SPATIO-TEMPORAL PATTERNS AND DRIVERS OF ENERGY CONSUMPTION IN CHINA, BASED ON THE ENERGY BALANCE SHEET

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Abstract. As the world's largest energy consumer, a timely assessment of China's energy consumption characteristics is critical for sustaining stable economic growth and advancing global decarbonisation efforts. Based on the energy balance sheet (EBS), this study presents the spatio-temporal patterns of energy consumption and production in China through the centre of gravity method from 2000 to 2020, and employs the Shapley value to quantify the contributions of 30 provinces to the migration of energy centres. Then, the Logarithmic Mean Divisia Index (LMDI) method is used to identify key drivers of energy consumption across successive Five-Year Plan periods. Results show that the energy consumption in China has a pronounced spatial heterogeneity and interdependencies. The rapid growth of energy consumption in regions such as Xinjiang and Shaanxi has driven the westward shift of the consumption centre, while Shanxi has restrained the movement of the centre. Additionally, economic development effect is the main contributing driver for energy consumption growth, while energy intensity effect is the key factor in reducing energy consumption. Notably, with the continuous adjustment of policies, the optimisation of economic structure in China has begun to curb the growing energy demand. These results could guide the future formulation of energy supply and demand policies while facilitating the construction of an ecological civilisation and the achievement of carbon neutrality targets.
Keywords: *spatial heterogeneity, centre of gravity, Shapley value, LMDI, The Five-Year Plan*

Introduction

Energy is an essential material foundation for modern society and economic development. In recent decades, energy consumption in China has increased dramatically, driven by multiple factors such as rapid economic development (Wang et al., 2011). This growth has transformed the nation from a net energy exporter last century into a major global importer. Nevertheless, fossil fuels continue to dominate both China's and the global energy mix (Wei et al., 2020). The resultant greenhouse gas emissions from massive combustion of fossil fuels contribute to significant negative impacts, such as global warming and heightened frequency of extreme weather events (Quadrelli and Peterson, 2007). As the world's largest energy consumer and carbon emitter, China is under enormous pressure from the international community to reduce carbon emissions. Demonstrating commitment to global climate governance, China formally announced its "3060" target at the 2020 United Nations General Assembly, pledging to achieve carbon peak by 2030 and carbon neutrality by 2060 (Zhao et al., 2022). This ambitious goal means that the energy system in China is facing systemic and disruptive change. Consequently, systematically analysing the spatio-temporal evolution and identifying key drivers of China's energy

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consumption become imperative – both for navigating short-term challenges and long-term goals, and for accelerating the essential transition towards a future low-carbon energy.

Recognising the imperative for enhanced energy management, the National Development and Reform Commission (NDRC) in China proposed to improve control over both total energy consumption and intensity in 2021. Since the 12th Five-Year Plan, reducing energy intensity has been incorporated as a binding target within China's national economic and social development plans, subsequently cascaded to provincial levels (Liu et al., 2015). However, as a vast country with diverse geography and pronounced inter-regional economic disparities, China exhibits significant spatial heterogeneity in energy consumption patterns (Kang and Yang, 2010). Compounded by varying resource endowments and close inter-provincial economic and energy linkages, energy consumption in China has a strong spatial correlation (Wu and Li, 2008). Meanwhile, the use of medium- and long-term plans, such as the Five-Year Plan, to guide the low-carbon energy transition and even socio-economic development is one of China’s key governance approaches (Yuan and Zuo, 2011). The distinct policy priorities of each Five-Year Plan period reflect the evolving strategic focus of the Chinese government. Therefore, analysing China's energy consumption necessitates explicit consideration of its spatially uneven and spatially correlated patterns, as well as the impact of different policy cycles.

Many previous studies have analysed the spatio-temporal distribution pattern of energy consumption in China through the heat map method, centre of gravity model, spatial econometrics, social network analysis, etc, and further distinguished the role positioning of different regions (Li and Han, 2023; Liu et al., 2015, 2022; Peng et al., 2021; He et al., 2024). This paper also adopts the centre of gravity model to analyse the spatial distribution and dynamic evolution of energy consumption in China. The location of the centroid of energy consumption depends on the geographical attributes and energy consumption of the study object. If the geographical attributes are constant, changes in the trajectory of the centre correspond to changes in energy consumption. Therefore, the centre of gravity model can show the evolution of the spatio-temporal distribution of energy consumption in a concise form. The centre of gravity originates from physics and was first introduced into the population field by Hilgard (Hilgard, 1872). Its application has since expanded significantly to study the spatio-temporal distribution of population, economy, energy, and carbon emissions (Fesharaki, 1996; Klein, 2009; McKee et al., 2015; Zhang and Wang, 2014). Specifically, some scholars have analysed the distribution of energy consumption and production in China through the changes in the centre (Zhang et al., 2012). Some have also studied the migration paths of different types of fuel consumption centres, such as coal, oil, and electricity, and further analysed the changes in the position, distance, and rate of energy consumption centres (Liu et al., 2019; Sun et al., 2015; Zhang et al., 2014).

In the literature on energy consumption change, many studies use the decomposition method to analyse the drivers behind energy consumption change. Ang and Choi propose the Logarithmic Mean Divisia Index (LMDI) method based on the traditional exponential decomposition, which overcomes the problems of decomposition residuals and zero values (Ang and Choi, 1997). Therefore, the LMDI method is an ideal method for studying changes in energy consumption (Ang, 2004) and has been adopted in a large number of related studies. Some examine the changes in energy consumption in the European Union, China, Turkey, and other regions or countries (Akyurek, 2020; Gonzalez et al., 2014). Some studies analyse the consumption of individual energy types

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(Rogan et al., 2012). Beyond its inherent simplicity and computational ease, the LMDI framework offers significant versatility: it supports multi-level decomposition (e.g., by region, sector, or fuel type) (Yu et al., 2020) and integrates effectively with complementary analytical tools such as Cobb-Douglas production functions and energy allocation models (Chong et al., 2017; Wang et al., 2014).

Although previous literature provides valuable insights into the spatio-temporal pattern of energy consumption in China, there are still some research gaps: (1) Prior analyses fail to quantify the specific contributions of individual regions to national energy consumption changes or reveal the underlying spatial interdependencies governing these changes. (2) Few studies systematically address the distinct functional roles played by different provinces within the national energy landscape. While Liu et al. (2015) employed social network analysis to explore provincial roles within spatial correlation networks, this approach cannot quantify the actual energy flow across regions due to data availability. (3) Decomposition analyses of energy consumption drivers frequently neglect the energy lost during processing, conversion, and transportation. Suppose this component linking total energy consumption to terminal consumption is not taken into account during the decomposition process, the accuracy of the results and the effectiveness of policies may be compromised.

This study uses the centre of gravity model to reveal the spatio-temporal distribution patterns of energy consumption in China, while estimating the contribution of each province that caused the centre shifts through the Shapley value. Additionally, we also identify the functional role by combining the energy transfers in and out of provincial energy balance sheets. Finally, this study analyses the key drivers of energy consumption changes in China's 10th to 13th Five-Year Plans since the 21st century (covering four periods: the 10th five-year plan from 2000 to 2005, the 11th five-year plan from 2006 to 2010, the 12th five-year plan from 2011 to 2015, and the 13th five-year plan from 2016 to 2020). The possible marginal contributions of this study: (1) Based on the quantitative energy relations in the EBS, it explores the contribution of 30 provinces to the centre shift and their role in the energy consumption relationship. (2) By decomposing total primary energy consumption, including processing, conversion, and transport losses, we supplement energy efficiency analysis from the perspective of energy loss. (3) Taking the Five-Year Plan as consecutive policy cycles, this allows us to directly link observed patterns and drivers to evolving national policy priorities, offering concrete guidance for formulating effective low-carbon transition strategies within the framework of the future Five-Year plan.

This study is organised as follows: Section 2 introduces the research methodology, data sources and processing; Section 3 analyses the dynamic development of the spatio-temporal patterns of energy consumption in China, and also explores the key drivers of energy consumption changes at different five-year plans; Section 4 presents the conclusions of this study and explains the research gaps.

Methods and data

Centre of gravity model

This study uses the centre of gravity to reflect the evolution of the spatio-temporal distribution of energy consumption in China. In summary, the spatial distributions of different fuel consumption are displayed by the locations of the centres, and the trends over time are reflected by the trajectories of these centres. It is hypothesised that the centre

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moves in the two-dimensional plane determined by latitude and longitude, without considering the effect of altitude in the third dimension (Zhang et al., 2012). This simplification can achieve the research objective without compromising the accuracy and applicability of results. In the absence of city-level energy balance sheets, this study uses provincial energy data to calculate the corresponding energy centre. Additionally, the geographical attributes use the latitude and longitude of the administrative location (provincial government) of 30 provinces (excluding four provincial administrative regions, including Tibet, Hong Kong, Macao and Taiwan, owing to data availability). The centre of energy consumption is calculated by *Equation 1*:

$$\begin{cases} \bar{X}_t = \sum_{d=1}^{30} Q_{dt} \cdot X_d \Big/ \sum_{d=1}^{30} Q_{dt} \\ \bar{Y}_t = \sum_{d=1}^{30} Q_{dt} \cdot Y_d \Big/ \sum_{d=1}^{30} Q_{dt} \end{cases} \tag{Eq.1}$$

(X_d, Y_d) are the geographical coordinates of the longitude and latitude of region d, and Q_{dt} is the energy consumption of region d at time t. The results $(\bar{X}_t, \bar{Y}_t)$ are the location of the energy consumption centre in China in year t[1]. To further compare the spatio-temporal patterns of different fuels, this study also calculates the results of their production and consumption centres.

Shapley value

The Shapley value method originates from cooperative game theory (Shapley, 1953), which concerns the distribution of benefits or costs among players in a bureau. Shorrocks and Anthony (2013) propose a factor contribution measurement based on the Shapley value. The shift of energy consumption centre decomposition is essentially nonlinear, so we can apply the Shapley value to calculate the contributions of each province when energy consumption centres shift. Specifically, the research area of this study is composed of 30 provinces $K = \{1,2,\cdots,k,\cdots,30\}$. *Equation 2* provides the calculation for the marginal contribution of region k to the shift of energy consumption centre.

$$MC_k = \Delta\bar{x}(K) - \Delta\bar{x}(K\backslash\{k\}) \tag{Eq.2}$$

However, the contribution obtained by *Equation 2* is not an exact decomposition, as the sum of individual marginal movements does not necessarily equal the total movement. Therefore, consider the ranking order $\sigma = (\sigma_1, \sigma_2, \cdots, \sigma_{30})$ for all regions $K = \{1,2,\cdots,k,\cdots,30\}$ must be considered. Let region k be in the r-th position, i.e., $\sigma = (\sigma_1, \sigma_2, \cdots, \sigma_{r-1}, \sigma_r = k, \cdots, \sigma_{30})$, then define the set of $r-1$ regions in front of k to be $Pre^k(\sigma) = (\sigma_1, \sigma_2, \cdots, \sigma_{r-1})$. The marginal contribution of region k under this arrangement is given by *Equation 3*.

$$MC_k(\sigma) = \Delta\bar{x}(Pre^k(\sigma) \cup \{k\}) - \Delta\bar{x}\left(Pre^k(\sigma)\right) \tag{Eq.3}$$

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[1] The latitude and longitude ranges in China are all within the region of north latitude and east longitude, so the influence of north-south latitude and east-west longitude need not be considered in calculating the centre of gravity.

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To eliminate path dependence, consider $n!$ permutations, and all combinations are denoted as $\prod(n)$. Therefore, the contribution of the k-th region for the movement of the centre is obtained from *Equation 4*.

$$C_k = \frac{1}{n!}\sum_{\sigma\in\prod(n)} MC_k(\sigma) = \frac{1}{n!}\sum_{\sigma\in\prod(n)} \left[\Delta\bar{x}(Pre^k(\sigma)\cup\{k\}) - \Delta\bar{x}\left(Pre^k(\sigma)\right)\right] \quad \text{(Eq.4)}$$

The contribution decomposition based on Shapley value considers the influence of the geographical location of the k-th region, and also takes into account the influences among other regions. Moreover, the results have both positive and negative effects, which can reflect the contribution of each province while also providing its direction of effect. In practical calculations, we need to calculate the permutations of 30 provinces, which can reach up to 30!. To solve the problem of huge computational load, we adopt a polynomial algorithm based on sampling theory for approximate calculation (Castro et al., 2009). The principle is to replace the expected value with the sample mean value, and the calculation accuracy of the results also meets the requirements.

LMDI decomposition

The dynamic changes in the spatio-temporal patterns of energy consumption are caused by changes in energy consumption. This requires further analysis of the drivers behind energy consumption in China (Liu et al., 2019). Therefore, we employ the LMDI method to study the drivers of energy consumption, but made some adjustments based on the quantitative relationship of EBS. There is an energy gap between the total energy consumption and the final energy consumption, that is, the loss caused by energy processing, conversion and transportation. This gives *Equation 5*:

$$E_{total} = E_{loss} + E_{final} \quad \text{(Eq.5)}$$

E_{total} is the total energy consumption; E_{loss} is the energy loss; E_{final} is the final energy consumption, which indicates the actual final energy consumption of each industry. Thus, the change in energy consumption in China can be divided into two parts according to *Equation 5*.

$$\Delta E_{total} = E_{total}^T - E_{total}^0 = \Delta E_{loss} + \Delta E_{final} \quad \text{(Eq.6)}$$

Meanwhile, based on the Kaya model and existing studies (Wang et al., 2014), a factorial formula for final energy consumption is obtained.

$$\begin{aligned} E_{final} &= \sum_{i,j} E_{ij} = \sum_{i,j} \frac{E_{ij}}{E_i}\cdot\frac{E_i}{G_i}\cdot\frac{G_i}{G}\cdot\frac{G}{P}\cdot P \\ &= \sum_{i,j} ECS_{ij}\cdot ECI_i\cdot GS_i\cdot PCE\cdot POP \end{aligned} \quad \text{(Eq.7)}$$

In *Equation 7*, E_{ij} is the final energy consumption of energy type j in industry i; E_i is the final energy consumption of industry i; G_i is the economic output of industry i; G is the gross domestic product (GDP); and P is the total population. The final energy consumption depends on the five factors: energy consumption structure (ECS), energy

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consumption intensity (ECI), economic structure (GS), per capita gross domestic product (PCE) and population size (POP). This study adopts the “additive” method in LMDI decomposition, which is not fundamentally different from the “multiplication” method (Ang, 2015). Therefore, the change in final energy consumption is decomposed by the relationship in *Equation 8*.

$$\Delta E_{final} = E_{final}^{T} - E_{final}^{0} = \Delta E_{ecs} + \Delta E_{eci} + \Delta E_{gs} + \Delta E_{pce} + \Delta E_{pop} \quad \text{(Eq.8)}$$

Finally, the driving factors for the change in total energy consumption can be obtained by combining *Equation 6*.

$$\Delta E_{total} = \Delta E_{loss} + \Delta E_{ecs} + \Delta E_{eci} + \Delta E_{gs} + \Delta E_{pce} + \Delta E_{pop} \quad \text{(Eq.9)}$$

where ΔE_{loss} is the loss effect, which reflects the losses in thermal power generation, heat supply, transport, etc. ΔE_{ecs} is the energy structure effect, which measures the restructuring of energy consumption. ΔE_{eci} denotes the energy intensity effect, reflecting the efficiency of the combined energy use. ΔE_{gs} is the economic structure effect, reflecting the impact of economic restructuring. ΔE_{pce} is the economic scale effect, reflecting the impact of economic development. ΔE_{pop} is the population scale effect, reflecting the change in total energy consumption due to population change. The expressions for the calculation of each effect are:

$$\Delta E_{loss} = E_{loss}^{T} - E_{loss}^{0} \quad \text{(Eq.10)}$$

$$\Delta E_{index} = \sum_{i,j} \frac{E_{ij}^{T} - E_{ij}^{0}}{lnE_{ij}^{T} - lnE_{ij}^{0}} \cdot ln\frac{INDEX^{T}}{INDEX^{0}} \quad \text{(Eq.11)}$$

Equation 11 is a representative equation for the remaining five effects, and the index replaces each effect symbol.

Data and processing

This study selects statistical data from 30 provincial-level regions in China from 2000 to 2020. The latitude and longitude data of the provincial government location come from the coordinate picking system of Baidu Maps (https://api.map.baidu.com/lbsapi/getpoint/index.html). The data on energy production, consumption, transfer in and out at the provincial level, and the energy conversion coefficients for standard coal are all drawn from the China Energy Statistical Yearbook, which provides national and provincial energy balance sheets. The data concerning population and GDP are drawn from the annual data section of the National Bureau of Statistics.

The primary energy and secondary energy products in the provincial EBS are converted into coal, oil, natural gas, primary electricity and other energy based on energy conversion factors. Then, this study calculates the amount of energy production, consumption, and transfer to and from each province according to the quantitative relationship of EBS. The provincial energy inflow includes the amount of energy

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transferred from other provinces and imported from abroad. Conversely, the energy outflow exerts an opposing treatment.

Results and discussions

The trajectory of the energy centre

This study presents a geospatial visualisation of the dynamic evolution of different fuel consumption centres with the help of the ArcGIS software. We also calculate the geographical centre of the study area, whose latitude and longitude are the arithmetic mean of the coordinates of the administrative locations of 30 provinces. The geographical centre can be regarded as the point of uniform spatial distribution, as well as a reference point for the migration of energy consumption and production centres (*Fig. 1*).

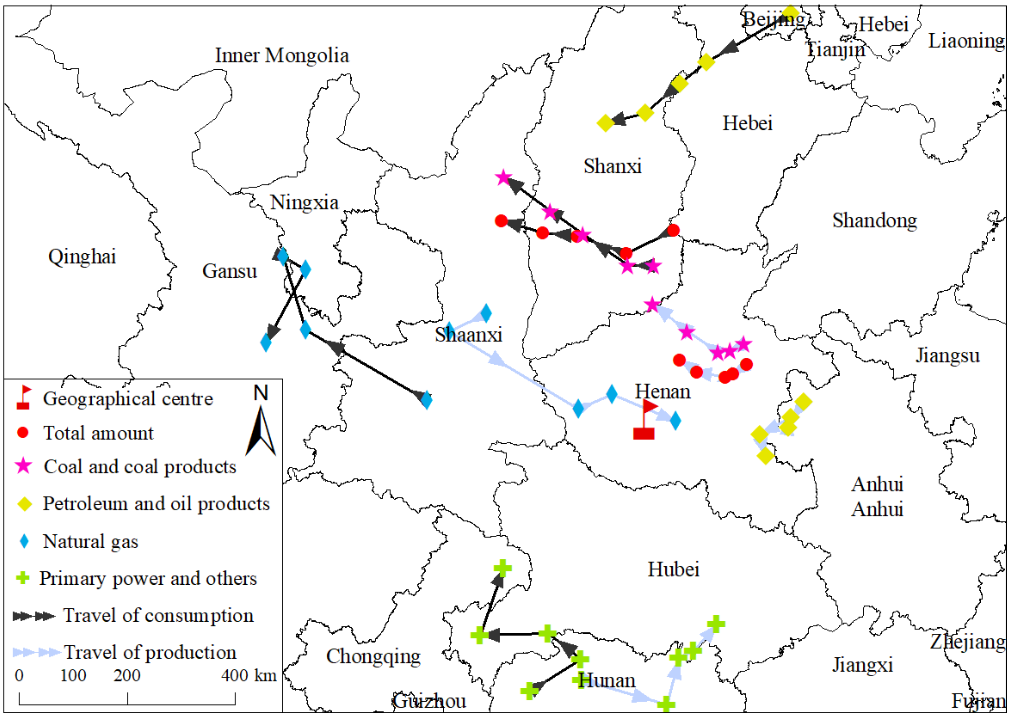

Figure 1. *The trajectories of consumption and production centres in China by energy types*

The centres of energy consumption and production deviate from the geographical centre, indicating a spatial imbalance between energy consumption and production in China. The considerable distance between these two centres suggests a spatial separation between energy supply and demand. The energy consumption centre is located in the northeast of the geographical centre, as the economically developed provinces in China are mainly concentrated in the coastal areas. During the study period, the energy consumption centre shifted westwards from Zhoukou City to Zhengzhou City, Henan Province, meaning that the energy consumption growth rate in western China is faster than that in the eastern region. The western region is poised to emerge as the primary catalyst for future energy consumption growth, which would reshape relevant spatio-temporal patterns. Consequently, it is imperative to recalibrate the layout of supporting energy infrastructure accordingly. In addition, the distance between the energy consumption centre and the geographical centre has decreased, meaning that the spatial imbalance of energy consumption has been alleviated. These indications offer indirect evidence suggesting an improvement and enhancement in regional coordinated development in China.

Besides, the shifting trends of consumption centres of coal and total energy are highly synchronised. This is because coal dominates the energy consumption structure in China. However, the share of coal in energy consumption has been declining in recent years, from 71.5% in 2000 to 62.2% in 2020. The synchronisation of these two centres has decreased. The oil consumption centre is concentrated in the eastern part of the geographical centre, indicating that the core consumption area of oil and oil products is mainly in the east. The natural gas consumption centre shifts westward during the 10th Five-Year Plan period, but it remains largely stagnant since then. The western regions have consistently served as China's primary natural gas production and consumption area. However, with the diversification of gas sources and the ongoing development of transport infrastructure such as the West-East Gas Pipeline, natural gas consumption in eastern regions has also been steadily increasing. Finally, this study analyses the consumption of primary electricity and other energy, which is mainly composed of hydropower. The “West-East Electricity Transmission Project” transport the abundant hydropower from the southwestern region to the eastern and southern coastal regions. Consequently, the primary electricity consumption centre is mainly concentrated in the south of the geographical centre, with a tendency to move eastwards.

The spatio-temporal patterns of energy consumption are contingent on the production situation. The energy production centre is located north of the geographical centre, showing that current energy production areas are mainly concentrated in northern China. Meanwhile, the spatial unevenness of energy production is more pronounced than that of energy consumption. In terms of temporal dynamics, there is a discernible shift in the geographical distribution of energy production centres. Specifically, the energy production centre is migrating westwards from Changzhi City, Shanxi Province, to Yan'an City, Shaanxi Province. This migration is concomitant with a substantial increase in production in specific regions, including the coal industry in Shaanxi and the natural gas industry in Xinjiang. The locations of the different fuel production centres also accurately reflect the energy endowments across regions. China's mineral wealth is geographically concentrated, with coal reserves found predominantly in the Shanxi, Shaanxi, and western Inner Mongolia regions. Oil reserves are primarily located in northern areas, such as Heilongjiang, while natural gas reserves are concentrated in western regions, including Xinjiang. Primary power and other energy sources, such as hydropower, are mainly concentrated in southwestern areas, such as Yunnan and Guizhou.

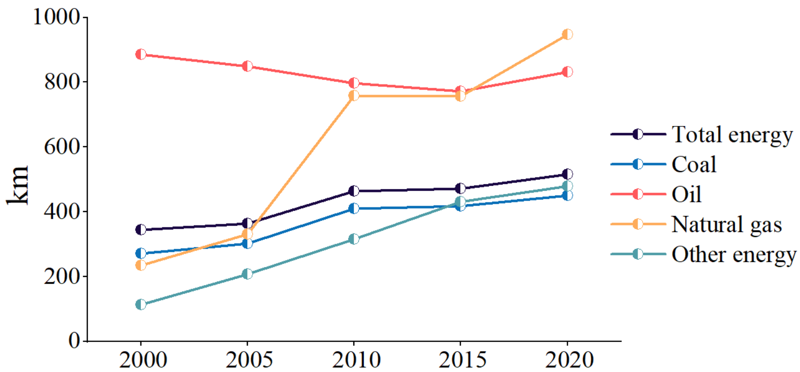

Figure 2. *The distance between the centres of energy supply and demand in China*

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Finally, this study analyses the distance between the centres of energy consumption and production (*Fig. 2*). The substantial distance indicates a pronounced spatial imbalance in China's energy system. In response to this issue, China has established extensive energy transport infrastructure to connect energy suppliers and consumers, enabling energy to flow across regions. Consequently, energy consumption between regions exhibits a strong spatial correlation. Coal-rich regions such as Shanxi and Inner Mongolia transfer electricity from thermal power generation through the power grids. This has led to coal consumption and production centres located in northern China. However, the centres of oil consumption and production are far apart. This is because China's dependency on imported oil has increased in recent years, with most of the petroleum and oil products coming from shipping lanes. Notably, the distance between natural gas supply and demand centres abruptly widened from 2005 to 2010. China's natural gas production and import hubs are predominantly concentrated in the western regions. In recent years, imported liquefied natural gas via sea routes has been unable to meet the growing demand in the eastern region.

The contribution to energy centre shift

This study further utilised the Shapley value to identify the contributions of 30 provinces. Notably, the movement of the centre is the result of the resultant force, and each region affects the direction and distance of the centre migration. We then mainly discuss the influence on the distance (*Table 1*).

Table 1. *Contributions of 30 provinces to the migration process of different energy centres*

Energy type	Total energy (%)		Coal (%)		Oil (%)		Natural gas (%)		Other energy (%)	
	Cons.	Prod.	Cons.	Prod.	Cons.	Prod.	Cons.	Prod.	Cons.	Prod.
Beijing	0.0	-6.5	0.4	1.7	0.0	27.5	305.0	6.9	0.2	5.1
Tianjin	-3.4	-14.7	0.0	-1.7	-11.5	30.2	533.2	6.2	0.6	3.2
Hebei	0.0	-15.2	0.8	-0.6	0.0	15.1	8.3	2.2	10.1	11.3
Shanxi	-14.0	40.1	-17.2	21.5	0.0	3.8	740.0	-1.4	7.7	0.7
Inner Mongolia	-1.3	88.2	14.2	52.5	-0.2	11.5	145.0	-2.4	22.6	2.2
Liaoning	1.6	-161.1	2.3	-33.7	5.9	234.1	-293.9	5.8	16.3	22.1
Jilin	-0.6	-60.2	1.4	-14.7	-1.1	49.9	492.0	4.9	6.0	0.2
Heilongjiang	7.1	-104.7	-0.3	-26.2	101.9	29.0	1131.0	0.3	7.2	5.5
Shanghai	-0.5	-39.2	0.0	1.4	-0.2	51.7	402.9	16.8	0.0	15.6
Jiangsu	-0.4	-110.3	2.2	-36.2	0.0	28.2	102.9	31.3	3.8	26.5
Zhejiang	-2.2	-92.5	0.1	-20.9	0.0	35.6	0.0	23.0	-0.1	36.2
Anhui	-5.5	-38.9	-8.3	-16.2	0.0	3.5	51.5	7.5	0.7	-1.0
Fujian	-1.3	-51.7	1.6	-19.3	0.0	-19.3	0.0	10.6	-9.1	10.3
Jiangxi	0.6	-15.7	2.1	-8.5	0.0	-14.9	0.0	3.4	-1.3	2.8
Shandong	-2.9	-83.8	-2.8	-23.6	2.7	63.5	-26.9	12.8	9.4	22.3
Henan	-1.2	2.5	-1.8	-0.9	-0.4	1.3	-219.0	1.9	3.5	5.0
Hubei	-0.9	-10.9	0.8	-4.6	-0.1	-28.4	2.1	4.4	-2.0	2.7
Hunan	0.1	1.7	1.1	-5.7	0.0	-53.0	0.5	3.2	-3.5	0.0
Guangdong	-2.5	-63.4	0.6	-21.2	-2.3	66.1	2070.9	31.6	-20.0	0.7
Guangxi	0.3	30.2	0.3	-0.5	0.8	-55.1	2.1	2.4	-10.8	-8.0
Hainan	0.0	4.8	0.0	-0.6	0.5	-24.9	15.2	5.5	-2.6	-0.7
Chongqing	-0.2	20.8	0.7	1.2	0.0	-44.9	494.4	-4.4	-0.3	-6.1
Sichuan	6.6	88.1	-0.1	3.8	-0.2	-119.1	125.5	-20.1	7.4	-32.0

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Guizhou	3.0	29.2	-2.7	0.4	0.0	-72.9	22.4	-0.2	-5.2	-2.3
Yunnan	7.3	72.2	0.1	7.1	0.0	-119.1	-0.1	-0.9	-12.4	-25.6
Shaanxi	17.2	57.8	6.7	18.0	20.8	-2.1	3119.2	-5.4	2.9	1.0
Gansu	4.4	47.5	1.9	13.8	15.0	-3.7	-23.3	-4.6	12.2	-6.1
Qinghai	3.4	27.8	1.1	3.3	0.5	-11.3	-640.4	-7.0	13.5	-10.0
Ningxia	3.9	78.5	5.3	35.6	-1.5	0.3	0.1	-3.4	6.8	10.7
Xinjiang	81.4	379.3	89.3	175.1	-30.7	17.5	-8460.9	-31.0	36.5	7.8

Over the past two decades, the centre of total energy consumption shifted by 404.71 km from east to west, with Xinjiang and Shaanxi contributing 81.4% and 17.2%, respectively, to this movement. For example, energy consumption in Xinjiang rose dramatically from 29.92 million tons coal equivalent (Mtce) in 2000 to 203.86 Mtce in 2020, marking an increase of 581.42%. In contrast, Shanghai's energy consumption grew by 83.05% during the same period. The shares of these regions in China's total energy consumption have also experienced contrasting trends. The proportion of energy consumption in Xinjiang increased from 2.18% to 4.18%, while that of Shanghai decreased from 3.99% to 2.05%. Additionally, Yunnan and Sichuan contributed 7.3% and 6.6%, respectively. Shanxi emerged as a primary region restraining the shift of the energy consumption centre, exhibiting a contribution rate of -14%. Meanwhile, the production centre moved 153.59 km from east to west, with regions such as Xinjiang, Inner Mongolia, Sichuan, and Ningxia being key contributors to this shift; provinces like Liaoning, Jiangsu, and Heilongjiang played opposite roles. For instance, energy production in Xinjiang surged from 51.13 Mtce in 2000 to an impressive level of 289.75 Mtce by 2020, whereas Liaoning's production declined from 53.81 Mtce to 45.96 Mtce during the same timeframe.

The centres of coal consumption and production both shifted northwest by 404.44 km and 226.38 km, respectively, primarily due to the influence of regions such as Xinjiang and Inner Mongolia. The centres of oil consumption and production moved southwest by 519.16 km and 145.63 km, respectively. The former shift is mainly attributed to Heilongjiang, Shaanxi, Xinjiang, etc, while the latter is predominantly influenced by Liaoning, Sichuan, and Yunnan. The centre of natural gas consumption migrated northwest by 389.68 km, whereas the production centre shifted southwest by 492.16 km. These changes are largely driven by Shaanxi, Guangdong, Heilongjiang, Xinjiang, among others. Additionally, the consumption centre for other energy sources relocated northward by 268.07 km—primarily due to influences from Xinjiang, Inner Mongolia, and Guangdong—while the production centre advanced northeast by 313.03 km, mainly owing to provinces in Zhejiang, Jiangsu, Liaoning, and Yunnan.

The functional roles of provinces

This study identifies the roles of Chinese provinces in the energy system based on energy transfers in and out of provincial EBS (*Fig. 3*).

Provinces with net energy transfer in China have abundant energy resources and provide significant support for the rapid economic development of other provinces. The provinces receiving net energy transfer are predominantly concentrated along the eastern coast of China, where economic activity is stronger than in other parts of the country. Shanxi and Heilongjiang were the main provinces with energy outflow in 2000. Shanxi's net energy outflow reached 187.50 Mtce, while Heilongjiang's reached 63.02 Mtce. Other

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provinces with net energy outflows included Inner Mongolia, Shandong, Henan, Guizhou, Shaanxi, and Xinjiang. In 2010 and 2020, Shanxi, Inner Mongolia, and Shaanxi became the main provinces with net energy outflows, with significant increases in net energy transfer. Provinces that accept net energy transfer include Jiangsu, Shandong, Hebei, Guangdong, Zhejiang, Shanghai, Hubei, whose local resources cannot meet their huge energy demand, making them highly dependent on external energy sources. In contrast, Hainan, Sichuan, Guizhou, Yunnan, and other regions have basically achieved self-sufficiency. These areas can be divided into two categories: one with relatively low energy demand, such as Hainan; and the other with rich energy resources that could meet their energy demand, such as Sichuan (*Fig. 4*).

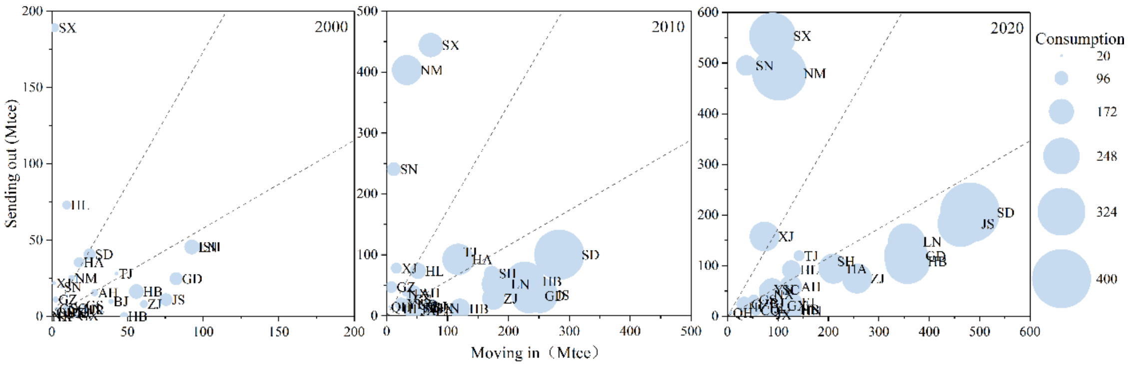

Figure 3. *Comparison of energy inflow, outflow, and consumption across China's provinces*

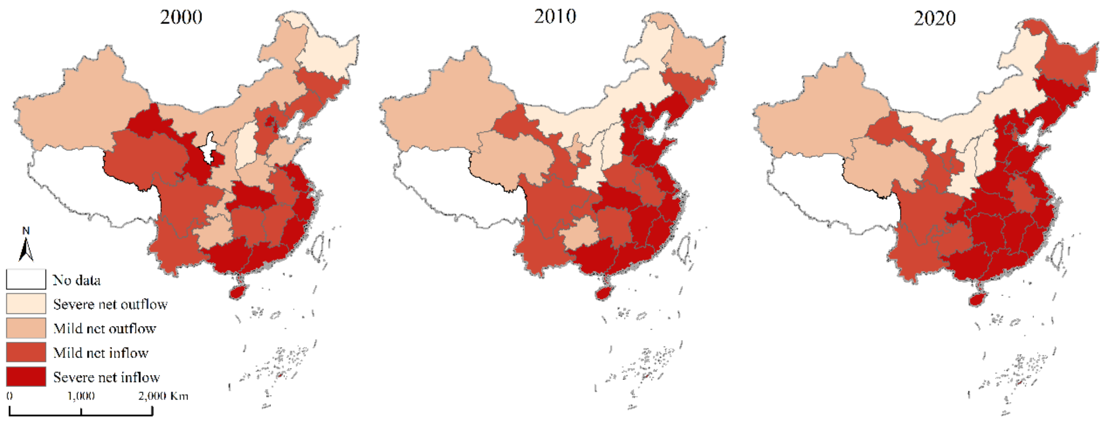

Figure 4. *The functional roles of provinces in China's energy consumption patterns. Note: These provinces were categorised based on energy dispatch and dependence coefficients, both set at 50%. GS(2024)0650*

Finally, we distinguish the functional roles of the 30 provinces in China's spatio-temporal energy consumption patterns. Shanxi, Shaanxi, and Inner Mongolia are all provinces with severe net energy outflows. They take on the core task of securing China's energy supply, mainly supplying fuels to eastern and northern areas. Meanwhile, many provinces have an energy dependence coefficient exceeding 50%, with energy supplied by neighbouring provinces or imported. The roles of Heilongjiang, Shandong, Henan, and Chongqing changed significantly during the study period. Hegang City and Qitaihe City

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in Heilongjiang Province entered the list of resource-exhausted cities in China, meaning that Heilongjiang will encounter increased pressure of economic transformation in the future. Shandong, Chongqing, and Henan, have transitioned from provinces with mild net outflows to provinces with severe net inflows. Their energy production cannot meet the energy demand for rapid economic development.

The drivers behind changes in energy consumption

The energy, economic, and population data were obtained from the China Energy Statistical Yearbook and the National Bureau of Statistics of China. To eliminate the effect of inflation, the GDP and industrial GDP were adjusted by the GDP index and the industrial value-added indices, respectively. Meanwhile, this study classifies agriculture, forestry, hunting, and fishing as the primary industry; The secondary industry covers industrial manufacturing and construction, while the tertiary industry refers to all other industries, excluding the primary and secondary industries. The main variables after adjustment are shown in *Table 2*.

Table 2. *Overview of relevant indicators in LMDI*

	Indicators	2000	2005	2010	2015	2020
Nation level	Total energy consumption (Mtce)	1409.93	2508.35	3436.01	4063.12	4557.37
	Energy losses (Mtce)	348.20	580.67	840.24	870.02	978.23
	Total population (Million)	1267.43	1307.56	1340.91	1383.26	1412.12
	GDP (billion RMB)	10028.01	15985.76	27308.78	40007.47	52797.24
Primary industry	Coal energy consumption (Mtce)	8.67	15.98	16.87	20.39	17.50
	Oil energy consumption (Mtce)	11.50	21.18	20.18	25.31	25.89
	Natural gas energy consumption (Mtce)	0.00	0.00	0.07	0.12	0.16
	Other energy consumption (Mtce)	8.50	13.13	16.23	17.84	24.18
	GDP (billion RMB)	1471.74	1770.79	2191.81	2679.47	3166.95
Secondary industry	Coal energy consumption (Mtce)	420.50	898.99	1112.87	1198.67	1072.51
	Oil energy consumption (Mtce)	137.15	176.60	256.08	280.04	399.37
	Natural gas energy consumption (Mtce)	22.41	35.68	61.26	108.84	202.84
	Other energy consumption (Mtce)	156.63	274.82	442.07	591.68	767.53
	GDP (billion RMB)	4566.37	7642.62	13627.46	20049.64	25603.15
Tertiary industry	Coal energy consumption (Mtce)	97.63	140.76	129.89	141.36	86.88
	Oil energy consumption (Mtce)	140.54	229.13	318.69	461.51	471.44
	Natural gas energy consumption (Mtce)	5.37	17.31	50.07	88.65	130.86
	Other energy consumption (Mtce)	52.82	104.11	171.51	258.69	379.99
	GDP (billion RMB)	3989.91	6589.75	11597.54	17502.08	24173.33

We divide the research period into four policy planning periods: the 10th Five-Year Plan (2001-2005), the 11th Five-Year Plan (2006-2010), the 12th Five-Year Plan (2011-2015), and the 13th Five-Year Plan (2016-2020), and 2000 is the starting benchmark. Therefore, we can analyse and compare changes in the drivers affecting energy consumption in each five-year plan. Although total energy consumption in China has increased over the past two decades, the growth rate has slowed. The average annual growth rate of energy consumption reached 12.21% during the 10th Five-Year Plan. Since

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then, the growth rate has declined, dropping to 2.32% during the 13th Five-Year Plan. The amount of energy consumption in China reached 4,557.37 Mtce in 2020, an increase of 3,147.44 Mtce over 2000. Its energy consumption structure is still dominated by fossil fuels, which determines that it faces enormous pressure to reduce carbon emissions and prevent environmental pollution. Therefore, to achieve green development, it is necessary to identify the factors influencing changes in energy consumption. This will enable us to understand the changing spatio-temporal patterns of energy consumption in China.

Figure 5 shows the results obtained through the LMDI method for the effects of loss, energy structure, energy intensity, economic structure, economic scale, and population scale on energy consumption in China for each five-year plan. Economic development is the main driver for promoting energy consumption growth, given that China's rapidly developing economy requires a large amount of energy. It contributed 3646.49 Mtce over two decades, accounting for 115.86% of the total increase. The loss effect followed, adding 630.03 Mtce and contributing 20.02%. Coal is the primary source of secondary energy, including electricity, heat, etc. With the increasing demand for these secondary energy sources, more energy is lost in the processing and conversion process. Meanwhile, the population increased by 144.69 million during this period, contributing an additional increase of 260.52 Mtce. The structures of the economy and energy consumption also promote energy consumption growth, increasing by 106.96 Mtce and 6.68 Mtce, respectively. Energy intensity is the key factor restraining the rapid growth of energy consumption. It reduced energy consumption by 1503.25 Mtce, and the contribution rate reached -47.76%.

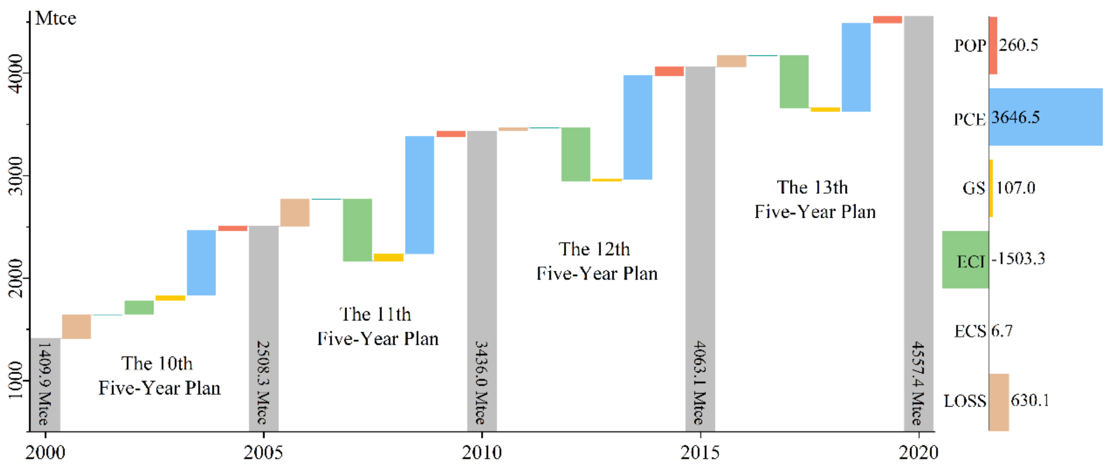

Figure 5. *Contributions of drivers to energy consumption changes during China's four Five-Year Plans*

However, the impact of these factors varies across different policy cycles. For example, energy intensity was an important driver for energy consumption growth during the 10th Five-Year Plan, accounting for 12.37% of the total. Subsequently, it became the core factor in restricting energy consumption growth, with a more pronounced effect. The contribution of energy intensity to energy consumption growth during the 13th Five-Year Plan reached -103.65%. Accordingly, China's energy consumption intensity showed an increasing trend during the 10th Five-Year Plan, after which it has been steadily declining (see *Fig. 6*). The year 2005 was an important turning point for China's economy to shift

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from extensive to intensive development, and it began to focus on development efficiency. In the 11th Five-Year Plan, China set an energy intensity target for the first time, proposing to reduce energy consumption per unit of GDP by about 20%. Since then, the five-year plans have consistently included energy intensity as one of the mandatory indicators of economic development. Since 2005, energy intensity has been on a downward trend, gradually curbing the rapid growth of energy consumption.

Another notable effect is the economic structure, which has driven energy consumption growth from the 10th to the 12th Five-Year Plan. However, it became a factor restraining energy consumption growth in the 13th Five-Year Plan, reducing by 37.14 Mtce. At the end of 2015, China initiated supply-side structural reform and began optimising its industrial structure. In particular, the 13th Five-Year Plan saw China introduce stricter requirements for developing high-energy-consuming and high-polluting industries. Measures were explicitly proposed to control carbon emissions in key sectors such as electricity, iron and steel, building materials, and chemicals while promoting low-carbon development in critical sectors such as industry, energy, construction, and transport. Alongside these environmental sustainability efforts, China further advocated high-quality development in 2017 and emphasised the importance of optimising economic structures to foster economic growth. Consequently, economic restructuring began to constrain energy consumption growth during the 13th Five-Year Plan.

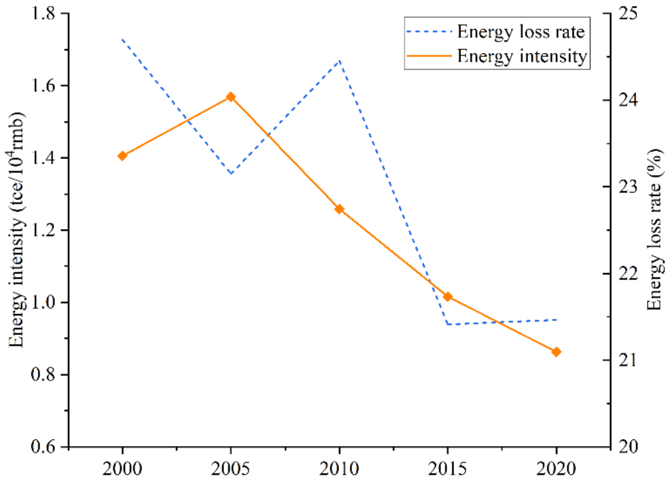

Figure 6. *Trends in energy intensity and energy loss rate in China*

Moreover, both economic scale and loss effects have consistently served as significant drivers of energy consumption growth; conversely, contributions from changes in energy structure and population scale remain relatively inconspicuous. Specifically, the contribution of the loss effect showed a fluctuating downward trend throughout the study period, which is likely attributable to improvements in thermal power generation and transportation efficiency in China. Similar trends have also been observed in the loss rate associated with energy transformation and transport in recent years (see *Fig. 6*). This is inextricably linked to initiatives aimed at dismantling small thermal power plants alongside stringent entry barriers concerning coal power efficiency standards. Finally, it is important to note that changes in China's energy structure have driven increased energy consumption.

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Conclusions

As China enters the decisive phase of its carbon peaking and carbon neutrality commitments, clarifying the spatio-temporal patterns and identifying the drivers of energy consumption in China can provide useful complements for formulating the future-oriented policy planning. This can help to reconcile economic development and energy consumption growth, as well as achieve the “3060” target. This study examines the spatio-temporal patterns of energy consumption in China and the functional role of each province from 2000 to 2020 by provincial energy balance sheets, and further analyses the key drivers of changes in energy consumption at policy cycles through the LMDI method.

We find that energy consumption in China exhibits significant spatial heterogeneity and interdependence. Geographically, the national consumption centre resides in the east, yet demonstrates a westward shift, reflecting the energy consumption growth rate in select central and western provinces is markedly faster compared to the eastern region. Consumption centres for specific fuels display distinct regional patterns: the coal consumption centre aligns closely with major production basins, while the oil centre remains concentrated in the east. Conversely, the consumption centres of natural gas and primary electricity are predominantly located in the west and south. In terms of spatial correlation, energy flows between different provinces are closely interlinked, and the functional roles of these provinces within the energy system also vary considerably. It is evident that the provinces of Shanxi, Shaanxi and Inner Mongolia play a pivotal role in ensuring national energy security. In contrast, the central and eastern provinces demonstrate a significant reliance on interprovincial transfers and imports. The positions of other provinces, such as Heilongjiang and Shandong, are shifting due to resource depletion or surging demand. Additionally, the decomposition results reveal that economic development is the primary driving force of energy consumption growth, while energy intensity serves as an important restraining factor. Policy-driven economic restructuring is progressively restraining consumption growth.

These findings also suggest some significant policy insights. It is crucial to plan the construction of energy infrastructure based on the spatial patterns of supply and demand, with particular emphasis on inter-regional transmission networks and storage. Proactive transition in resource-depleting areas represented by Heilongjiang requires integrated policies addressing the energy issue and economic diversification. Meanwhile, the decomposition results indicate that China needs to intensify efforts to enhance energy efficiency to mitigate unreasonable demand surges, particularly in regions exhibiting rapid consumption growth. Furthermore, China should continuously optimise its economic and energy structures through the mechanism of successive five-year plans, primarily owing to its institutional strengths. This capacity for iterative optimisation can simultaneously advance high-quality development and energy targets by decoupling growth from resource intensity.

This study acknowledges some inherent limitations, which can guide further research. We focus on the spatio-temporal patterns and driving forces of primary energy consumption in China, but actual final energy consumption is secondary energy, such as electricity and gasoline. Comparing the distribution of primary and secondary energy in future work can inform insights to optimise the operational efficiency of China's energy system. Meanwhile, in the analysis of driving factors, future work could be further refined to the provincial or even municipal level. Detailed decomposition can facilitate targeted policy formulation, allowing for the implementation of energy management based on the local development and resource endowments.

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