RESEARCH ARTICLE

Research on the relation of Economy-Energy-Emission (3E) system: evidence from heterogeneous energy in China

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Abstract
To achieve China’s carbon peak and carbon neutrality goals, conducting systematic research on the energy, economy, and emission factors that affect the sustainable development of society is of great significance. This paper first uses the vector error correction model (VECM)-based Granger causality test to analyze the joint causal relations and feedback correction mechanisms among energy consumption, economic growth, and CO2 emissions in China from 1980 to 2019 at the energy heterogeneity level; then, analyzes the decoupling effect of China’s four major energy sources (coal, oil, natural gas, and electricity) and economic growth from the perspective of energy heterogeneity; finally, the Tapio decoupling elastic model is decomposed into the emission reduction elasticity and energy saving elasticity to analyze the decoupling causality chain of the economy, energy, and carbon emissions. The research results show that there is a long-term, two-way causal relation between coal consumption and CO2; coal consumption has a one-way causal relation with economic growth; and long-term, two-way causal relations exist between oil and CO2, natural gas and CO2, electricity and CO2, electricity, and economic growth. In addition, when energy consumption, economic growth, and CO2 emissions deviate from their equilibrium states in the short term, various energy consumption, economic growth, and CO2 emissions in the previous year will be adjusted by 19.5%, 0.6%, …, 7.7%, and 3.4% to bring the nonequilibrium states back to the long-term equilibrium states. Furthermore, the energy-saving elasticity of China’s total energy, coal, oil, and natural gas is the main factor affecting the corresponding decoupling elasticity, but the emission reduction elasticity of electricity has a stronger impact on the decoupling elasticity than the emission reduction elasticity does.

Keywords Heterogeneous energy consumption · Carbon emissions · Economic growth · Joint causality · Feedback mechanism · Granger causal model based on VECM · Decoupling causality chain model

Introduction
The latest report released by the United Nations Environment Programme pointed out that green recovery after the new coronavirus epidemic is expected to promote a global reduction of 25% of the predicted greenhouse gas emissions in 2030; however, the global temperature is still developing in the direction of rising above 3°C by the end of this century, and the global environmental situation is still grim. According to public data released by the International Energy Agency (IEA), global carbon dioxide emissions exceeded growth expectations and reached a peak of 33 billion tons in 2019; Asian countries contributed more than 300 million tons of added value associated with carbon emissions, and coal power generation is still increasing. As the world’s largest developing country, China has increased its national independent contribution since 2020 and promised to the international community to achieve carbon peak by 2030 and carbon neutrality by 2060 (Xi 2021). Carbon neutralization, as a product of the development of carbon emission reduction to a certain stage, refers to the realization of relatively “zero emissions” by offsetting the carbon dioxide generated...
by itself through energy conservation, emission reduction, and enhancement of carbon sinks. Therefore, the necessary conditions for achieving carbon neutrality lie in building an energy-saving and low-carbon social development mode, and improving the carbon sink capacity and increment of the ecosystem.

As early as the United Nations Climate Change Conference in 2010, energy conservation and emission reduction had become a hot topic in China. Chinese scholars focus on energy structure and energy efficiency (Ma et al. 2019a, b; Wang et al. 2019; Zhao et al. 2020; Kongkuah et al. 2021; Ma et al. 2021a) to explore the clean and low-carbon energy system, simultaneously, deepening research on energy and emissions into industry (Ma et al. 2019a, b), manufacturing (Yang et al. 2022), transportation (Shao and Wang 2021), finance (Cao and Yao 2014), tourism (Ma et al. 2021b), electricity (Ma et al. 2017), and other specialized fields (Dong et al. 2020) to explore innovative paths for industrial structure optimization. With the launch of China’s carbon market pilot work, research in China’s carbon field has expanded to carbon assets (Lv et al. 2019), carbon trading (Wei 2015), carbon tax (Liu and Li 2011; Wang and Fan 2012), and carbon finance (Lou 2014), to explore policy innovations using market mechanisms to control carbon emissions. Due to the continuous deepening of carbon neutrality, research on deep decarbonization technologies such as carbon capture, carbon sequestration, and ecological carbon sinks has received extensive attention in China, but only theoretical discussions are currently being conducted (Zhong et al. 2012a, b; Xie et al. 2014; Huang et al. 2016; Jiang et al. 2019; Zhang and Zhang 2021), and few practical studies has been carried out in specific fields.

Since carbon peaking and carbon neutrality goals were proposed, China adheres to the system concept and coordinates the relationship between development and emission reduction, overall and local, short term and medium-term-long term. The realization of carbon neutrality means building a green, low-carbon, and circular economy, which involves systemic changes in energy, environment, and economy. Energy, economy, and emissions are the three major elements affecting the sustainable development of the world. In social and economic operations, these three elements interact with each other to form a circular 3E (Economy-Energy-Emission) system. In order to better promote the realization of the 3060 targets, it is necessary to clarify the interaction relationship of the 3E system.

Figure 1 shows the changes in China’s carbon emissions, economic growth, and energy consumption from 1980 to 2019. China’s economy has maintained a steady growth trend since 1980, but the rapid growth of China’s economy from 2003 to 2013 is accompanied by substantial increases in energy consumption and carbon emissions. Following the introduction of the new normal for economic development in 2013 and the high-quality development in 2017, China’s economic development has shifted from “high speed” to “high-quality,” and the growth trend of energy consumption and carbon emissions has slowed down significantly, indicating that policy measures such as energy conservation and emission reduction have all produced beneficial effects. However, carbon emissions are still growing, and the peak inflection point has not appeared. Simultaneously, China’s energy structure is still dominated by coal, which accounts for more than half of the total energy consumption. The penetration rate of natural gas is not sufficiently high, and coal-fired power generation is still the main power-generation method. All these show that the problem of China’s energy structure is still prominent. Therefore, based on China’s energy structure, in-depth exploration of the interaction among energy consumption, economic growth, and carbon emissions, which is in line with current research hotspots and social needs, has important theoretical value and guiding significance, and provide a theoretical reference for China to achieve carbon peak and carbon neutrality on schedule.

The rest of this paper is structured as follows: the “Literature review” section is literature review; the “Research method and data sources” section introduces the construction method of the theoretical model; the “Empirical analysis” section is an empirical analysis; and the “Conclusion and recommendations” section summarizes the conclusions, and puts forward policy recommendations and further research recommendations.

**Literature review**

Since the 1970s, using causality to test the relation between energy consumption and economic growth has become an important research topic. Kraft and Kraft (1978) pioneered the discovery that economic growth can effectively drive energy consumption growth, and received extensive support in other studies. For example, a large number of scholars have concluded through empirical tests that there are one-way relations between economic growth and energy consumption in South Korea, Singapore, and China (Yu and Choi 1985; Glasure and Lee 1998; Hwang and Gum 1991; Wu et al. 2013; Ma et al. 2019a, b; Zhu et al. 2019). However, the research conclusions of different scholars on the relation between energy consumption and economic growth in the same country or region are not completely consistent (Cheng and Lai 1997; Yang 2000; Ozturk 2010; Ma et al. 2017). In recent years, with the continuous deepening of international research on carbon emissions, the causal relations among carbon emissions, energy consumption, and economic growth have become a hot issue for scholars in China and globally. Internationally, most scholars, such as Ang (2007), Ang (2008), Xu and Li (2012), Stern and Dijk (2017), and
Mirza and Kanwal (2017), have explored the dynamic causality among economic growth, energy consumption, and carbon emissions in the long term and short term in various countries at the total national energy level. However, the research methods used differ among different scholars, and the obtained research conclusions also differ. Kraft and Kraft (1978) were the first to use the Granger causality test method to study the relation between economic growth and energy consumption in the USA and found that a one-way causal relation existed from economic output to energy consumption in the USA from 1947 to 1974. However, follow-up studies found that the results of the Granger causality test may appear as false regressions, causing the test results to be unreliable. To solve the above-described problems, the cointegration test came into being and became an indispensable part of the Granger test. Three main cointegration methods are currently used in the world: panel cointegration (Pao and Tsai 2010; Chen et al. 2016), ARDL (autoregressive distributed lag model), boundary cointegration (Acaravci and Ozturk 2010) and combinatorial cointegration tests (Bastola and Sapkota 2015; Mirza and Kanwal 2017; Appiah 2017). Scholars use the Granger test to explore the relations among economic growth, energy consumption, and carbon emissions in various countries through different cointegration methods. The exploration of the relations among China’s energy consumption, economic growth, and carbon emissions started late, and few research results exist. Xu et al. (2012) explored the long-term and short-term effects of environmental regulatory factors (CO₂ emissions, pollution control investments, and sewage charges) and energy consumption on the level of economic development based on the translogarithmic production function model from a spatial perspective. Hu and Liu (2015) incorporated energy consumption indicators and pollution emission indicators into a regional economic growth model and examined the dynamic relations among energy consumption, pollution emissions (wastewater, exhaust gas, and solid waste), and economic growth. In addition, domestic scholars have used cointegration analyses and Granger causality tests to study the long-term relations among economic growth, energy consumption, and carbon emissions at the level of total energy (Tao et al. 2010; Wang et al. 2011; Yang et al. 2012).

In the past few decades, international academia has carried out a variety of empirical studies on the relations among economic growth, energy consumption, and carbon emissions. The exploration of the relations among China’s energy consumption, economic growth, and carbon emissions started late, and few research results exist. Xu et al. (2012) explored the long-term and short-term effects of environmental regulatory factors (CO₂ emissions, pollution control investments, and sewage charges) and energy consumption on the level of economic development based on the translogarithmic production function model from a spatial perspective. Hu and Liu (2015) incorporated energy consumption indicators and pollution emission indicators into a regional economic growth model and examined the dynamic relations among energy consumption, pollution emissions (wastewater, exhaust gas, and solid waste), and economic growth. In addition, domestic scholars have used cointegration analyses and Granger causality tests to study the long-term relations among economic growth, energy consumption, and carbon emissions at the level of total energy (Tao et al. 2010; Wang et al. 2011; Yang et al. 2012).
between economic growth and carbon emissions and between economic growth and energy consumption at the national and industry levels, but controversies still exist. Initially, under the EKC hypothesis, it was believed that an inverted U-shaped relation exists between economic growth and carbon emissions (Ang, 2007), but not all studies have supported the EKC hypothesis (Begum et al. 2015; Stern 2016; Wang et al. 2017; Li et al. 2021a, b). Since the twenty-first century, the introduction of decoupling theory into economic research has provided a new perspective for analyzing the relation between the environment and economic growth. Tapio (2005) proposed the Tapio decoupling index model based on the concept of elasticity and divided the decoupling states into eight types, strong decoupling, weak decoupling, recession decoupling, expanding negative decoupling, strong negative decoupling, weak negative decoupling, expanding coupling, and recession coupling, thus opening up a new path for the study of the relation between the economy and environment. Since then, scholars have determined the decoupling relation between economic growth and carbon emissions or energy consumption according to the range of the decoupling elasticity coefficient, providing a basis for formulating effective environmental regulatory policies (Zhou 2019). At the national level, Narayan and Narayan (2010) selected 43 developing countries as research objects to test the EKC hypothesis on the decoupling effect between national economic growth and CO₂ emissions; Niu et al. (2011) selected 4 developed countries and 4 developing countries as the research objects and compared the differences in decoupling effects among the economic growth, energy consumption, and CO₂ emissions of the studied countries; other scholars have separately studied the decoupling effect between CO₂ emissions and economic growth in Brazil, EU countries, Greece, and China (de Freitas and Kaneko 2011; Davidsdottir and Fisher 2011; Roinioti and Koroneos 2017; Zhong et al. 2012b; Ma et al. 2021c). At the industry level, the Tapio decoupling index has been used in the fields of transportation (Wang et al. 2018), industry (Ma et al. 2019a, b), tourism (Sun and Yang 2020), manufacturing (Yang and Hu 2021), and agriculture (Kuang and Hu 2021), and other industries have been widely considered in studies of energy consumption or carbon emissions.

In summary, international research on the relations among economic growth, energy consumption, and carbon emissions is mainly divided into two categories: the first involves constructing a causality test model to explore the long-term and short-term dynamic relations among economic growth, energy consumption, and carbon emissions in various countries at the total energy level; the second involves using the EKC hypothesis or decoupling elasticity model to explore the development trend between economic growth and energy consumption or between economic growth and carbon emissions. However, as far as existing research results are concerned, the exploration of the relations among China’s energy consumption, economic growth, and carbon emissions started late, and most of the existing research has focused on the analysis of the total energy, with refined research at the energy heterogeneity level lacking. At the same time, while the decoupling theory is currently an important method used to explore the relation between national economic development and carbon emissions, it fails to integrate energy consumption and energy structure factors, and it is therefore impossible to comprehensively analyze the “media role” of energy consumption on the decoupling of economic growth and carbon emissions at the system level.

In response to the above problems, the marginal contributions of this paper are as follows: (1) based on energy structure, conduct a comprehensive analysis of the causal relations and decoupling effects among China’s energy consumption, economic growth, and carbon emissions from the perspective of energy heterogeneity levels, making up for the lack of research at the energy heterogeneity level and aiming to better clarify the scale and structure of China’s energy economy; (2) use the Granger causality test method based on VECM to explore the causal feedback mechanisms among energy consumption, economic growth, and carbon emissions in China from the perspective of energy heterogeneity, systematically studying the long-term and short-term causality relations among these factors and building a feedback correction mechanism of the mutual influence within the 3E system; (3) on the basis of existing research, a decoupling causal chain model including the economy, energy, and carbon emissions is constructed, and a systematic and comprehensive analysis of the decoupling effect is carried out from the perspective of energy heterogeneity to comprehensively analyze the actual effects of governmental energy conservation and emission reduction measures providing suggestions for China to achieve a low-carbon economy, optimize its energy structure, and achieve carbon peak and carbon neutrality.

**Research method and data sources**

**Granger causal feedback model construction**

**Cointegration test**

In economic operations, although nonstationary processes are represented by sets of time series variables, one of the linear combinations of these sets may be stationary. In this case, there is a cointegration relation between the variables. The cointegration test is used to determine whether a long-run equilibrium relation and pseudoregression exist between nonstationary variables (Song and Zhang, 2009).
In macroeconomic econometric analyses, the cointegration method proposed by Granger has become one of the most important tools for analyzing the quantitative relations among nonstationary economic variables. The linear adjustment mechanism between economic variables can be described via the linear error correction model (ECM), namely, the linear cointegration method. With the development of economic theory, traditional linear cointegration analysis is no longer a universal analysis method. Johansen proposed a method based on the VAR model to test regression coefficients jointly with Juselius in 1988 and 1990; this method can perform a multivariate cointegration test. Therefore, this study selected the Johansen method to cointegrate the considered variables.

First, the Johansen test is divided into a trace test and a maximum eigenvalue test, both of which start from the null hypothesis that there is no cointegration relation, i.e., $R \leq 0$. If the trace test statistics or the maximum eigenvalue test statistics are less than the critical value, $H_{0}$ cannot be rejected; i.e., there is no cointegration relation. If the test statistics are greater than the critical value, $H_{0}$ can be rejected; i.e., there is a cointegration relation. If there is at most one cointegration relation, the null hypothesis is $R \leq 1$. Then, the statistics are compared to the threshold values, and the process is repeated until the null hypothesis that there are at most $r$ cointegration relations cannot be rejected.

Second, a standardized cointegration equation is constructed (Ahmad et al. 2016):

$$\text{LnC}_t = \alpha_0 + \beta_1 \text{LnE}_t + \beta_2 \text{LnY}_t + e_t$$

(1) where $\text{LnC}_t$ indicates the natural logarithm of carbon emissions from per-capita energy consumption, $\text{LnE}_t$ notes the natural logarithm of per-capita energy consumption, and $\text{LnY}_t$ represents the natural logarithm of per-capita real GDP. In addition, $e_t$ is an error term, and $\alpha_0$ is a constant term.

This paper explores how energy consumption at the total and heterogeneous energy levels (mainly including coal, oil, natural gas, and electricity) and economic growth affect carbon emissions in China. Therefore, separate regression equations are used for the cointegration analysis:

$$\text{LnCEC}_t = \alpha_0 + \beta_1 \text{LnEC}_t + \beta_2 \text{LnY}_t + e_t$$

(2)

$$\text{LnCCoal}_t = \alpha_0 + \beta_1 \text{LnCoal}_t + \beta_2 \text{LnY}_t + e_t$$

(3)

$$\text{LnCOil}_t = \alpha_0 + \beta_1 \text{LnCOil}_t + \beta_2 \text{LnY}_t + e_t$$

(4)

$$\Delta \text{LnE}_t = \alpha_2 + \sum_{i=1}^{p-1} \varphi_{2i} \Delta \text{LnC}_{t-i} + \sum_{i=1}^{p-1} \psi_{2i} \Delta \text{LnE}_{t-i} + \sum_{i=1}^{p-1} \xi_{2i} \Delta \text{LnY}_{t-i} + \gamma_2 \text{ECM}_{t-1} + e_{2t}$$

(7)

$$\text{LnCGas}_t = \alpha_0 + \beta_1 \text{LnGas}_t + \beta_2 \text{LnY}_t + e_t$$

(5)

$$\text{LnCElc}_t = \alpha_0 + \beta_1 \text{LnElc}_t + \beta_2 \text{LnY}_t + e_t$$

(6)

where $\text{LnCEC}_t$ indicates the natural logarithm of carbon emissions from per-capita aggregated energy consumption, $\text{LnEC}_t$ represents the natural logarithm of per-capita aggregated energy consumption, $\text{LnCCoal}_t$, notes the natural logarithm of carbon emissions from per-capita coal consumption, $\text{LnCoal}_t$, states the natural logarithm of per-capita coal consumption, $\text{LnCOil}_t$, refers to the natural logarithm of carbon emissions from per-capita oil consumption, $\text{LnOil}_t$, stands for the natural logarithm of per-capita oil consumption, $\text{LnCGas}_t$, indicates the natural logarithm of per-capita natural gas consumption, $\text{LnElc}_t$, represents the natural logarithm of carbon emissions from per-capita natural gas consumption, and $\text{LnGas}_t$, notes the natural logarithm of per-capita electricity consumption. By estimating the coefficients of the cointegration equations, the trends and influences among the variables can be obtained.

**Granger causality test based on VECM**

When there is a cointegration relation between a set of vectors, a simple VAR model loses the long-term information between variables, leading to errors in the analysis results. The VECM can overcome this shortcoming well and is mostly applied to nonstationary time series with cointegration relations (Walter, 1995; Yang et al., 2012); it can be derived from the ARDL model. If a cointegration relation exists between sequences, the ARDL model can only show that the variables have a long-term stable equilibrium relation but cannot explain the causal relation or direction between the sequences. Therefore, this paper uses the VECM-based Granger causality test to dynamically analyze the carbon emissions, energy consumption, and economic growth at the total and heterogeneous energy levels in both the long term and the short term. The formula for the VECM Granger causality test is modeled as follows:

$$\Delta \text{LnC}_t = \alpha_1 + \sum_{i=1}^{p-1} \varphi_{1i} \Delta \text{LnC}_{t-i} + \sum_{i=1}^{p-1} \psi_{1i} \Delta \text{LnE}_{t-i} + \sum_{i=1}^{p-1} \xi_{1i} \Delta \text{LnY}_{t-i} + \gamma_1 \text{ECM}_{t-1} + e_{1t}$$

(7)
\[
\Delta \text{Ln} Y_t = a_3 + \sum_{i=1}^{r-1} \psi_{3i} \Delta \text{Ln} C_{t-i} + \sum_{i=1}^{r-1} \psi_{4i} \Delta \text{Ln} E_{t-i} + \sum_{i=1}^{r-1} \xi_{3i} \Delta \text{Ln} Y_{t-i} + \eta_i \text{ECM}_{t-i} + \epsilon_t
\]  
(9)

where \(\text{ECM}_{t-i}\) represents the error correction term of the long-term cointegration relation. Since the VECM decomposes causality into long-term and short-term causal relations, long-term causality is determined by error correction (ECM). Therefore, if the negative \(\text{ECM}_{t-i}\) coefficient passes the significance test, it indicates that there is a long-term causal relation from the independent variable to the dependent variable (Johansen, 1991). This long-term equilibrium relation is achieved by continuous adjustment during short-term fluctuations. Through an error-correction mechanism, the imbalance in a certain period can be corrected in a later period, and the long-term equilibrium relation between the variables can be determined via their short-term adjustment behavior. To determine the short-term causality, this paper uses the VECM-based Granger causality test to empirically study the relations among energy consumption at the total and heterogeneous energy levels, economic growth, and carbon emissions in China.

**Tapio decoupling causal chain model**

The decoupling theory is used to describe the link between economic growth and energy consumption or carbon emissions based on statistical index calculation methods. The Tapio decoupling index uses the ratio of the rates of change between variables to reveal the relevance of the variables. According to the decoupling elasticity value, the decoupling state can be subdivided into 8 categories (Tapio 2015), as shown in Table 1. This classification standard has also been widely adopted by scholars (Luo et al. 2020; Peng et al., 2020; He and Liu, 2015). The basic formula is as follows:

\[
\text{Tapio} = \frac{\% \Delta x_1}{\% \Delta x_2}
\]

(10)

Based on the above theory and referring to the method of Sun and Yang (2020), this paper establishes a decoupling causal chain model to fully explore the decoupling effects among carbon emissions, energy consumption, and economic growth. The decoupling elasticity is broken down into two aspects, energy savings and emission reductions, to explore the specific causes of decoupling.

The Tapio decoupling causal chain model under heterogeneous energy is shown in formulas (11)–(15):

\[
\frac{\% \Delta \text{EC}}{\% \Delta Y} = \frac{\% \Delta \text{EC}}{\% \Delta \text{EC}} \times \frac{\% \Delta \text{EC}}{\% \Delta Y}
\]  
(11)

\[
\frac{\% \Delta \text{Coal}}{\% \Delta Y} = \frac{\% \Delta \text{Coal}}{\% \Delta \text{Coal}} \times \frac{\% \Delta \text{Coal}}{\% \Delta Y}
\]  
(12)

\[
\frac{\% \Delta \text{Oil}}{\% \Delta Y} = \frac{\% \Delta \text{Oil}}{\% \Delta \text{Oil}} \times \frac{\% \Delta \text{Oil}}{\% \Delta Y}
\]  
(13)

\[
\frac{\% \Delta \text{Gas}}{\% \Delta Y} = \frac{\% \Delta \text{Gas}}{\% \Delta \text{Gas}} \times \frac{\% \Delta \text{Gas}}{\% \Delta Y}
\]  
(14)

\[
\frac{\% \Delta \text{Elc}}{\% \Delta Y} = \frac{\% \Delta \text{Elc}}{\% \Delta \text{Elc}} \times \frac{\% \Delta \text{Elc}}{\% \Delta Y}
\]  
(15)

where \(\% \Delta Y\) represents the percentage of change in China’s economic growth; \(\% \Delta \text{EC}, \% \Delta \text{Coal}, \% \Delta \text{Oil}, \% \Delta \text{Gas}, \) and \(\% \Delta \text{Elc}\) represent the percentages of the total energy, coal, oil, natural gas, and electricity consumption changes, respectively; \(\% \Delta \text{EC}, \% \Delta \text{Coal}, \% \Delta \text{Oil}, \% \Delta \text{Gas}, \) and \(\% \Delta \text{Elc}\) represent the percentages of carbon emissions changes resulting from total energy, coal, oil, natural gas, and electricity consumption, respectively; \(\% \Delta \text{EC}, \% \Delta \text{Coal}, \% \Delta \text{Oil}, \% \Delta \text{Gas}, \) and \(\% \Delta \text{Elc}\) represent the emission reduction elasticity values generated by total energy, coal, oil, natural gas, and electricity consumption, respectively; \(\% \Delta \text{EC}, \% \Delta \text{Coal}, \% \Delta \text{Oil}, \% \Delta \text{Gas}, \) and \(\% \Delta \text{Elc}\) represent the emission reduction elasticity values.

**Table 1** Criteria for judging the degree of Tapio decoupling index

| Decoupling status               | \(\% \Delta x_1\) | \(\% \Delta x_2\) | Growth rate       | Numerical range |
|--------------------------------|-------------------|-------------------|-------------------|-----------------|
| Strong decoupling             | < 0               | > 0               | \(X_1\): negative growth \(X_2\): positive growth | (− ∞,0)         |
| Weak decoupling               | > 0               | > 0               | \(X_1 < X_2\)    | [0, 0.8]        |
| Recessive negative decoupling | < 0               | < 0               | \(X_1 > X_2\)    | (1.2, + ∞)      |
| Strong negative decoupling    | > 0               | < 0               | \(X_1\): positive growth \(X_2\): negative growth | (− ∞,0)         |
| Weak negative decoupling      | < 0               | < 0               | \(X_1 > X_2\)    | [0, 0.8]        |
| Expansive negative decoupling | > 0               | > 0               | \(X_1 < X_2\)    | (1.2, + ∞)      |
| Expansive coupling            | > 0               | > 0               | Approximately proportional linear relation | [0.8, 1.2]      |
| Recessive coupling            | < 0               | > 0               | Approximately proportional linear relation | [0.8, 1.2]      |
between total energy, coal, oil, natural gas, electricity consumption, and the corresponding carbon emissions, respectively; and \( \% \Delta Y \), \( \% \Delta \), and \( \% \Delta E_{\text{FC}} \) represent the energy-saving elasticity of total energy, coal, oil, natural gas, electricity consumption, and economic growth, respectively.

**Carbon emissions calculation and data sources**

According to the referenced methods and parameters provided in Chapter 6 of Volume II (Energy Volume) of the National Greenhouse Gas Inventory Guidelines formulated by the IPCC (2006), the carbon dioxide emissions of various energy sources are estimated in combination with the relevant parameters published by China. The specific formula is as follows:

\[
C_i = E_i \times CV_i \times CCF_i \times COF_i \times \varepsilon_i \times \left(\frac{44}{12}\right)
\]  

(16)

where \( i = 1, 2, ..., 8 \) indicates the type of energy; \( E_i \) represents the \( i \)th energy consumption source, in Mt or m\(^3\); \( CV_i \) represents the average low calorific value of the \( i \)th energy source, in kJ/kg or kJ/m\(^3\); \( CCF_i \) represents the carbon content per unit calorific value of the \( i \)th energy source, in TC/TJ; \( COF_i \) represents the carbon oxidation rate of the \( i \)th energy source; 44/12 represents the ratio of carbon dioxide to its carbon content, which is used to convert the unit of calculation from carbon to carbon dioxide; and \( \varepsilon_i \) is the unit conversion coefficient used to ensure that each indicator unit can be calculated.

Considering the availability of data, this paper selects China’s raw coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, and electricity consumption data from 1980 to 2019 to calculate the carbon emissions of energy sources. The consumption of various energy sources and the conversion coefficient of standard coal are derived from the China Energy Statistical Yearbook, and the carbon emission factor is derived from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Volume 2). After calculating the carbon emissions of the eight energy sources listed above, the consumption of raw coal and coke and their carbon emissions are summed to obtain the total coal consumption amount and the carbon emissions produced in the corresponding year; the consumption of crude oil, gasoline, kerosene, diesel, fuel oil, and their carbon emissions are summed to obtain the total amount of oil consumption and the carbon emissions produced in the corresponding year. In this way, the consumption of coal, oil, natural gas, and their respective carbon emissions from 1980 to 2019 are obtained.

Since there is no effective calculation method to obtain the carbon emissions of electricity, this section selects China’s coal power and heat generation emissions in 1980-2019 from the International Energy Agency (IEA) as the carbon emissions data from China’s electricity consumption. At the same time, the per-capita GDP (in yuan) and total population data recorded at the end of each year from 1980 to 2019 are selected from the National Bureau of Statistics. Due to the large amount of data and complicated calculations, this paper calculates and models the natural logarithm of the per-capita GDP, per-capita energy consumption, and per-capita carbon emissions. This treatment can eliminate the heteroscedasticity of data fluctuations and avoid pseudo regression, in line with the statistical and economic significance of the results.

**Empirical analysis**

**Analysis of the joint causality of energy heterogeneity**

**Equilibrium test**

The terms \( \Delta \ln Y \), \( \Delta \ln EC \), \( \Delta \ln Coal \), \( \Delta \ln Oil \), \( \Delta \ln Gas \), \( \Delta \ln Elec \), \( \Delta \ln CEC \), \( \Delta \ln CCCoal \), \( \Delta \ln CCOil \), \( \Delta \ln CGas \), and \( \Delta \ln CCElec \) represent the first-order differences of \( \ln Y \), \( \ln EC \), \( \ln Coal \), \( \ln Oil \), \( \ln Gas \), \( \ln Elec \), \( \ln CEC \), \( \ln CCCoal \), \( \ln CCOil \), \( \ln CGas \), and \( \ln CCElec \), respectively. The ADF test was performed on each of the above sequences (Table 4 of the Appendix), and the test statistics of the first-order difference sequence were all significant. Therefore, \( \ln Y \), \( \ln EC \), \( \ln Coal \), \( \ln Oil \), \( \ln Gas \), \( \ln Elec \), \( \ln CEC \), \( \ln CCCoal \), \( \ln CCOil \), \( \ln CGas \), and \( \ln CCElec \) are first-order single-integral sequences.

After determining the stationarity of the \( \ln Y \), \( \ln EC \), \( \ln Coal \), \( \ln Oil \), \( \ln Gas \), \( \ln Elec \), \( \ln CEC \), \( \ln CCCoal \), \( \ln CCOil \), \( \ln CGas \), and \( \ln CCElec \) sequences, it is necessary to explore whether long-term equilibrium exists among the sequences and reduce the possibility of false returns. Therefore, this paper uses the Johansen method to test for cointegration relations among the \( \ln Y \), \( \ln EC \), and \( \ln CEC \) sequences (GDP, energy consumption and the associated carbon emissions); the \( \ln Y \), \( \ln Coal \) and \( \ln CCCoal \) sequences (GDP, coal consumption and the associated carbon emissions); the \( \ln Y \), \( \ln Oil \) and \( \ln CCOil \) sequences (GDP, oil consumption and the associated carbon emissions); the \( \ln Y \), \( \ln Gas \), and \( \ln CGas \) sequences (GDP, natural gas consumption and the associated carbon emissions); and the \( \ln Y \), \( \ln Elec \), and \( \ln CCElec \) sequences (GDP, electricity consumption and the associated carbon emissions).

Since the Johansen cointegration test is sensitive to the selection of the lag order, we construct the vector autoregressive model VAR \((k)\) of \( \ln Y \), \( \ln EC \), and \( \ln CEC \) and determine the vector autoregressive order \( k \) by comprehensively
H0 Trace test Max. Eigen test Co-integration

|                          | H0          | Trace test | Max. Eigen test | Co-integration |
|--------------------------|-------------|------------|-----------------|----------------|
| Total energy consumption | $R \leq 0$  | 29.72166 (0.0510)** | 21.34633 (0.0467)** | $\checkmark$ |
|                          | $R \leq 1$  | 38.75331 (0.4262) | 8.085050 (0.3701) | $\times$       |
|                          | $R \leq 2$  | 0.290281 (0.5900) | 0.290281 (0.5900) | $\times$       |
| Coal consumption         | $R \leq 0$  | 32.68111 (0.0226)** | 24.34997 (0.0170)** | $\checkmark$ |
|                          | $R \leq 1$  | 8.331135 (0.4307)  | 8.074331 (0.3712)  | $\times$       |
|                          | $R \leq 2$  | 0.256803 (0.6123)  | 0.256803 (0.6123)  | $\times$       |
| Oil consumption          | $R \leq 0$  | 40.71213 (0.0019)*** | 22.11899 (0.0362)** | $\checkmark$ |
|                          | $R \leq 1$  | 18.59313 (0.0165)** | 18.57556 (0.0098)** | $\checkmark$ |
|                          | $R \leq 2$  | 0.017576 (0.8944)  | 0.017576 (0.8944)  | $\times$       |
| Gas consumption          | $R \leq 0$  | 26.26489 (0.1209)  | 20.84789 (0.0547)** | $\checkmark$ |
|                          | $R \leq 1$  | 5.417003 (0.7630)  | 4.523801 (0.8003)  | $\times$       |
|                          | $R \leq 2$  | 0.893202 (0.3446)  | 0.893202 (0.3446)  | $\times$       |
| Electricity consumption  | $R \leq 0$  | 35.49808 (0.0099)*** | 27.39423 (0.0058)*** | $\checkmark$ |
|                          | $R \leq 1$  | 8.103845 (0.4544)  | 7.991732 (0.3794)  | $\times$       |
|                          | $R \leq 2$  | 0.110112 (0.7400)  | 0.110112 (0.7400)  | $\times$       |

The $P$-values are given in parentheses. *, **, and *** show significance at the 10%, 5%, and 1% levels

Using the AICc, AIC, Schwarz information criterion, final prediction error, and Hannan-Quinn information criterion. This paper sets the lag period at 2 to establish a second-order VAR model. The specific lag-order selection criteria are shown in Tables 5, 6, 7, 8, and 9 of the Appendix. According to formulas (2)–(6), this paper selects the hypothesis model with intercept terms and trend terms for the Johansen cointegration test. The test results are shown in Table 2.

The cointegration test of the five models rejects the null hypothesis in the trace test and the maximum eigenvalue test, i.e., $R \leq 0$, and can therefore judge $R = 1$. Therefore, there is one cointegration relation between the sequences of each model, indicating that long-term equilibrium exists among carbon emissions, energy consumption, and economic growth at the total and heterogeneous energy levels. Due to this cointegration relation, further research on economic growth and energy consumption at the total and heterogeneous energy levels is necessary to determine the long-term and short-term effects of carbon emissions.

Joint causality and feedback mechanism

To further clarify the relations among the three considered variables and avoid the mutual influence of the long-term equilibrium relation in the test process, this paper uses short-term and long-term Granger causality tests based on the VECM for $\Delta \ln \text{Y}$, $\Delta \ln \text{EC}$, and $\Delta \ln \text{CEC}$ (GDP, total energy consumption and the associated carbon emissions); $\Delta \ln \text{Y}$, $\Delta \ln \text{Coal}$, and $\Delta \ln \text{CCoal}$ (GDP, coal consumption and the associated carbon emissions); $\Delta \ln \text{Y}$, $\Delta \ln \text{Oil}$, and $\Delta \ln \text{COil}$ (GDP, oil consumption and the associated carbon emissions); $\Delta \ln \text{Y}$, $\Delta \ln \text{Gas}$, and $\Delta \ln \text{CGas}$ (GDP, natural gas consumption and the associated carbon emissions); and $\Delta \ln \text{Y}$, $\Delta \ln \text{Elc}$, and $\Delta \ln \text{CElc}$ (GDP, electricity consumption and the associated carbon emissions). The test results are shown in Table 3.

In the short term, there are two-way causal relations between CO2 emissions and energy consumption and between CO2 emissions and economic growth at the total energy level. At the heterogeneous level, there are two-way causal relations between coal consumption and carbon emissions, coal consumption and economic growth, oil consumption and carbon emissions, oil consumption and economic growth, CO2 generated by natural gas and electricity and economic growth, and CO2 generated by natural gas and electricity and their respective energy consumption.

In the long term, there are two-way causal relations between CO2 emissions and total energy consumption and between CO2 emissions and economic growth; that is, energy consumption and economic growth promote carbon emissions, which in turn drive energy consumption and economic growth. At the heterogeneous level, there is a two-way causal relation between coal consumption and CO2; that is, economic growth causes CO2 generation via coal consumption. There are two-way causal relations between oil consumption and CO2 emissions, natural gas consumption and CO2 emissions, electricity consumption and CO2 emissions, and electricity consumption and economic growth.

Moreover, at the total energy level, the $ECM_{t-1}$ coefficients of all functions are $-0.19487, -0.00678 \ldots -0.07723$, and $-0.03443$, indicating that in the short term, the nonequilibrium error of each variable is corrected by the corresponding ratio to the economic variables in the considered year when energy consumption, economic growth, and CO2 emissions deviate from equilibrium; this result basically conforms to the negative feedback correction mechanism. That is, the energy consumption, economic growth, and CO2 emissions of the previous year pull the nonequilibrium state back to the long-term equilibrium state with adjustment ranges of 19.5%, 0.6%, 7.7%, and 3.4%. Among them, at the heterogeneous level, the $ECM_{t-1}$ coefficients of the carbon emissions due to coal, oil, gas, and electricity are $-0.233$, $-0.581$, $-0.261$, and $-0.166$, respectively.
| Variables                  | Short term | Long term |
|----------------------------|------------|-----------|
|                           |            | Intercept | ΔLaC & ECM | ΔLaY & ECM | ΔLaE & ECM |
|                           |            | ΔLaC       | ΔLaY       | ΔLaE       | ECM        | Intercept | ΔLaC & ECM | ΔLaY & ECM | ΔLaE & ECM |
| Total energy consumption  |            | 1.94929 (<0.0001) | /          | 0.23453 (<0.0001) | 0.55436 (<0.0001) | -0.19487 (0.0141) | -0.04757 (0.0149) | /          | 0.97844 (<0.0001) | 0.22962 (0.0268) |
| ΔLaY                      | -4.5504 (<0.0001) | 1.75186 / | /          | -0.03078 (0.9272) | -0.06678 (0.7267) | 0.06889 (0.0003) | 0.3422 / | /          | -0.02706 (0.0158) |
| ΔLaE                      | -1.38066 (0.005) | 1.05696 / | /          | -0.00786 (0.9272) | /          | -0.11801 (0.2147) | 0.04187 (0.0042) | 0.77175 / | -0.38116 (0.3951) |
| Coal consumption          |            | Intercept | ΔLaC       | ΔLaY       | ΔLaE       | ECM        | Intercept | ΔLaC & ECM | ΔLaY & ECM | ΔLaE & ECM |
| ΔLaCCoal                  | 2.40304 (<0.0001) | /          | 0.03286 (0.7189) | 0.72899 (<0.0001) | -0.23256 (0.002) | -0.04737 (0.049) | /          | 0.97454 (0.0013) | 0.15684 (0.0285) |
| ΔLaY                      | -0.81631 (0.3246) | 0.11405 / | /          | 1.33348 (<0.0001) | 0.00923 (0.6844) | 0.07221 (0.0044) | 0.23648 / | /          | 0.00881 (0.8898) |
| ΔLaCoal                   | -2.13833 (0.002) | 0.64283 / | /          | 0.33881 (<0.0001) | /          | -0.26455 (0.0454) | 0.02931 (0.0088) | 0.74227 / | -0.0935 (0.8556) |
| Oil consumption           |            | Intercept | ΔLaC       | ΔLaY       | ΔLaE       | ECM        | Intercept | ΔLaC & ECM | ΔLaY & ECM | ΔLaE & ECM |
| ΔLaCOil                   | 1.60505 (<0.0001) | /          | -0.01649 (0.3935) | 0.85788 (<0.0001) | -0.581 (0.0022) | -0.0082 (0.4913) | /          | 0.0541 (0.7152) | 0.90852 (<0.0001) |
| ΔLaY                      | 1.8629 (0.4382) | 1.26627 / | /          | 2.7905 (0.0279) | 0.00923 (0.6844) | -0.01345 (0.0057) | 0.07331 (0.2834) | 0.19817 / | 0.07489 (0.7329) |
| ΔLaOil                    | -1.76015 (<0.0001) | 1.05616 / | /          | 0.04682 (0.0279) | /          | -0.44733 (0.0048) | 0.02931 (0.0088) | 0.74227 / | -0.0935 (0.8556) |
| Gas consumption           |            | Intercept | ΔLaC       | ΔLaY       | ΔLaE       | ECM        | Intercept | ΔLaC & ECM | ΔLaY & ECM | ΔLaE & ECM |
| ΔLaCGas                   | -0.16111 (0.4804) | /          | 0.13611 (0.001) | 0.80117 (<0.0001) | -0.26167 (0.0351) | 0.00602 (0.8751) | /          | 0.1488 (0.7608) | 0.69016 (<0.0001) |
| ΔLaY                      | 4.47385 (<0.0001) | 1.98159 / | /          | -0.83677 (0.1191) | 0.01778 (0.1911) | 0.07836 (0.0001) | 0.0321 (0.5769) | /          | 0.02916 (0.6574) |
| ΔLaGas                    | -0.16994 (0.3516) | 1.13232 / | /          | -0.08123 (0.1191) | /          | -0.12072 (0.2427) | 0.01667 (0.5657) | 0.71191 / | 0.42545 (0.3545) |
| Electricity consumption   |            | Intercept | ΔLaC       | ΔLaY       | ΔLaE       | ECM        | Intercept | ΔLaC & ECM | ΔLaY & ECM | ΔLaE & ECM |
| ΔLaCEl                    | -0.01533 (0.9762) | /          | 0.66721 (<0.0001) | 0.19477 (0.1325) | -0.16658 (0.1512) | -0.02444 (0.2689) | /          | 0.27418 (0.375) | 0.90447 (0.0005) |
| ΔLaY                      | 2.26041 (<0.0001) | 0.70997 / | /          | 0.49333 (0.0008) | -0.07723 (0.1053) | 0.04818 (0.1094) | 0.08257 (0.0094) | /          | 0.3722 (0.0151) |
| ΔLaE                      | -3.70822 (<0.0001) | 0.32592 / | /          | -0.03443 (0.3052) | 0.01884 (0.1603) | 0.33448 (0.0004) | 0.43017 (0.0164) | /          | 0.3722 (0.0158) |

The $P$-values are given in parentheses.
These findings are similar to the research of A. Ahmad et al. (2016) in India. These results indicate that the speed of adjustment toward the long-term equilibrium of the oil energy function is faster than the speeds of other energy source functions. Such a situation can be attributed to several factors, such as increasing oil prices, decreasing oil energy use, and the effective use of technology. The adjustment toward the long-term equilibrium of electricity is slower than those of other energy sources. The results also show that, from the perspectives of economic growth and environmental protection, gas energy is better than other energy sources.

**Model stability test**

We test the stability of the estimation model using the unit circle test method, and the results are shown in Fig. 2. The inverse roots of AR characteristic polynomials are in the unit circles, indicating that the VECM is stable.

Figure 3 shows the impulse response of models at the disaggregated level. The response of variable $x$ to variable $y$ indicates a reaction or response to $x$ caused by a change in $y$. The pulse response diagram coincides with our above analysis.

**Analysis of the decoupling effect of energy heterogeneity**

In order to further explore the coordinated changes and development trends of carbon emissions, energy consumption, and economic growth in China, the classified study on the decoupling causality relation among China’s carbon emissions, energy consumption, and economic growth from 2001 to 2019 is conducted, and comprehensively analyzes the internal mechanisms that affect China’s main energy decoupling.

**Heterogeneity decoupling between energy consumption and economic growth**

According to formula (10), the decoupling elasticity of China’s economic growth and varying energy consumption from 2001 to 2019 is calculated, and the decoupling state is divided according to the elasticity value. The results are shown in Fig. 4.
Fig. 3 Impulse response of models at the disaggregated level. *Data source: application results

Fig. 4 Decoupling elasticity of heterogenous energy from 2001 to 2019 in China. *Data sources: National Bureau of Statistics, the China Statistical Yearbook, the China Energy Statistics Yearbook and IEA database
Figure 4 shows the decoupling relation between China’s main energy consumption and economic growth. By comparing the decoupling elastic curves of China’s total energy and each major energy source, a significant difference is found. The reason for this phenomenon is that, on the one hand, various energy sources account for different proportions of China’s energy structure, leading to differences in the effects of different energy sources on the operation of the national economy; on the other hand, the reason for this phenomenon lies in the changes in China’s economic development policies and development models that have occurred over the past 20 years.

Coal is the energy source accounting for the highest proportion and is the most commonly used energy source in the operation of China’s national economy. From 2001 to 2005, the decoupling index of coal experienced “weak decoupling-expansive negative decoupling-expansive coupling.” During this period, China focused on economic development, using coal as the main energy source, and the coal consumption also increased rapidly from less than the economic growth rate to basically equal to it, indicating that China’s economic development was highly dependent on coal consumption during this period. From 2006 to 2012, the carbon emissions generated by coal consumption and economic growth were always in a fluctuating weak decoupling state, indicating that the growth rate of coal consumption was under control. During this period, China constantly adjusted its energy structure and industrial structure, and tertiary industries gradually emerged. The high dependence of China’s economic development on energy consumption eased. At the same time, the continuous emergence of the greenhouse effect, extreme weather, environmental degradation, and other problems also caused energy conservation, emission reductions, sustainable development, and other issues to appear in the historical stage of China’s development. In 2013, the decoupling index of coal showed a leapfrog development, from weak decoupling in 2012 to expansive negative decoupling. This was due to China’s four trillion financial plan enacted in response to the 2008 financial crisis, which enabled China to maintain steady economic growth from 2009 to 2012. However, in 2013, the global economy was in a state of low growth, low inflation, and high debt. The economic development dividends brought about by the financial plan gradually disappeared, and China was in a period of shifting growth rates, which caused a jump in the coal decoupling index in 2013. From 2014 to 2019, China successively proposed a new economic normal and high-quality development, gradually shifting its economic growth from “high speed” to “high quality,” and a sustainable green circular economy gradually became the mainstream economic orientation. During this period, coal consumption and economic growth also showed a decoupling state from strong to weak, fully demonstrating that China’s series of measures aimed at saving energy, reducing emissions, and achieving green development have achieved remarkable results.

As the second major energy source in China, oil also plays an important role in economic development. From 2001 to 2019, oil consumption and economic growth were basically in a weak decoupling state. Only a short-term expansive coupling period occurred in 2004, and the oil decoupling index was basically within the range of 0~0.8, indicating that China’s economic growth was not highly dependent on oil. In comparison, coal has always been the dominant energy source in China’s energy structure.

Natural gas was basically in an expansive coupling state from 2001 to 2019; that is, the rate of natural gas consumption was basically the same as the rate of economic growth. This was due to China’s continuous promotion of clean energy to replace high-carbon energy and continuously popularize the use of natural gas in social life. The natural gas decoupling index from 2015 to 2017 was in a weak decoupling state. The main reason for this change trend is that China gradually began to reduce the speed of economic development and pay attention to the quality of economic development while increasing efforts to implement energy-saving and emission-reduction policies and develop clean energy, resulting in major changes in natural gas consumption and economic growth at this stage.

The electricity decoupling index was basically in a weak decoupling state from 2001 to 2019, with only a short period of expansive negative decoupling from 2002 to 2003 and a short period of strong decoupling in 2014 to 2015. As a representative of clean energy, electricity guarantees the production and activity of Chinese society. Although electricity consumption does not produce carbon dioxide, indirect carbon emissions from electricity consumption are directly related to carbon emissions from coal consumption since China mainly uses coal as the main electricity generation method. The change trend of the electricity decoupling index and the coal decoupling index in Fig. 4 are basically the same, which can also prove the above point of view.

However, by looking at the change trend of each energy decoupling index, we find that after 2016, each energy carbon emission decoupling index displayed a relatively obvious growth trend, indicating that the dependence of economic growth on various energy sources was rebounding. The overall situation in which China’s economic growth largely depends on energy consumption has not been fundamentally reversed; China still has a long way to go to truly decouple economic growth from energy consumption, economic growth, and carbon emissions. However, it can also be found from the above analysis that the multiple measures
currently taken by China for energy conservation and emission reductions have achieved relatively significant results and have effectively alleviated China’s energy and environmental crises to a certain extent. Therefore, determining how to maintain and surpass the current good development trend requires guidance regarding energy and economic development policy with greater intensity and higher precision.

**Decoupling decomposition of energy carbon emissions and economic growth**

According to formulas (11) – (15), the carbon emissions of different energy sources are added to the decoupling model, and the decoupling elasticity is decomposed into the emission reduction elasticity and energy saving elasticity according to the formula to carry out a comprehensive decoupling analysis of energy consumption, carbon emissions, and economic growth. This paper calculates the decoupling elasticity, emission reduction elasticity, and energy-saving elasticity of China’s economic growth and the carbon emissions of various energy sources from 2001 to 2019 and divides the decoupling state according to the elasticity values. The results are shown in Fig. 5.

At the total energy level, the energy-saving elasticity experienced the fluctuation of “weak decoupling-expansive coupling-expansive negative decoupling-expansive coupling” from 2001 to 2005, which is closely related to the high-speed economic development dominated by high energy consumption in China during this period. From 2005 to 2019, the energy-saving elasticity was in a weak

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*Data sources: National Bureau of Statistics, the China Statistical Yearbook, the China Energy Statistics Yearbook and IEA database*
As shown in Fig. 5d, both the energy-saving elasticity of electricity and emission reduction elasticity have shown a weak decoupling state since 2004. This shows that the emission reduction effect produced by electricity consumption has effectively promoted the formation of decoupling. Establishing a cleaner and more efficient way to generate and use electricity and increase the proportion of clean electricity will aid in the far-reaching development of energy-saving and emission-reduction strategies.

Conclusion and recommendations

Research conclusion

This paper explores the systemic interaction among CO$_2$ emissions, energy consumption, and economic growth. First of all, the Granger causality test based on VECM is used to determine and analyze the long-term and short-term relations among China’s CO$_2$ emissions, energy consumption, and economic growth at the level of energy heterogeneity from 1980 to 2019 and improves the feedback correction mechanism of the 3E (Economy-Energy-Emissions) system. Afterwards, the Tapio decoupling elasticity is decomposed into the emission reduction elasticity and energy-saving elasticity, and it is shown that the decoupling elasticity of electricity has基本上 converged to a weak decoupling state since 2004.

First, there are long-term equilibrium relations among total energy consumption, economic growth, and CO$_2$ emissions in China. Energy consumption has two-way causal relations with both economic growth and CO$_2$ emissions. For every 1% increase in GDP, CO$_2$ emissions increase by 0.98%, and for every 1% increase in energy consumption, CO$_2$ emissions increase by 0.23%.

Second, there is a two-way causality relation between coal consumption and CO$_2$ emissions, while economic growth and CO$_2$ emissions from coal consumption only have a one-way causality relation from economic growth to CO$_2$ emissions with no causal feedback connection. There are two-way causality relations between oil consumption, natural gas consumption, and electricity consumption and CO$_2$ emissions,
and there is a two-way causality relation between electricity consumption and economic growth.

Third, the error correction coefficients of the model are $-0.19487, -0.00678, ..., -0.07723$, and $-0.03443$; that is, the various energy consumption sources, economic growth, and CO$_2$ emissions in the previous year are adjusted by 19.5%, 0.6%, ..., 7.7%, and 3.4% to bring the nonequilibrium state back to long-term equilibrium. The economic variables of the considered year are basically in line with the negative feedback revision mechanisms.

Fourth, the energy-saving elasticity of total energy which has relatively optimistic development trend is the main reason for the decoupling elasticity in China. But the state of the emission reduction elasticity is not optimistic, showing that improving energy efficiency and promoting the cleanliness of traditional energy sources are important ways to promote the decoupling of energy consumption and economic growth.

Fifth, the energy-saving elasticity of coal, oil, and natural gas is the main factor affecting the decoupling elasticity. Paying attention to the energy-saving properties of coal, oil, and natural gas helps promote the sustainable development of their decoupling states. Moreover, both the energy-saving elasticity and emission reduction elasticity of electricity impact the decoupling elasticity, but the relative influence of the emission reduction elasticity is stronger. Therefore, the establishment of a cleaner and more efficient power generation method and an increase in the proportion of clean electricity would contribute to the far-reaching development of energy conservation and emission reduction strategies.

**Policy recommendations**

First, optimize the energy structure, and construct a clean, low-carbon, safe, and efficient energy system. Using clean coal, optimizing the energy structure, and increasing the proportion of clean energy are still the main future directions for China’s energy-related economic development. China’s government should vigorously introduce advanced energy technologies, promote transformations from coal to gas and from coal to electricity as primary energy sources, develop large-scale hydropower, wind power, and photovoltaic power generation applications, actively develop biomass energy technology, broaden the channels for foreign trade imports of new energy sources, and fundamentally reduce the consumption costs of new types of energy, thereby reducing dependence on fossil energy.

Second, deepen the reform of the electricity system, and construct a new electricity system based on new energy. Coal electricity is currently the main electricity generation method in China, which is one of the main reasons why China’s power decoupling is similar to coal decoupling. China should continue to develop clean energy to replace fossil energy, and gradually build a new energy-based electricity generation system to reduce fossil fuel consumption from the source, forming a positive chain effect on energy, environment, and economy.

Third, improve the top-level design, and accelerate the realization of the 3060 targets. Achieving carbon peak and carbon neutrality is a systematic change in an economic society. It is not only necessary to improve green and low-carbon policies and market systems, forming a green and low-carbon economic market environment, but also to focus on improving the capacity of ecological carbon sinks and the carbon sequestration of resources and environment. China should make comprehensive efforts in policy, market, environment, ecology, and other fields to form an overall layout of ecological civilization construction, and implement policy regulation with a systematic concept.

**Further discussion**

This paper starts a study on the systemic relation among economy, energy, and environment from a macro perspective in China. With the continuous changes of the current world situation and the continuous development of research needs, the related research can be further extended in the following aspects: (1) Improve the micro perspective. Integrate social and personal behaviors and other factors into the 3E system, such as residents’ well-being and social lifestyles, to improve the research chain of environment, energy, economy, and society. (2) Incorporate digital factors. With the integration of digital technology into the social economy, the traditional economic model has gradually shifted to a platform economic model based on digital technology. It is necessary to explore the impact of the platform economic model on energy and environment. (3) Open a global perspective. Saving resources and tackling climate change are global issues. Countries around the world continue to trade, exchange, and cooperate to coordinate international resources and respond to climate change. Therefore, 3E system research can be extended to a global perspective to explore the effects of globalization-related factors.
### Table 4: Results of ADF unit root analysis

| Variable | T-statistic | Prob.* | Critical value at each significance | Decision |
|----------|-------------|--------|-------------------------------------|----------|
| LnY      | −3.366768*  | 0.0772 | 3.646342, 2.954021                  | I(1)     |
| LnEC     | −5.526245***| 0.0003 | 4.234972, 3.540328                  | I(1)     |
| LnCoal   | −5.516024***| 0.0003 | 4.234972, 3.540328                  | I(1)     |
| LnOil    | −4.294081***| 0.0017 | 3.626784, 2.945842                  | I(1)     |
| LnGas    | −5.194797***| 0.0008 | 3.540328, 3.202445                  | I(1)     |
| LnElc    | −2.928621*  | 0.0519 | 3.626784, 2.945842                  | I(1)     |
| LnCEC    | −3.046450*  | 0.0573 | 3.587527, 3.229230                  | I(1)     |
| LnCCoal  | −3.366768*  | 0.0772 | 3.626784, 2.945842                  | I(1)     |
| LnCOil   | −5.049402***| 0.0002 | 3.626784, 2.945842                  | I(1)     |
| LnCGas   | −3.732206***| 0.0076 | 3.626784, 2.945842                  | I(1)     |
| LnCElc   | −4.525827***| 0.0009 | 3.626784, 2.945842                  | I(1)     |

* *, **, and *** show significance at the 10%, 5%, and 1% levels

### Table 5: Selection of VAR lag order of Total Energy consumption

| Lag  | AICc   | AIC    | SC     | FPE    | HQC   |
|------|--------|--------|--------|--------|-------|
| AR0  | −8.996944 | −9.001212 | −8.871929 | 0.001233 | −8.955214 |
| AR1  | −19.85721 | −19.93583 | −19.41337 | 2.20E-09 | −19.75164 |
| AR2  | −20.31566* | −20.59727* | −19.67355* | 1.15E-09* | −20.27487* |
| AR3  | −19.90009 | −20.58581 | −19.25265 | 1.21E-09 | −20.1256 |
| AR4  | −18.9381 | −20.35827 | −18.60744 | 1.63E-09 | −19.76118 |
| AR5  | −17.38457 | −20.12254 | −17.9458 | 2.38E-09 | −19.39013 |

### Table 6: Selection of VAR lag order of Coal consumption

| Lag  | AICc   | AIC    | SC     | FPE    | HQC   |
|------|--------|--------|--------|--------|-------|
| AR0  | −8.849427 | −8.853694 | −8.724411 | 0.001429 | −8.807697 |
| AR1  | −18.97896 | −19.05759 | −18.53513 | 5.30E-09 | −18.8734 |
| AR2  | −19.49615* | −19.81174* | −18.85404* | 2.61E-09* | −19.45535* |
| AR3  | −19.12602 | −19.77775 | −18.47858 | 2.61E-09 | −19.35153 |
| AR4  | −18.10212 | −19.52229 | −17.77146 | 3.76E-09 | −18.92521 |
| AR5  | −16.81908 | −19.55705 | −17.38031 | 4.19E-09 | −18.82464 |

### Table 7: Selection of the VAR lag of Oil consumption

| Lag  | AICc   | AIC    | SC     | FPE    | HQC   |
|------|--------|--------|--------|--------|-------|
| AR0  | −12.53255 | −12.53681 | −12.40753 | 3.59E-06 | −12.49082 |
| AR1  | −21.00674 | −22.08536 | −20.5629 | 2.57E-10 | −21.90117 |
| AR2  | −21.91275* | −22.19436* | −21.27064* | 2.33E-10* | −21.97195* |
| AR3  | −21.30554 | −21.99126 | −20.6581 | 2.96E-10 | −21.53105 |
| AR4  | −20.63072 | −22.05089 | −20.30007 | 3.00E-10 | −21.45381 |
| AR5  | −18.96676 | −21.70473 | −19.52799 | 4.89E-10 | −20.97233 |
Table 8: Selection of VAR lag order of gas consumption

| Lag | AICc  | AIC   | SC    | FPE   | HQC   |
|-----|-------|-------|-------|-------|-------|
| AR0 | -6.811134 | -6.815402 | -6.686119 | 0.0010968 | -6.769404 |
| AR1 | -18.13642  | -17.21504  | -16.69258  | 1.33E-08  | -17.03085 |
| AR2 | -18.872*   | -18.15361* | -17.22989* | 1.33E-08* | -17.83121* |
| AR3 | -17.25254  | -17.93825  | -16.60509  | 1.70E-08  | -17.47805 |
| AR4 | -16.42755  | -17.84772  | -16.09689  | 2.01E-08  | -17.25064 |
| AR5 | -15.05305  | -17.79101  | -15.61428  | 2.45E-08  | -17.05861 |

Table 9: Selection of VAR lag order of electricity consumption

| Lag | AICc  | AIC   | SC    | FPE   | HQC   |
|-----|-------|-------|-------|-------|-------|
| AR0 | -10.75916 | -10.76342 | -10.63414 | 0.0000212 | -10.71743 |
| AR1 | -21.06386  | -21.14248  | -20.62002  | 6.59E-10  | -20.95829 |
| AR2 | -21.74538* | -22.02699* | -21.10327* | 2.76E-10* | -21.70458* |
| AR3 | -21.11201  | -21.79773  | -20.46457  | 3.59E-10  | -21.33752 |
| AR4 | -20.3635   | -21.78367  | -20.03284  | 3.92E-10  | -21.18659 |
| AR5 | -18.93816  | -21.67613  | -19.49939  | 5.04E-10  | -20.94373 |

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Data availability The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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