies, Energy 89 (2015) 421–434.

[50] Z.-G. Li, H. Cheng, T.-Y. Gu, Research on dynamic relationship between natural gas consumption and economic growth in China, Struct. Change Econ. Dynam. 49 (2019) 334–339.

[51] C. Magazzino, M. Mele, N. Schneider, A D2C algorithm on the natural gas economic growth: new insight from difference between pandemic-free scenario and actual electricity consumption in China, J. Clean. Prod. 313 (2021), 127897.