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Spatial and Temporal Patterns of Green Energy Development in China

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Abstract: The development of non-conventional energy sources is not only an important guarantee for national energy security but also a key support for the realization of carbon peaking and carbon neutrality goals. However, there is limited knowledge of the spatial and temporal patterns and changing characteristics of green energy development in China. Here, based on the energy production and consumption data of the last decade, we combined the gravity center model and statistical model to assess the spatial and temporal patterns of non-conventional energy in 31 provinces of China. The research results show: (1) under the impetus of the development of green low-carbon and ecological civilization strategy, the rate of increase in the production of non-conventional energy in China and the proportion of it increase year by year, and the energy structure obviously presents the characteristics of being low-carbon and cleaner. (2) For the spatial patterns of non-conventional energy development, due to the development of wind power and photovoltaic constraints by natural resource conditions and technology, their development trend is best in northeast, north, and northwest China. (3) The generation of PV and wind power is dominated by northwest China and north China, and the generation of nuclear power is dominated by southeast China, whereas the consumption is dominated by east China and central China; there is an obvious spatial imbalance between non-conventional energy production and consumption. (4) The proportion of photovoltaics in non-conventional energy production has increased significantly over the 2010–2020 period, which is the main driver of the overall shift in the gravity center of non-conventional energy production towards the northwest region of China. (5) In recent years, the gradual transfer of industries from the east to the central and western regions of China and the improvement in the economic level of the western regions have led to an increase in energy production and consumption, promoting a shift in the gravity center of energy production and consumption to the west. Overall, the structural transformation of China's energy production and consumption (from a high-carbon black structure to a low-carbon and carbon-free green structure) is progressing, and some provinces have achieved significant results, presenting a non-conventional energy industry in accordance with local conditions and the development trend of the non-conventional energy industry.

Keywords: non-conventional energy sources; gravity center model; spatial and temporal patterns; green development of energy

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1. Introduction

The state of national energy development affects a country's politics and economy [1], and energy security is related to a country's social development and is an important part of national security [2,3]. As the world's largest developing country, China is rich in coal resources but poor in oil and gas [4]. Due to its high energy consumption, China has become a net importer of oil since the 1990s [5], and its dependence on oil has been increasing year by year [6]. By the end of 2021, China's dependence on crude oil and natural gas will be as high as 73% and 45%, respectively [7]. The long-term coal-based energy consumption structure has caused China to face serious environmental problems and enormous energy security challenges [8,9]. It is urgent to vigorously develop new low-carbon energy sources and change the energy structure [10,11]. However, there is still a great uncertainty in the knowledge of non-conventional energy development in China. Therefore, it is important to study the spatial and temporal changes in the production and consumption of new and conventional energy sources and to clearly understand the development of non-conventional energy sources in China, which will be conducive to improving the energy structure, guaranteeing national energy security, mitigating climate change, and improving the ecological environment [6].

At present, numerous studies have investigated energy from different scales and multiple aspects. For example, the overall global energy security pattern shows a negative growth trend, and the contradiction between supply and demand is prominent [12,13]; There are significant differences in per capita energy consumption between provinces [14], and the scale of energy consumption in Chinese cities shows a trend of decreasing total consumption from east to west [15]. In terms of specific content, there are analyses of temporal and spatial changes in the production and consumption of single energy sources, such as coal and natural gas [16], and studies on the forecast of future energy demand [17]. Currently, various methods have been applied to the research of energy distribution and developmental changes [18–26], such as cluster analysis, two-factor trend graph analysis, K-mean clustering, ESDA analysis, the coefficient of variation method, the gravity center model, the unintended output SBM model, the Malmquist index, and so on. Among them, the gravity center model can combine spatial–temporal information with production and consumption information to realize research on the spatial pattern and evolution trajectory problems of the regional economy, resource consumption, and pollution emission [20]. Compared with other methods, the gravity center model can show the distribution and change in the center of gravity of energy. Using the gravity center model to study energy production and consumption can visualize the direction and trend in changes in energy production and consumption [18].

In September 2020, China proposed the goals of "Carbon peaking" by 2030 and "carbon neutrality" by 2060 [27]. In order to better realize the "Carbon peaking" and "carbon neutrality" goals, it is crucial to accelerate the upgrading of the energy industry and to complete the transformation of the energy structure [28], and it is especially necessary to increase a clearer understanding of the pattern of energy development [29,30]. In comparison, although there are many studies on the distribution and development of traditional energy sources, there is a lack of studies describing the evolution of the spatial and temporal patterns of non-conventional energy production and consumption and research on China's non-conventional energy production as well as consumption. Through trend analysis and the center of the gravity model, calculating the center of gravity of energy production and consumption in recent years and analyzing the trajectory of changes in the center of gravity to understand the characteristics of the spatial and temporal distribution of non-conventional energy sources, we can have a clearer understanding of China's energy development situation and make reference to achieving the carbon peaking and carbon neutrality goals.

Hence, based on the research of 31 provincial-level administrative regions (Taiwan, Hong Kong, Macao, and Tibet are not yet available), we obtained the energy production and consumption data from 2010 to 2020 and used the gravity center model to study the evolution of the spatial pattern of non-conventional energy production and consumption and analyze the migration pattern. The goals of this study were to accomplish the following: (1) to understand the spatial pattern evolution of the development of the non-conventional energy source in China and (2) to analyze China's non-conventional energy source development potential and provide a reference for optimizing China's energy structure.

2. Data Source and Methods

2.1. Data Source

As shown in Table 1,the energy and GDP datasets were obtained from the yearbooks and bulletins issued by national and local statistical offices, which include the *Communiqué on indicators such as the rate of reduction in energy consumption of 10,000 CNY of gross regional product*, *CHINA ENERGY STATISTICAL YEARBOOK*, *CHINA ELECTRIC POWER YEARBOOK*, and *ANNUAL REPORT* [31,32]. The maps are based on standard maps downloaded from the website of the Standard Map Service of the Map Technical Review Center of the Ministry of Natural Resources, and the base maps are unaltered.

Table 1. Research data.

Data Type	Time Scale (Yearly)	Data Source
Primary energy production	2010–2019	CHINA ELECTRIC POWER YEARBOOK
wind power, PV, nuclear energy production	2010–2020	CHINA STATISTICAL YEARBOOK
National electricity consumption	2010–2020	CHINA ELECTRIC POWER YEARBOOK
Installed generating capacity	2000–2021	CHINA ELECTRIC POWER YEARBOOK
GDP	2010–2020	CHINA STATISTICAL YEARBOOK
Electricity consumption per unit of GDP/10,000 CNY	2014–2019	Communiqué on indicators such as the rate of reduction in energy consumption of 10,000 CNY of gross regional product
Energy consumption per unit of GDP/10,000 CNY	2014–2019	Communiqué on indicators such as the rate of reduction in energy consumption of 10,000 CNY of gross regional product

Although non-conventional energy sources usually refer to wind energy, PV, nuclear energy, geothermal energy, biomass energy, etc., due to the shortcomings in some of the non-conventional energy sources development and utilization technology, at present, China's development of relatively more mature technology and mass production of non-conventional energy sources are wind energy, nuclear energy, PV, and other non-conventional energy sources [33]. For these reasons, we used wind, PV, and nuclear power generation to represent China's non-conventional energy production. According to the research needs and data availability, specific data used are the rate of increase and decrease in GDP energy consumption, the rate of increase and decrease in GDP electricity consumption in the country by province from 2014 to 2019, national data on installed electricity generation capacity from conventional and non-conventional energy sources from 2000 to 2021, primary energy, wind power, PV, nuclear power production, total electricity consumption, and GDP per 10,000 CNY for the period 2010–2020 by province.

2.2. Analytical Methods

2.2.1. Gravity Center Model

We used the gravity center model and energy production and consumption data to calculate the gravity center of energy production and consumption, including wind power production, PV production, nuclear power production, primary energy production, and national electricity consumption (http://www.stats.gov.cn/sj/ndsj/ accessed 10 August 2022). The gravity center of energy production and consumption is an average energy location derived from a weighted average of energy production or consumption values. It is a characteristic point that takes into account both quantity and spatial distance, which can summarize the distribution of production and consumption in a region [34]. Combined with the map, the center of gravity of energy production and consumption over the years can accurately indicate the central position and trend of change in the distribution of regional energy production and consumption. The direction of its deviation indicates the "hot spot" part of the energy development, and the distance of its deviation can indicate the balanced degree of the distribution of energy production and consumption.

The calculation method of gravity center model is similar to the law of synthesis and decomposition of forces. Assuming that a region has n sub-regions, and the total amount of energy in each sub-region is m_i, and (x_i, y_i) is the latitude and longitude coordinates of region i, the center of gravity of energy of this region in the coordinates of longitude X and latitude Y is calculated as follows:

$$X = \frac{\sum_{i=1}^{n} m_i x_i}{\sum_{i=1}^{n} m_i}, Y = \frac{\sum_{i=1}^{n} m_i y_i}{\sum_{i=1}^{n} m_i} \tag{1}$$

2.2.2. Solving for Gravity Center Offset Distance and Trajectory

According to the sphere surface distance calculation formula, the gravity center displacement distance D can be expressed as Equation (2), where b_t and a_t denote the latitude difference and longitude difference of the gravity center of energy, corresponding to Equations (3) and (4), respectively; R is the radius of the Earth; π is ratio of the circumference of a circle to its diameter; and the offset distance unit is km.

$$D = 2R\arcsin\left(\left(\sin\frac{a_t}{2}\right)^2 + \cos\left(Y_{t+1} \times \frac{\pi}{180}\right) \times \cos\left(Y_t \times \frac{\pi}{180}\right) \times \left(\sin\frac{b_t}{2}\right)^2\right)^{\frac{1}{2}} \tag{2}$$

$$b_t = (X_{t+1} - X_t) \times \frac{\pi}{180} \tag{3}$$

$$a_t = (Y_{t+1} - Y_t) \times \frac{\pi}{180} \tag{4}$$

Equation (6) shows the calculation of the gravity center offset angle θ_{kt} for the calendar year. In this case, if $0 < \theta_{kt} < 90°$, the gravity center is shifted to the northeast; if $90° < \theta_{kt} < 180°$, the gravity center is shifted to the northwest; if $-180° < \theta_{kt} < -90°$, the gravity center is shifted to the southwest; and if $-90° < \theta_{kt} < 0$, the gravity center is shifted to the southeast.

$$\omega_{kt} = \arctan\frac{Y_k - Y_t}{X_k - X_t} \tag{5}$$

$$\begin{cases} \theta_{kt} = -\omega_{kt}, X_k - X_t \leq 0 \\ \theta_{kt} = -\omega_{kt} \times \frac{180}{\pi} + 180, X_k - X_t > 0, Y_k - Y_t \geq 0 \\ \theta_{kt} = -\omega_{kt} \times \frac{180}{\pi} - 180, X_k - X_t > 0, Y_k - Y_t < 0 \end{cases} \tag{6}$$

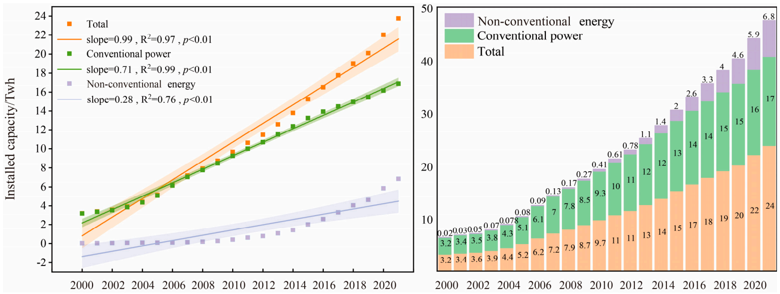
2.2.3. Trend Analysis

We used linear fitting to estimate the trends in production and consumption of each energy source in each province over the last decade. A positive slope in the results indicates an upward trend in production and consumption, while a negative slope indicates a downward trend. We used a 1% significance level in all of the significance tests. We used a hierarchical color scheme to classify the energy production and consumption values of each province in the maps. The energy production and consumption values of different provinces are represented by colors of the same shade with different luminance levels, with smaller luminance levels corresponding to larger values and vice versa.

3. Results

3.1. Spatial and Temporal of Non-Conventional Energy Sources

Figure 1 shows the trend in the installed capacity of energy power generation and conventional power generation from 2000 to 2020 in China. The total installed energy generation capacity gradually increased from 3.2 Twh in 2000 to 24 Twh in 2021 with a significant temporal tendency of 0.99 Twh/year (R^2 = 0.97, $p < 0.01$, Figure 1a). Similarly, the installed capacity of traditional energy generation grew from 3.2 TWh in 2000 to 1.7 Twh in 2021 with a significant temporal tendency of 0.71 TWh/year (R^2 = 0.99, $p < 0.01$, Figure 1a). The installed capacity of non-conventional power generation gradually grew from 0.02 TWh in 2000 to 6.8 TWh in 2021 with a significant temporal tendency of 0.28 Twh/year (R^2 = 0.76, p < 0.01, Figure 1a).



(**a**) (**b**)

Figure 1. This figure shows the linear regression trend (**a**) and annual trend (**b**) of regional inter-annual installed capacity for the period 2020–2021. The dots represent the annual series of the index under consideration, and the line represents the linear trend. The light shading represents 99% confidence intervals (**a**). The orange bar indicates the total installed generating capacity during the period of 2000–2021, while the green and violet bars indicate the installed conventional and non-conventional energy source generation capacity during the same period, respectively (**b**). (Source: based on (*CHINA ELECTRIC POWER YEARBOOK*)).

As shown in Figure 2, wind power generation in the country has risen significantly during the study period (2011–2020). In 2011, only Inner Mongolia's wind power production exceeded 150 Twh per year with an output of 227 Twh. As of 2020, the annual output of wind power in Inner Mongolia exceeded 600 Twh with an output of 726 Twh; the national production of wind power is in the range of 300–400 Twh for two provinces, and the production of wind power is in the range of 150–300 Twh for eight provinces. Meanwhile, our results revealed the spatial characteristics of national wind power between 2011 and 2020. The nation has high values of wind power, principally distributed in the north with little change in wind energy production in the southwest over the years.

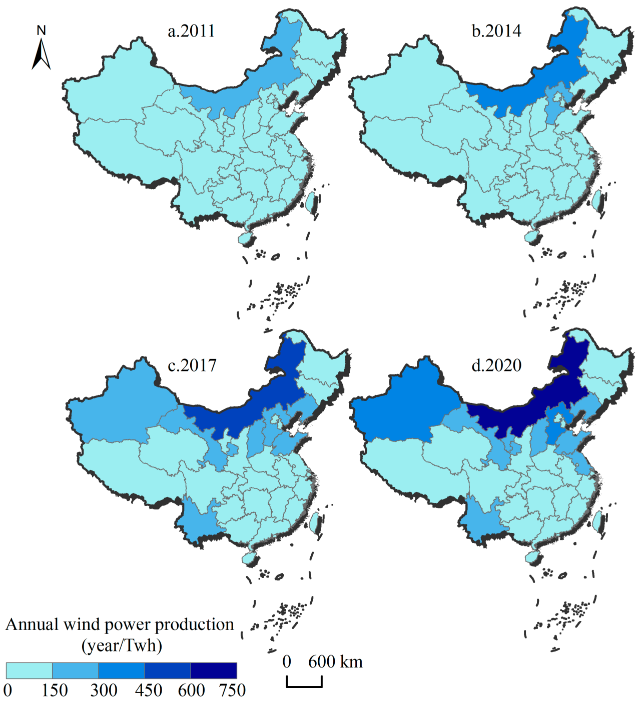


Figure 2. Spatial distribution of wind power production per region in China, 2011–2020. (Source: based on (*CHINA STATISTICAL YEARBOOK*)).

As shown in Figure 3, during the study period, there were significant changes in PV production across different regions. In 2011, the PV production in all regions of the country was below 50 Twh. However, by 2020, the PV production in most regions of the country had increased to more than 150 Twh. In terms of spatial patterns, PV production shows characteristics of being high in the east and low in the west, with the north having higher production than the south. Shandong and Hebei have the highest PV production at 206 Twh and 201 Twh, respectively. However, PV production in southwestern regions, such as Sichuan and Yunnan, remains low at less than 50 Twh.

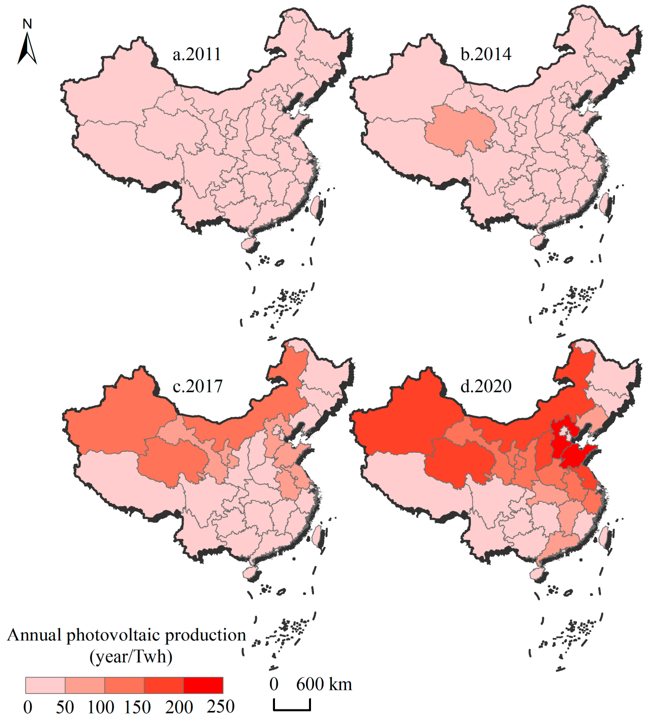


Figure 3. Spatial distribution of PV power production per region in China, 2011–2020. (Source: based on (*CHINA STATISTICAL YEARBOOK*)).

Figure 4 shows the spatial distribution of commercial, expanding, and under-construction nuclear power plants (Figure 4a), a heat map of nuclear power generation capacity by province from 2010 to 2020 (Figure 4b), and the number of commercial, expanding, and under-construction nuclear power plants by region (Figure 4c). The nuclear power plants in China are located only in the southeast coastal area (Figure 4a). Guangdong and Zhejiang have the largest number of nuclear power plants, each with four nuclear power plants in commercial operation and one under construction. Guangxi, Hainan, Fujian, Liaoning, and Jiangsu, respectively, have a nuclear power plant under expansion. Shandong and Fujian also have two nuclear power plants under construction and one in commercial operation, respectively. As can be seen from Figure 4b, among the several cities with nuclear power plants, Guangdong has the largest nuclear power output followed by Zhejiang and Fujian, respectively. Guangxi and Shandong have lower nuclear power output, and Fujian and Guangdong's nuclear power output is growing at a fast rate.

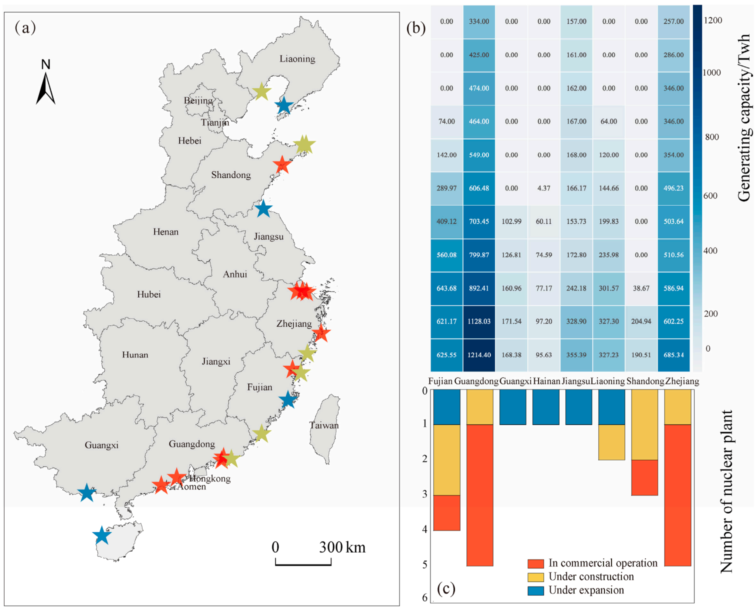


Figure 4. The location of the stars on the map represents the location of the nuclear power plant. Blue stars are nuclear power plants under expansion, yellow stars are nuclear power plants under construction, and orange stars are nuclear power plants already in commercial operation (**a**). Heat map of nuclear power generation capacity by province, 2010–2020 (**b**). Histogram of the number of nuclear power plants (**c**). (Source: based on (*CHINA STATISTICAL YEARBOOK*)).

3.2. Spatial and Temporal Variations in Energy Development

We applied the gravity center model to calculate the gravity center of energy and its offset trajectory over the period 2010–2020. As shown in Figure 5, the migration of the gravity center of energy production and consumption in China has the following characteristics: First of all, in terms of latitudinal and longitudinal coordinates, the cumulative longitudinal shift is greater than the cumulative latitudinal shift of energy, and their changes in the east–west direction are greater than changes in the north–south direction. The gravity center of non-conventional energy production, primary energy production, and electricity consumption shifts from west to east. Secondly, the gravity center of non-conventional energy production and electricity consumption are close to each other, located in Anhui and Henan, while the gravity center of primary energy production is farther away from the gravity center of electricity consumption and non-conventional energy production, located at the junction of Shaanxi and Shanxi. Thirdly, the migration distance of the center of non-conventional energy production is large, totaling 561.2 km (Figure 6f), with an average migration speed of 56 km/year, and the migration trajectory is in the shape of an "Ω", crossing two provinces and six cities, with the largest migration distance in the period 2010–2016; the gravity center of China's primary energy production migrated from Lvliang City, Shanxi Province, to Yan an City, Shaanxi Province, with a total migration distance of 204.6 km (Figure 6e) and an average migration speed of 20 km/year; the gravity center of China's electric power consumption migrated from Zhumadian City, Henan Province, to Pingdingshan City, with a total migration distance of 144.5 km (Figure 6d) and an average migration speed of 14.5 km/year.

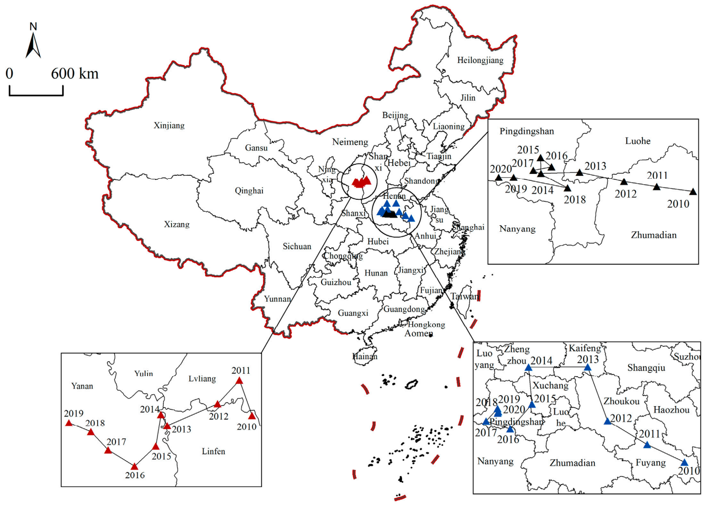


Figure 5. 2010–2020 energy gravity center of migration trajectory in China from 2010 to 2020. The black triangle is the gravity center of electricity consumption, the red triangle is the gravity center of primary energy production, and the blue triangle is the gravity center of non-conventional energy production. (Source: based on (*CHINA STATISTICAL YEARBOOK*) and (*CHINA ELECTRIC POWER YEARBOOK*)).

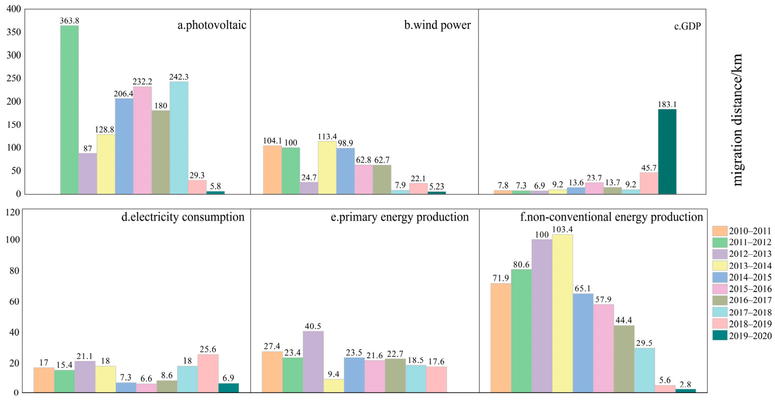


Figure 6. Distance of migration of each energy center of gravity between 2010 and 2020. (Source: based on (*CHINA STATISTICAL YEARBOOK*) and (*CHINA ELECTRIC POWER YEARBOOK*)).

Figure 7 illustrates the migration routes for the gravity centers of wind, nuclear, and PV power generation in China. During the study period (2010–2020), the gravity centers of wind energy production and PV production were mainly distributed in the central and northern parts of the country, while the gravity center of nuclear energy production was concentrated in the coastal region in the southeast of the country. Specifically, the gravity center of wind energy migrated in the southwestern direction, and the migration trajectory showed a "J" shape, passing through Hebei, Shaanxi, and Shanxi provinces. The gravity center of PV power migrated in the northwestern direction during the period of 2011–2014 and in the southeastern direction during the period of 2014–2020, passing through Gansu, Qinghai, Inner Mongolia, Ningxia, Shaanxi, and Shanxi. The gravity centers in the three years of 2018–2020, with a short migration distance, were adjacent to each other. The gravity center for nuclear energy production has been clustered at the junction of Jiangxi and Fujian with no apparent shift.

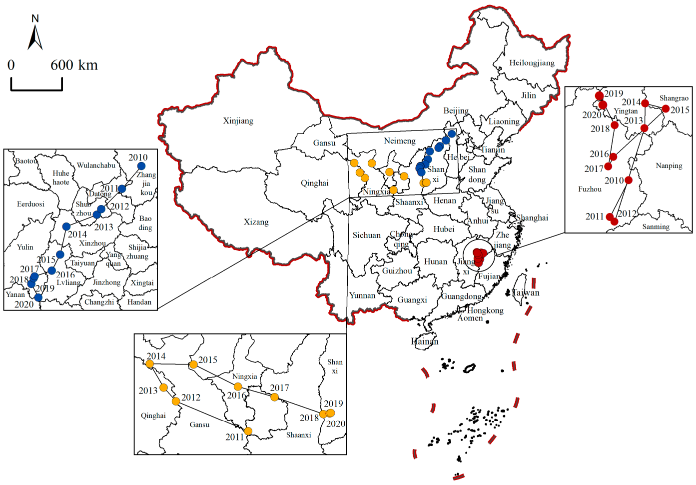


Figure 7. 2010–2020 Non-Conventional Energy Sources: Gravity Center of Migration Trajectory in China. Red dots show the gravity center of nuclear power production, blue dots show the gravity center of wind power production, and yellow dots show the gravity center of PV production. (Source: based on (*CHINA STATISTICAL YEARBOOK*)).

Figure 8 shows the trajectory of GDP migration between 2010 and 2020, as well as the characteristics of national GDP electricity consumption and GDP energy consumption changes between 2014 and 2019. The overall gravity center of GDP in China has migrated to the southwest, from Henan Province to Hubei Province, and the migration rate after 2015 is significantly greater than that before 2015. During the period of 2014–2019, the GDP energy consumption in most regions of the country declined to varying degrees, while the GDP electricity consumption saw a small increase in a large area of the country in 2018. However, most regions have shown varying degrees of decline in the rest of the years.

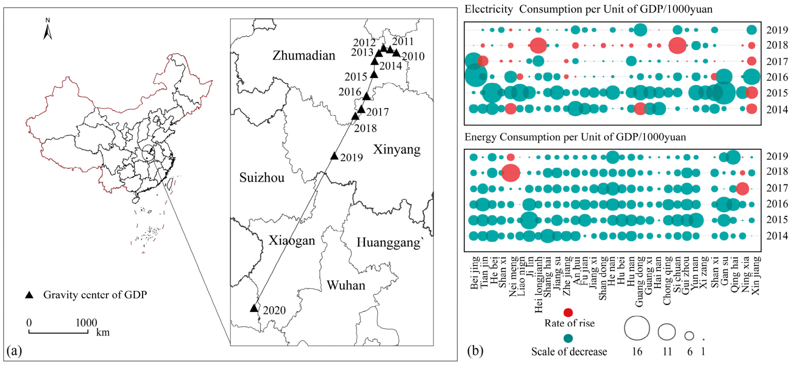


Figure 8. Migration trajectory of GDP in China, 2010–2020. The triangle in (**a**) represents the gravity center of GDP. Energy Consumption per Unit of GDP and Electricity Consumption per Unit of GDP in China, 2014–2019. (**b**) shows the red circle representing the rate of increase, the green circle representing the rate of decrease, and the size of the circle representing the scale of the rate of change. (The data used in this figure are based on the *CHINA STATISTICAL YEARBOOK* and the Communiqué on indicators such as the rate of reduction in energy consumption of 10,000 CNY of gross regional product.).

Figure 9a–d depicts regional inter-annual rates of change and significance levels in four types of energy production and consumption data (non-conventional energy production, hydropower generation, thermal power production, and electricity consumption). At the 0.99 confidence level, there are significant increases in non-conventional energy source power generation and total electricity consumption in all regions of China, with the highest inter-annual rate of increase in electricity consumption. Hydroelectric power generation in southwest China and thermal power generation in northwest China both show significant growth trends, with the most significant hydroelectric power generation in Sichuan and Yunnan provinces and the most significant thermal power generation in Xinjiang, Inner Mongolia, and Shandong provinces. However, the rate of change in hydropower is negative in Fujian, Guangdong, and Jilin provinces (Figure 9b), and the rate of change in thermal power is negative in Tibet, Sichuan, and Yunnan provinces (Figure 9c).

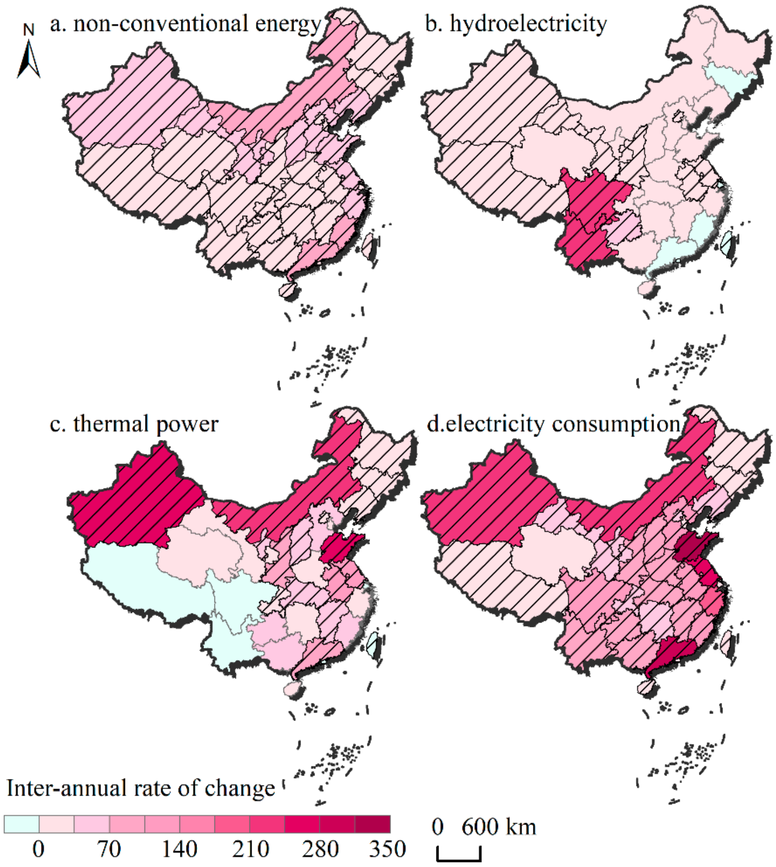


Figure 9. Linear regression trends were analyzed for regional annual energy production or consumption indices for each energy source for the period 2010–2020. Additionally, spatial patterns of annual trends were examined. The magnitude of the rate of change was represented by shades of red, while blue represented a negative rate of change. Grey lines indicated statistical significance at the 99% confidence level. (Source: based on (*CHINA STATISTICAL YEARBOOK*) and (*CHINA ELECTRIC POWER YEARBOOK*)).

4. Discussion

Since the 12th Five-Year Plan, China has introduced a large number of policies to promote the conservation of natural resources, promote the development and utilization of renewable energy [35], improve the energy structure, and improve energy efficiency [3,4,29]. According to the National Bureau of Statistics, by 2021, there will be 2.38 billion kilowatt-hours of installed power generation capacity in China, a seven-fold increase over the 2000 installed power generation capacity; among them, the installed capacity of non-conventional energy generation has changed the most significantly, and the magnitude of its change has increased significantly since 2010 (Figure 1). In 2017, the new installed capacity of PV power generation in China was 53.06 GW, a record high, and then it increased to 48.2 GW in 2020, with a year-on-year growth of 60%, and continues to be the world's first in PV power generation. Until 2021, there have been 51 nuclear power units in operation in mainland China, there have been 18 nuclear power units under construction, and the power generation capacity was at the leading level in the world. In the meantime, nearly half of the total generation capacity came from hydropower, wind power, and other clean energy sources. Under the support of various policies and the efforts of the non-conventional energy industry, the share of non-conventional energy production in China continues to grow, and the energy structure is becoming increasingly cleaner and low-carbon [33].

As a renewable and clean resource, wind and PV resources are abundant in our country, but the distribution differences between geographical regions are very obvious. Zhu et al. and Xue et al. divided the whole country into 4 major zones and 30 sub-zones, namely, the wind energy resource-rich zone, richer zone, utilizable zone, and poor zone [36]; PV resources were also divided into four zones, namely, the rich zone, richer zone, utilizable zone, and poor zone, based on the amount of PV radiation. Considering northeast, north China, northwest China, and the southeast coastal areas of wind energy resources [37], the three northern regions of wind energy can be easily developed; however, in the southeast coastal areas, due to limitations such as the terrain, ecological environment, and mining technology, wind energy can be developed relatively weakly [36,38]. As shown in Figure 2, it can be seen that the wind power production in the north of China is significantly higher than in the rest of the region; the three northern regions are wind energy resources-focused on the use and development of the region, and Inner Mongolia is largest wind power production in China [39].

The Tibetan Plateau is the high-value center of PV in China, and the Sichuan Basin is the low-value center of PV [40]. Most areas of China are rich in PV resources [41], with higher daily radiation in the north than in the south, higher daily radiation in the west than in the east, and a large total amount of PV radiation in areas such as Tibet, Qinghai, Xinjiang, southern Ningxia, Gansu, southern Inner Mongolia, Shanxi, northern Shaanxi, and a small number of areas [42], such as Sichuan, Guizhou, and Chongqing, where there is a lot of rain and fog and where the total amount of annual radiation from the short duration of sunshine is small [43]. Combined with Figure 3, it can be seen that the PV generation in each region of China is closely related to the natural resource conditions of PV, which also shows that the west has higher PV generation than the east, and the north has more PV generation than the south.

Unlike wind and PV, the requirements for nuclear power generation are very stringent, and there are five internationally accepted principles for the siting of nuclear power plants: economic, technical, safety, environmental, and social [44]. From safety considerations [45], the nuclear power plant must be built in an area where an earthquake of a magnitude that has not occurred in hundreds of years is unlikely to happen, deep underground without fracture zones, and with no large- or medium-sized cities within 50 km of the population density of the area. From an economic analysis, the nuclear power plant needs to be built in an area with a larger consumption of electricity to reduce the cost of electricity transport and losses. In addition, due to the large amount of heat generated during the operation process, it is necessary to select a site near a water source [43]. As a result, there are currently more than 20 nuclear power plants in commercial operation and under construction in China, all of which are located in relatively undeveloped cities along the southeastern coast (Figure 7).

At the 99% confidence level, non-conventional energy power generation in all regions of China shows significant growth (Figure 9a), indicating that the development and utilization of non-conventional energy sources in China are showing good progress. Hydropower and thermal power development, on the other hand, show very obvious regional differences. Sichuan, Yunnan, and other western regions with plenty of rain and fog are rich in hydropower resources, while Shaanxi and Inner Mongolia located in the north of the country are rich in coal resources and have obvious advantages in thermal power generation. The development of regional advantageous energy resources in accordance with local conditions has obvious effects.

In 2010, the total annual output of wind power, nuclear power, and PV was 74.8 billion kilowatt-hours. PV production accounted for only 715 million kWh, which was less than 1%. At that time, the main source of wind energy was located in the north of Inner Mongolia, and nuclear power originated in the southeast coastal region. The gravity center of non-conventional energy production was located in east China, Anhui Province, Huzhou City. However, non-conventional energy production has risen dramatically over the decade, with output having risen from 74.8 billion kWh to 1094.2 billion kWh. PV production reached 261.2 billion kWh annually, accounting for 23.9% of the total. The rapid growth of PV production in the northern part of the country over the past decade has been the main driver for the migration of the non-conventional energy production's gravity center towards the northwest. The generation of PV and wind power is dominated by northwest China and north China, and the generation of nuclear power is dominated by southeast China, whereas the consumption is dominated by east China and central China. There is an obvious spatial imbalance between non-conventional energy production and consumption.

Since 2005, the northeastern region began to carry out industrial transfer, and the central and western regions undertook the transfer of expertise from the east. The rapid development of industries in the western region has led to a migration of the gravity center of GDP in China to the southwestern direction (Figure 8). Therefore, the rising level of economic development in the western region has led to a rise in the production and consumption of energy, and the gravity center of primary energy production and electricity consumption has continued to migrate to the west.

China's coal resources are mainly distributed in the western and northern regions, and its hydroelectric resources are mainly concentrated in the southwestern region, while the eastern region has a scarcity of primary energy resources and a relatively high concentration of electricity consumption loads. The "West-to-East Electricity Transmission" project of the Western Development Project is to convert energy from coal- and hydro-energy-rich western provinces and regions into electric power resources and to transmit them to the eastern coastal areas where electricity is in short supply. This is one of the main reasons for the geographical imbalance in China's energy production and consumption.

In general, China's energy development is improving, and the production capacity continues to improve. The energy structure is also being decarbonized and cleaned up. However, the dominance of fossil energy in the short term is difficult to change fundamentally. We also need to continue to adhere to the long-term structural adjustment of energy production and consumption, innovation, and development of principles and technologies and vigorously develop non-conventional energy sources and clean energy. Localities should combine non-conventional energy natural resource conditions difference characteristics and improve the development of non-conventional energy sources as well as the utilization rate.

5. Conclusions

This study analyzes the spatial and temporal changes in the production and consumption of conventional and non-conventional energy sources in China during the period of 2010–2020 by means of a mean-weighted central approach with a large amount of energy production and consumption data. Various energy center of gravity migration trajectory characteristics and trends were studied to explore the underlying mechanisms driving these changes. The research results show that: (1) Under the impetus of the development of green low-carbon and ecological civilization strategy, the rate of increase in the production of non-conventional energy sources in China and the proportion of it increase year by year, and the energy structure obviously presents the characteristics of being low-carbon and cleaner. (2) For the spatial patterns of non-conventional energy source development, due to the development of wind power and PV constraints by natural resource conditions and technology, their development trend is best in northeast, north, and northwest China. (3) The generation of PV and wind power is dominated by northwest China and north China, and the generation of nuclear power is dominated by southeast China, whereas the consumption is dominated by east China and central China. There is an obvious spatial imbalance between non-conventional energy production and consumption. (4) The proportion of photovoltaics in non-conventional energy production has increased significantly over the 2010–2020 period, which is the main driver of the overall shift in the gravity center of non-conventional energy production towards the northwest region of China. (5) In recent years, the gradual transfer of industries from the east to the central and western regions of China and the improvement in the economic level of the western regions have led to an increase in energy production and consumption, promoting a shift in the gravity center of energy production and consumption to the west. Overall, China's energy production and consumption structure is undergoing a gradual transformation process from a high-carbon black structure to a low-carbon, carbon-free green structure. Some provinces and municipalities have achieved significant results, presenting a non-conventional energy source industry in accordance with local conditions and the development of non-conventional energy source industry momentum in the process of industrial restructuring and upgrading has played an important role. This study highlights the spatial and temporal patterns of green energy development in China. This study identifies the characteristics of the development of traditional and non-conventional energy production and consumption in China, as well as non-conventional energy production and its influencing factors. It provides a reference for China to continue to promote the reform of its energy structure, rationalize its carbon reduction policies, and achieve the goal of carbon peaking and carbon neutrality.

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