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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.
Forecasting Energy Consumption of China's Economic Recovery post-Covid-19 Pandemic: Insights from Energy Sources and Regional Different

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Declaration of interests
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Forecasting Energy Consumption of China's Economic Recovery of post-Covid-19 Pandemic:

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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 stable energy supply and sustainable economic development requires accurate estimation energy consumption of China's economic recovery of post-Covid-19 pandemic. 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 economic growth between regional energy consumption equations with different energy consumption levels 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.

Keywords: Energy consumption; economic growth; China; regional differences;
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]. 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 at the lowest point in 30 years[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 pandemic. The relationship between
economic growth and energy consumption has always been a research hotspot[14, 15].
In general, these two variables for countries with different economic structures relates
to different stages of economic development[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 energy 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 in the US energy sector.
and actual GDP. The results of the time-varying causality technique show that all
departments have detected causality in different time periods [33]. There are also
some studies that focus on cities. Taking Anhui Province as an example, Ge et al.
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 in 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 different 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, Jiangsu, Liaoning, Inner Mongolia, Shandong, Shanxi, Sichuan, Zhejiang). Ten provinces with total energy consumption between 100-190 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
stand standard coal are called low energy consumption regions (Hainan, Qinghai, Hubei, Ningxia, Beijing, Gansu, Tianjin, Jilin, Jiangxi, Chongqing) (as shown in Figure 1).

Figure 1. The division of energy consumption levels in China's 30 provinces.

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 an energy consumption function 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 difference of the impact 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. Explanatory variables.

(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 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): There is no consensus on the impact of foreign trade on energy consumption in academia. 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
good (by domestic destination and source of goods).

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

Table 1. Statistical description of variables

| 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            | 2329.5138  | 2326.7408          | 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   |

3.2 Measurement model

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

$$\ln TEC_{nt} = \alpha_1 \ln GDP_{nt} + \beta X_{nt} + \delta_n + \epsilon_t + \mu_{nt}$$

Among them, n represents the cross-sectional unit of provinces, and the
benchmark model includes 30 provinces in China n=1, 2, …, 30; t represents time,
t=2000, 2001, …, 2017; $\ln TEC_{nt}$ represents the logarithm of the total energy
consumption; $\ln GDP_{nt}$ represents the logarithm of the GDP of each province,
reflecting the economic growth of each province; $\epsilon_t$ represents the time
non-observation effect, which reflects the influence of time-varying factors other than the main variable, such as changes in policy and technology. $\delta_n$ 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. $\mu_{nt}$ is a random error term that has nothing to do with time and region. $X_{nt}$ 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, coal consumption $lnCOAL_{nt}$, oil consumption $lnOIL_{nt}$, natural gas consumption $lnGAS_{nt}$ 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 [52], the Pesaran scaled LM test and the Pesaran CD test proposed by [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):

$$LM = \sum_{n}^{B-1} \sum_{m=n+1}^{B} A_{nm} \tilde{\beta}_{nm}^2 \rightarrow \chi^2 \frac{B(B-1)}{2}$$  \hspace{1cm} (2)

Pesaran scaled LM test is suitable for large samples, and the formula is as Eq (3)
LM = \sqrt{\frac{1}{B(B-1)} \sum_{n=1}^{B-1} \sum_{m=n+1}^{B} (A_{nm} \hat{\beta}_{nm}^2 - 1)} \rightarrow B(0,1) \quad (3)

A and B respectively represent the time dimension and the cross-sectional dimension. In this study, A=18 and B=30. \( \hat{\beta}_{nm}^2 \) 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: \( H_0: \hat{\beta}_{nm} = 0, n \neq m \), which means that there is no cross-sectional correlation, \( H_1: \hat{\beta}_{nm} \neq 0, n \neq m \), which means that there is cross-sectional correlation. But when \( n \rightarrow \infty \), the LM test may fail. The CD test proposed in [53] solves this problem, and the formula is as Eq (4):

\[ \text{CD} = \sqrt{\frac{2}{B(B-1)} \sum_{n=1}^{B-1} \sum_{m=n+1}^{B} A_{nm} \hat{\beta}_{nm}^2} \rightarrow B(0,1) \quad (4) \]

Among them, \( \hat{\beta}_{nm}^2 \) 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]:

\[ \Delta Q_{ef} = a_{ef} Y_{ef-1} + \sum_{p=1}^{3} b_{pe} \Delta Y_{ef-L} + c_{pe} d_{pf} + e_{ef}, \quad p = 1, 2, 3 \quad (5) \]

Where \( a_i \), \( c_{pe} \), \( d_{pf} \), \( e_{ef} \) 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):

\[ \text{Fisher}_\text{ADF} = -2 \sum_{m}^{p} \log(Mq) \rightarrow P \]  
\[ \text{Choi}_\text{ADF} = \frac{1}{\sqrt{T_{m-1}}} \sum_{m-1}^{K} \theta^{-1} \log(Mq) \rightarrow K(0,1) \]  

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 \( a_i=0 \) there is a unit root; if \( a_i<0 \) there is no unit root.

### 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 Eq (8) - Eq (12):

**A. Panel-\( \rho \)**

\[ F \sqrt{PQ_{\hat{\rho}_{A,F-1}}(P)} = F\sqrt{\left( \sum_{a=1}^{P} \sum_{\beta=1}^{F} \hat{L}_{11a}^{2} \epsilon_{a,\beta-1} \right)^{-1} \sum_{a=1}^{P} \sum_{\beta=1}^{F} \hat{L}_{11a}^{2} \left( \epsilon_{a,\beta-1} \Delta \hat{\epsilon}_{a,\beta} - \tilde{\theta}_{a} \right)} \]  

**B. Panel-\( \beta \)**

\[ Q_{\alpha,F} = (S_{P,F}^{2} \sum_{a=1}^{P} \sum_{\beta=1}^{F} \hat{L}_{11a}^{2} \epsilon_{a,\beta-1}^{2} \right)^{-\frac{1}{2}} \sum_{a=1}^{P} \sum_{\beta=1}^{F} \hat{L}_{11a}^{2} \epsilon_{a,\beta-1} \Delta \hat{\epsilon}_{a,\beta} \]  

**C. Group-\( \rho \)**

\[ F \hat{Q}_{\hat{\rho}_{A,F-1}} = F \left( \sum_{a=1}^{F} \left( \sum_{\beta=1}^{P} \epsilon_{a,\beta-1}^{2} \right)^{-1} \sum_{\beta=1}^{F} \left( \hat{\epsilon}_{a,\beta-1} \Delta \hat{\epsilon}_{a,\beta} - \tilde{\theta}_{a} \right) \right) \]  

**D. Group-\( \beta \)**
where

\[ \hat{\theta}_\alpha = \frac{1}{2}(\hat{\mu}_\alpha^2 - \hat{s}_\alpha^2); s^2_{F,P} = \frac{1}{P} \sum \alpha s^2_{\alpha} \] (12)

### 3.3.4 Panel cointegration estimates

The cointegration test is followed by regression estimation. Ordinary Least Squares (OLS) and Fully Modified Least Squares (FMOLS) 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]:

\[ Y_{mn} = l_m + m x_{mn} + \sum_{p=-P_m}^{P_m} \mu_{mp} \Delta x_{mn-p} + \theta_{mn} \] (13)

Define \( \rho_{mn} = (\hat{\theta}_{mn}, \Delta x_{mn}) \cdot \delta_{mn} = \lim_{D \to \infty} E \left[ \frac{1}{D} \frac{1}{(\sum_{d=1}^D \rho_{mn})(\sum_{d=1}^D \rho_{mn})} \right] \), \( \delta_{mn} \) is the long-term covariance. In this equation, \( x \) and \( Y_{mn} \) have a cointegration relationship.

The long-term covariance can be decomposed into \( \delta_m = \delta^0_m = \omega_m = \omega_m', \) where \( \delta^0_m \) is the weighted sum of the covariance, \( \omega_m \) is the automatic covariance and \( \omega_m \) The FMOLS criteria are as Eq (14):

\[ \hat{\alpha}_{FMOLS} = \frac{1}{Q} \sum_m \frac{1}{(\sum_{d=1}^D x_{mn} - \bar{x}_m)^2} \left( \sum_{d=1}^D (x_{mn} - \bar{x}_m) y_{mn} - \omega_{\mu_m} \right) \] (14)

Where \( y_{mn}^* = y_{mn} - \bar{y}_m - \left( \delta^0_{2,1,m} \bar{x}_{2,2,m} \right) \Delta x_{mn}, \hat{y}_m = \hat{\omega}_{2,1,m} + \delta^0_{2,1,m} - (\hat{\omega}_{2,1,m}/\hat{\omega}_{2,2,m}) (\hat{\omega}_{2,2,m} + \hat{\delta}_{2,2,m}) \)

### 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 Granger 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[62]. 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 Eq (15)- Eq (17):

\[
\Delta TEC_{mn} = \gamma_{1m} + \sum_t \gamma_{11m} \Delta TEC_{mn-t} + \sum_t \gamma_{12m} \Delta GDP_{mn-t} + \sum_t \gamma_{13m} \Delta X_{mn-t} + \alpha_{1m}ECT_{mn-1} + \beta_{1mn}
\]

(15)

\[
\Delta GDP_{mn} = \gamma_{2m} + \sum_t \gamma_{21m} \Delta TEC_{mn-t} + \sum_t \gamma_{22m} \Delta GDP_{mn-t} + \sum_t \gamma_{23m} \Delta X + \alpha_{2m}ECT_{mn-1} + \beta_{2mn}
\]

(16)

\[
\Delta X_{mn} = \gamma_{3m} + \sum_t \gamma_{31m} \Delta TEC_{mn-t} + \sum_t \gamma_{32m} \Delta GDP_{mn-t} + \sum_t \gamma_{33m} \Delta X_{mn-t} + \alpha_{3m}ECT_{mn-1} + \beta_{3mn}
\]

(17)

Where ECT, t, \( \Delta \) 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 Results of cross-sectional dependency (CSD) tests

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 single-integration. This result supports our next long-term cointegration test.

Table 2. Unit root test results

| Variables | LLC    | IPS    | ADF    | PP-Fisher |
|-----------|--------|--------|--------|-----------|
| lnTEC     | 1.0367 | 8.1139 | 34.4291| 29.645    |
| lnCOAL    | 4.4399 | 8.7338 | 18.9081| 10.5975   |
| lnOIL     | -3.2933*** | 0.6582 | 56.544 | 69.3393   |
| lnGAS     | -0.7111 | -0.5455 | 77.6073** | 167.3300*** |
| lnGDP     | 3.1513 | 6.9294 | 27.0282 | 6.0355    |
| lnIS      | -0.8201 | 0.3352 | 63.1201 | 46.8741   |
| lnOPEN    | -2.1690** | 4.0686 | 36.0776 | 21.3132   |

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

4.2 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.

4.3 Regression estimation results

According to the results of the cointegration test, there is a long-term cointegration relationship between total energy consumption, coal consumption, oil consumption, natural gas consumption and economic growth, industrial structure, and trade openness. Therefore, it is allowed to continue to test the degree of cointegration between variables through cointegration regression.
Table 3. Regression results of national economic growth and total energy consumption

| Variable | OLS            | FMOLS         |
|----------|----------------|---------------|
|          | Coefficient    | T value       | P value | Coefficient | T value       | P value |
| lnGDP    | 0.5685***      | 21.8430       | 0.0000  | 0.6993***   | 12.9632       | 0.0000  |
| lnIS     | 0.3701***      | 6.2476        | 0.0000  | 0.2162***   | 2.7655        | 0.0059  |
| lnOPEN   | 0.0545***      | 3.0210        | 0.0026  | 0.0736***   | 5.4936        | 0.0000  |
| C        | 4.4150***      | 33.0797       | 0.0000  |             |               |         |

Note: ***, **, and * indicate that they 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 | OLS | FMOLS | OLS | FMOLS | OLS | FMOLS |
|          | Statistics | P value | Statistics | P value | Statistics | P value | Statistics | P value | Statistics | P value |
| lnGDP    | 0.6621***      | 0.0000  | 0.6193***      | 0.0000  | 0.4393***      | 0.0000  | 0.6061***      | 0.0000  | 0.5815***      | 0.0000  |
|          | (14.8487)      | (21.6984) | (9.1156)      | (15.0140) | (14.2415)      | (5.8471) |         |         |         |         |
| 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  |
|          | (5.2096)       | (7.1600) | (1.8954)      | (1.8204) | (4.8308)       | (4.0789) |         |         |         |         |         |
| lnOPEN   | 0.0039         | 0.8946  | 0.0320*        | 0.0892  | 0.1602***      | 0.0000  | 0.1732***      | 0.0000  | -0.0079        | 0.8040  | 0.0312         | 0.2291  |
|          | (0.1327)       | (1.7102) | (4.8434)      | (8.8733) | (-0.2485)      | (1.2078) |         |         |         |         |         |
| Variable | lnCOAL | FMOLS | lnOIL | FMOLS | lnGAS | FMOLS |
|----------|--------|-------|-------|-------|-------|-------|
|          | OLS    | Statistics | P value | OLS    | Statistics | P value | OLS    | Statistics | P value | OLS    | Statistics | P value |
| lnGDP    | 0.47701*** | 0.0000 | 0.4736*** | 0.0000 | 0.1111 | 0.4841 | 1.5581*** | 0.0000 | 1.8362*** | 0.0000 | 0.8191*** | 0.0000 |
|          | (10.411) |       | (10.036) |       | (0.1124) |       | (33.2830) |       | (10.8222) |       | (16.6727) |       |
| lnIS     | 0.8809*** | 0.0000 | 0.3883*** | 0.0000 | 0.6803* | 0.0952 | 1.8463*** | 0.0000 | 0.5566 | 0.1644 | 2.4669*** | 0.0000 |
|          | (8.4346) |       | (7.0307) |       | (1.6716) |       | (32.3690) |       | (1.3926) |       | (42.2149) |       |
| lnOPEN   | 0.0656*** | 0.0393 | 0.1802*** | 0.0062 | 0.5167*** | 0.0000 | 1.5453*** | 0.0000 | -0.1339 | 0.2591 | -0.5610*** | 0.0000 |
|          | (2.0662) |       | (2.7538) |       | (5.7609) |       | (22.3867) |       | (-1.1299) |       | (-8.3862) |       |
| C        | 5.2339*** | 0.0000 | -1.3105 | 0.1124 | -8.1676*** | 0.0000 |       |       |       |       |       |       |
|          | (22.2775) |       | (-1.5904) |       | (-9.3318) |       |       |       |       |       |       |       |

Note: ***, **, and * indicate that they 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 difference. 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 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 with total energy consumption between 100 to 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.

4.3 Granger causality test

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            | 8.6550***   | 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          | 5.5953***   | 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 |
| lnOIL does not Granger Cause lnOPEN           | 1.6721      | 0.1891 |
| lnIS does not Granger Cause lnOIL             | 0.2504      | 0.7786 |
| lnOIL does not Granger Cause lnIS             | 3.5980**    | 0.0282 |
| lnGDP does not Granger Cause lnGAS            | 6.9807***   | 0.0010 |
| lnGAS does not Granger Cause lnGDP            | 12.4659***  | 0.0000 |
| lnOPEN does not Granger Cause lnGAS           | 11.4698***  | 0.0000 |
| lnGAS does not Granger Cause lnOPEN           | 2.8869*     | 0.0568 |
| lnIS does not Granger Cause lnGAS             | 0.5877      | 0.5561 |
| lnGAS does not Granger Cause lnIS             | 10.9694***  | 0.0000 |
| lnOPEN does not Granger Cause lnGDP           | 2.8785*     | 0.0572 |
| lnGDP does not Granger Cause lnOPEN           | 18.0967***  | 0.0000 |
| lnIS does not Granger Cause lnGDP             | 1.9574      | 0.1424 |
| lnGDP does not Granger Cause lnIS             | 21.0017***  | 0.0000 |
| lnIS does not Granger Cause lnOPEN            | 10.6223***  | 0.0000 |
lnOPEN does not Granger Cause lnIS  
13.9547***  0.0000

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

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 | 7.9765*** | 2.3111 | 3.5349** |
| lnTEC does not Granger Cause lnGDP | 9.1872*** | 1.0809 | 0.4046 |
| lnOPEN does not Granger Cause lnTEC | 2.5188* | 0.1395 | 1.5150 |
| lnTEC does not Granger Cause lnOPEN | 4.1131** | 6.5622*** | 2.1680 |
| lnIS 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 lnOPEN | 3.0494* | 7.7562*** | 10.1951*** |
| lnIS does not Granger Cause lnGDP | 1.0063 | 0.4061 | 0.7839 |
| lnGDP does not Granger Cause lnIS | 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 they can pass statistical tests with significance levels of 1%, 5%, and 10%, respectively.
Figure 2. Schematic diagram of Granger causality test at national and regional level.

Granger Causality testing can further help understand the interaction between variables. The test results focusing on energy sources and regional differences are shown in Table 6 and Table 7, respectively.

From Table 6 and Figure 2, bidirectional Granger causality from economic growth to energy consumption, coal consumption, and gas consumption was found at the national level. This validate the Feedback causality for the case of China. In addition, there is a bidirectional Granger causalities running from energy consumption, coal consumption to industrial structure. The industrial structure leads to the sources and changes of energy consumption. Moreover, bidirectional Granger causality also appears between 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 then, 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 pandemic

5.1 Insights from energy sources

Among fossil energy sources, China economic recovery has the greatest driving effect on oil consumption. For every 1% increase in regional GDP, the consumption for oil increases by 1.5581%. Oil is the blood of industry and penetrates into all aspects of the economy and society [68]. The expansion of the economic scale and the improvement of the level of social activities have directly promoted the growth of oil consumption [69]. Therefore, the oil market shows that oil consumption is highly correlated with economic trends. During the financial crisis, the global economy fell into recession, and oil demand grew negatively during the same period [70]; On the contrary, the global economy grew during 2017-2019, and the demand for oil increased during the same period [71]. As the world's largest industrial country, China's economic development is dependent on oil consumption. In the early stage of
China's reform and opening up, limited by the level of science and technology, China's pillar energy was coal [72]. However, with the rapid improvement of the economic and technological level, the technology of oil extraction, transportation, and refining has been improved [73, 74]. Combined with the advantages of higher oil heating value and more convenient transportation, so that the rate of oil consumption has continued to increase.

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.

Coal consumption is the least affected by economic growth. 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 percentage 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 large amount of 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

Figure 3 illustrates the spatial distribution of the relationship between energy consumption and economic growth in China 30 provinces. For high energy consumption region, energy consumption has increased the most. High energy consumption region includes Shandong, Guangdong, Jiangsu, Hebei, Henan, Liaoning, Zhejiang, 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.

Figure 3. The geographical distribution of the relationship between economic growth and total energy consumption in China 30 provinces.

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 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 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 pandemic 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 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 natural 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 National 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 production and sales, maintain the stability of coal market prices and standardize the use of coal price indices. Finally, the transformation of energy consumption structure is preferred. When laying out a new round of energy security strategies, the transition of clean energy should be considered to make balance between energy security and environmental protection. Based on the experience of developed countries during the two oil crises in 1973 and 1979, the government can take the opportunity to promote the transformation of energy consumption structure through regulations and policies such as fuel taxes.

The energy policy must consider local conditions due to the regional differences in increased energy consumption with economic growth. Because of the huge energy demand in Yangtze River Delta region, an energy institution in the Yangtze River Delta region can be established to optimize energy plans. For Guangzhou with high degree of opening to the outside world, the main body of energy consumption can be transited to clean energy through the establishment of clean energy production, 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 energy 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 energy 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.
Appendix A

Table A1. Cross-sectional dependence tests results.

| Variables | Breusch-Pagan LM test | Pesaran scaled LM test | Pesaran CD test |
|-----------|-----------------------|------------------------|----------------|
| lnTEC     | 7237.5170*** 0.0000   | 230.6269*** 0.0000    | 84.8822*** 0.0000 |
| lnCOAL    | 5900.9630*** 0.0000   | 185.3135*** 0.0000    | 69.8754*** 0.0000 |
| lnOIL     | 3209.7940*** 0.0000   | 94.0743*** 0.0000     | 45.5230*** 0.0000 |
| lnGAS     | 4718.0620*** 0.0000   | 145.2094*** 0.0000    | 65.4208*** 0.0000 |
| lnGDP     | 7714.1750*** 0.0000   | 246.7871*** 0.0000    | 87.8274*** 0.0000 |
| lnIS      | 3313.2940*** 0.0000   | 97.5833*** 0.0000     | 43.7949*** 0.0000 |
| lnOPEN    | 6882.3860*** 0.0000   | 218.5869*** 0.0000    | 82.7390*** 0.0000 |

Note: ***, **, and * indicate that they 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        |
| 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         | -3.5265***     | 0.0002         | -4.2808***     | 0.0000         |
| Panel ADF-statistic| -2.3217** 0.0101         | -4.2924***      | 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         |
| Group PP-statistic | -3.1322*** 0.0009        | -4.1215***      | 0.0000         | -6.3236***     | 0.0000         | -8.5190***     | 0.0000         |
| Group ADF-Statistic| -2.6831*** 0.0036        | -5.5972***      | 0.0000         | -6.7703***     | 0.0000         | -7.5637***     | 0.0000         |
| Kao Cointegration Test | ADF 0.0005 | 1.7327* | 0.0416 | -4.8174*** | 0.0000 | -5.4623*** | 0.0000 |
| | Residual variance 0.0055 | 0.0095 | 0.0086 | 0.0078 |
Table A3. Inter-provincial cointegration test results between total energy consumption and economic growth

| 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 rho-statistic     | 0.9602          | 0.8315     | 1.2958*** | 0.9025     | -0.0436   | 0.4826     |
| 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     | -8.9448*** | 0.0000     |
| Group rho-statistic     | 1.8353          | 0.9668     | 2.3201     | 0.9898     | 1.5464    | 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     | 0.0014     |            |            |            |
| HAC variance            | 0.0039          | 0.0025     | 0.0020     |            |            |            |

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

✧ Multiple linear regression panels and data from 30 provinces in China from 2000 to 2017 were used.

✧ China's economic growth has the largest increase in oil consumption, and the smallest increase in coal consumption.

✧ The energy consumption of provinces with different energy consumption levels is affected differently by China's economic recovery.

✧ Energy consumption growth in high-energy-consuming provinces is most affected by economic growth.
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: