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Industrial innovation characteristics and spatial differentiation of smart grid technology in China based on patent mining

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ABSTRACT

Based on the perspective of smart grid patent, this study crawls the smart grid patent data from 2009 to 2020, and extracts the hotspots of innovation space in different stages. By mining the patent information, this paper identifies the hot innovation fields of smart grid in China and the world, and selects IPC classifications of H02J, G01R and H04L as the main hot smart grid technologies for innovation space analysis. In further study, methods such as global autocorrelation analysis are used to comprehensively analyze the spatial distribution of smart grid innovation in China. It is found that innovation activities of China's smart grid industry are spatially agglomerated. However, during 2017–2020, such spatial distribution represents China's smart grid industry has approached the distribution pattern of normal innovation industries which tends to be discrete or competitive. According to autocorrelation analysis, China's smart grid innovation space has obvious agglomeration characteristics, showing a gradual decline trend from the center to the periphery, and the diffusion effect has initially appeared. Finally, the smart grid patent statistics and the spatial ellipse parameters intuitively present the innovation characteristics of China's smart grid industry in terms of the evolution of the spatial differentiation during 2009–2012, 2013–2016, and 2017–2020.

1. Introduction

With the transformation of electrification, the traditional power grid is increasingly unable to meet the growing needs of people [1–4]. At present, there is an urgent need for an intelligent system that can integrate energy resource development and transmission technology, existing power generation, transmission, distribution and sales functions of traditional power grids, as well as digital networks that connect and share information with various electrical equipment and other energy-using facilities of end users [5]. This intelligent system not only improves energy efficiency, but also takes into account environmental protection [6]. Out of this need, the concept of smart grid was born. Due to the different backgrounds of countries and regions, there are also different goals for the establishment of smart grid. So far, there has not been a worldwide definition of smart grid. The definition of smart grid in different countries and regions is shown in Table 1, which adapted from [7]. The research area of this paper is China. It can be seen from the table that the main goal of China's smart grid construction at the present stage is to coordinate all levels of power grids, optimize the allocation of power resources, and maximize the efficiency of power resource utilization.

Smart power grid is characterized by self-healing, reliability, compatibility, high efficiency and interactivity. Table 2 compares traditional power grid with smart power grid, and introduces the characteristics of smart power grid in detail. Through comparison, it can be seen that, compared with traditional power grid, smart grid can not only provide reliable and efficient power guarantee, but also be compatible with the access of all kinds of devices to further optimize the allocation of power resources. At the same time, the participation of consumers also enriches the way the grid operates. However, the smooth operation of the six links of smart grid, including power generation, transmission, substation, distribution, electricity consumption and dispatching, is

Abbreviations: R&D, Research and Development; SDE, Standard Deviation Ellipse; IPC, International Patent Classification; NNI, Nearest Neighbor Index; KDE, Kernel Density Estimation.

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Table 1
Definition of smart grid in different countries (regions) [7].

Countries (Regions)	Definition of Smart Grid
The United States	Using digital technologies to improve the reliability, safety, and efficiency (economy and energy efficiency) of power supply systems from large power plants to power users, and increasingly distributed generation and storage power systems [8]
European Union	The behaviors and actions of all power producers and consumers can be intelligently integrated to ensure the sustainability, economy and security of power supply [9].
Japan	A system that promotes greater use of renewable and unused energy and locally generated thermal energy for local consumption, helps to increase energy self-sufficient and reduce carbon dioxide emissions, provides stable electricity supply, and optimizes the operation of the entire grid from generation to users [10]
China	Based on the strong power grid with ultra-high voltage network as the backbone network frame and coordinated development of power grids at all levels, advanced communication, information and control technologies are utilized to build a unified strong intelligent power grid characterized by informatization, automation, digitalization and interaction [11].

Table 2
Comparison between traditional power grid and smart power grid [7].

Characteristic	Traditional Power Grid	Smart Power Grid
Self-healing	Unable to locate the fault location in time, power supply recovery depends on manual	Monitoring the power grid to reduce the probability of failure; The fault location can be located and automatically isolated within a short time after the fault occurs, so as to avoid large-scale power failure [12]
Reliability	Poor reliability, prone to large-scale power failure [13]	Real-time monitoring and evaluation of power grid operation status greatly improves the power grid's ability to withstand natural disasters and network attacks [14]
Compatibility	Large-scale centralized power generation, and cannot adapt to the access of small distributed power supply [15]	Compatible with access of a large number of small power generation equipment and energy storage equipment [16]
Operation Efficiency	The efficiency of power network operation is affected by factors such as manpower and system	Using digital information technology can optimize the allocation of power resources dynamically and improve the efficiency of power grid operation
Interaction	The end user is only a single consumer, and there is little information interaction between the user and the power supplier	Users can understand the electricity price and electricity consumption information in real time so as to arrange electricity reasonably, and transform from a single consumer to a participant in electricity trading [17].

based on the continuous progress of its key technologies and the guarantee of energy flow and information flow interconnection among all links. That is to say, the construction of smart grid requires the power industry to strengthen the production of complete sets of software and hardware equipment and comprehensive supporting capabilities, and to provide high-level supporting services in the fields of grid monitoring and control, intelligent management, two-way interaction, intelligent decision-making, planning and design, and market operation. To achieve this goal, the sustainability of smart grid technology innovation is critical.

Schumpeter believes that "innovation" is to put a new factor or condition of production (such as invention) into the original production system [32,33]. In practice, cities can use scientific and technological innovation to solve urban problems such as traffic congestion, social security and environmental pollution in the process of development. However, technological innovation is also influenced by factors embedded in cities. In case of smart grid technology, the geographical location of the research and development subjects [18], the satisfaction degree of supporting facilities [19], the relationship network structure of the research and development subjects [20], and the government drive [21] and other factors jointly affect the progress of technological innovation. At present, there are a variety of carriers to evaluate innovation activities, such as personnel training, the number of project contracts signed, the establishment of joint technical centers, cooperative outputs and joint papers published, etc. [22], but the mining and analysis of patents are more widely used [23]. Patent information includes information about people, knowledge, patent licensing transfers and geographical locations that are difficult to obtain through most other channels in the process of R&D cooperation [24]. It provides an important tool for the analysis of cooperation performance, identification of the role of the subject in the innovation network and market competition, exploration of potential cooperation opportunities, identification of key technology nodes and analysis of technological innovation level [25]. With the progress of visualization presentation methods of technology network, the literature on technological innovation activities based on the perspective of patent has gradually increased. For example, Chang et al. [26] studied the status and main research fields of each indigenous science cooperation subject in the technical field by drawing the 2-model cooperation network at the national and technical levels. In the field of energy storage, Mueller et al. [27] sorted and compiled electrochemical energy storage technologies using cooperative patents, and identified competitive technologies for electrochemical energy storage. Liu et al. [28] studied the convergence mode of energy storage technology by using the papers published in SCI-E and SSCI, and identified the core technology elements in the process of technology convergence. However, few studies related to energy technology patents involve industrial geographical layout.

The relationship between innovation diffusion and geographical pattern has a long theoretical history. Since the innovation diffusion theory appeared in the United States in 1920, Hagerstrand [34,35] found the similarity of spatial distance changes in the process of technological innovation diffusion, and then proposed a four-stage model of technological innovation diffusion, and concluded that spatial diffusion has neighbor effect and hierarchical effect. This research prompted geographers such as Pred [36] to discuss the process and dynamics of the hierarchical diffusion of innovation based on the urban system, and put forward that large cities occupy circular advantages in this process. Such urban innovation ideas, which are derived from the diffusion of technological innovation, have been widely integrated into regional economic policies and national strategies, namely "creative city" and "innovative city" that we often hear. However, due to the complexity of interdisciplinary research, the discussion of technological innovation diffusion and geographical pattern has received little attention, although its importance has been discussed. In case of smart grid, Park and Yoon [29] believes that the construction of smart grid industry cluster and the formation of the interconnection and coordinated development of the productivity of various enterprises in the field of smart grid are of positive significance to the optimization and upgrading of regional industrial structure. Smart grid industrial agglomeration is conducive to forming an industrial group based on power transmission and transformation technology and equipment, supported by information and intelligent power equipment, covering all links of power generation, transmission, power transformation, distribution, electricity consumption and dispatching, and able to provide high-tech equipment support for the realization of smart grid [30]. However, up to now, there has been little interdisciplinary combination of smart grid technology innovation and industrial geographical layout in previous studies. Although it was a surprise to find that team of Li et al. [37] came from Cambridge recently found that international knowledge flows were more important for countries with smaller patent absorptive capacity, while countries with larger absorptive capacity benefited more from domestic knowledge derived from other technological innovation systems (TISs). This answers the correlation between technological innovation and spatial distance to some extent from the international level, but it is undeniable that specific discussion on individual technologies such as smart grid and countries is still lacking.

To sum up, although there have been literatures on using patent data as a carrier to study technology-related innovation and evolution activities, there are still few in the field of energy storage. The recent research is more based on international level, the static perspective or overemphasis on the structure of knowledge network, and popular research methods dominated by social network analysis. Liu et al. [31], who is closest to our work, described the network characteristics of the patent output and connected subnet of the four cooperative subjects in China's smart grid cooperation field from the perspective of patent network. However, it has not further applied geographic information to study the innovation process of energy storage technologies such as smart grid, and discussed the innovation characteristics, spatial evolution, and industrial layout.

Based on the above discussion, this paper has two main purposes: 1) To compare the international and Chinese smart grid innovation trends and hotspots, and 2) To explore the relationship between smart grid technology innovation and space in China, and explain the differences. From the perspective of smart grid patent, this paper collects the global smart grid patent application and authorization data from 2009 to 2020. By mining the patent data, this paper identifies the current hot innovation fields of smart grid both globally and in China, and further extracts the innovation space of hotspot technologies in different development stages through the kernel density and geographic concentration index of geographical evolution. In this paper, the innovation space of five main hot smart grid technologies of H02J, G01R, H04L, G06Q and H04W is analyzed, and further, the industrial agglomeration of different technology categories is evaluated by using spatial statistical standard deviation ellipse (SDE) and descriptive methods.

2. Methodology

2.1. Data sources

The data in this paper were provided by PatSnap, a SaaS service provider of science and technology innovation intelligence, which focuses on two major sectors: science and technology innovation intelligence and intellectual property information service. Through machine learning, computer vision, natural language processing and other artificial intelligence technologies, it provides big data intelligence services for global technology companies, universities, scientific research institutions, and collects 120 million pieces of patent information from 120 different countries (regions). A total of 141,419 global patent applications for smart grid were retrieved from PatSnap database, among which 66,508 and 41,902 patents were from the United States and China, accounting for 47.02% and 29.62% respectively. Chinese and English keywords were combined in the retrieval process, and the retrieval mode was TACD(智能电网) OR TACD(smart grid) OR TACD (intelligent grid). The retrieval period was to May 2021. After the preliminary retrieval results were obtained, the final results were obtained through manual screening, homologous merging, data cleaning and indexing. The coding classification adopted for different types of smart grid technologies in this paper is the International Patent Classification (IPC), which was established in the Strasbourg Agreement in 1971. This classification provides a hierarchical system composed of language independent symbols for the classification of patents and utility models according to different technical fields. The new version of IPC comes into effect on January 1 of each year, and the version used in this article is the latest 2019 version.

2.2. Model setting

(1) Spatial Distribution and Kernel Density Estimation

In this paper, each patent is regarded as a smart grid technology innovation activity, so each patent can be abstracted as a pointlike geographic thing in geographical space, and the spatial distribution pattern of points can be regarded as a combination of a series of points in the research area. $S_i = (X_i, Y_i)$ is the spatial location of the ith observed innovation. There are three basic types of spatial distribution of abstract points in objective geography: random distribution, aggregation distribution and uniform distribution. Kernel density estimation (KDE) is a nonparametric probability density estimation method, which is less affected by data distribution compared with parametric model, and can well express the spatial distribution state of the innovation points [47,48]. Three forms of point distribution can be better explored through KDE: random distribution, aggregation distribution and uniform distribution. KDE assumes that a certain geographical event can occur at any location in space and the probability of occurrence is different at different locations [38]. If a region has dense point distribution, the probability of occurrence of geographical events in this region is high. Otherwise, the probability is low. Based on Pan et al. [39], this study uses kernel density estimation to measure the spatial distribution characteristics of innovation in China's smart grid industry. The specific calculation based on is as follows:

$$f_n(x) = \frac{1}{nh_n}\sum_{i=1}^{n} K\left(\frac{x-x_i}{h_n}\right) \tag{1}$$

Where, n is the number of samples; h_n is width, that is, the search radius; $K\left(\frac{x-x_i}{h_n}\right)$ is the kernel function.

(1) Nearest Neighbor Index (NNI)

NNI describes the spatial distribution pattern of points using the distance between the nearest point pairs [40,41]. NNI can assess the concentration of points and has been widely used [49,50]. Here we use it to make up for the deficiency of KDE in statistical intuitive comparison. Firstly, the mean distance between adjacent pairs of innovation points is calculated and compared with the similarity between random models. If the mean distance of the nearest neighbor of the observation pattern is larger than that of random distribution, the observation points tend to be uniform. If the nearest neighbor distance of the observed pattern is smaller than the nearest neighbor distance of the random distribution pattern, it tends to be clustered. The mean value calculation of NNI process based on Kint et al. [42] is as follows: Firstly, assume that there are n points in the study area and the area of the study area is A, then assume their expected mean distance:

$$D_e = \frac{0.5}{\sqrt{n/A}} \tag{2}$$

We define d_i as the distance between each element and its nearest element. Then calculate the mean observation distance of the actual data, and the formula is as follows:

$$D_o = \frac{\sum_{i=1}^{n} d_i}{n} \tag{3}$$

Finally, calculate the mean nearest neighbor index: $ANN = D_o/D_e$, and the Z-score statistic formula of ANN is as follows:

$$Z = \frac{D_o - D_e}{SE} \tag{4}$$

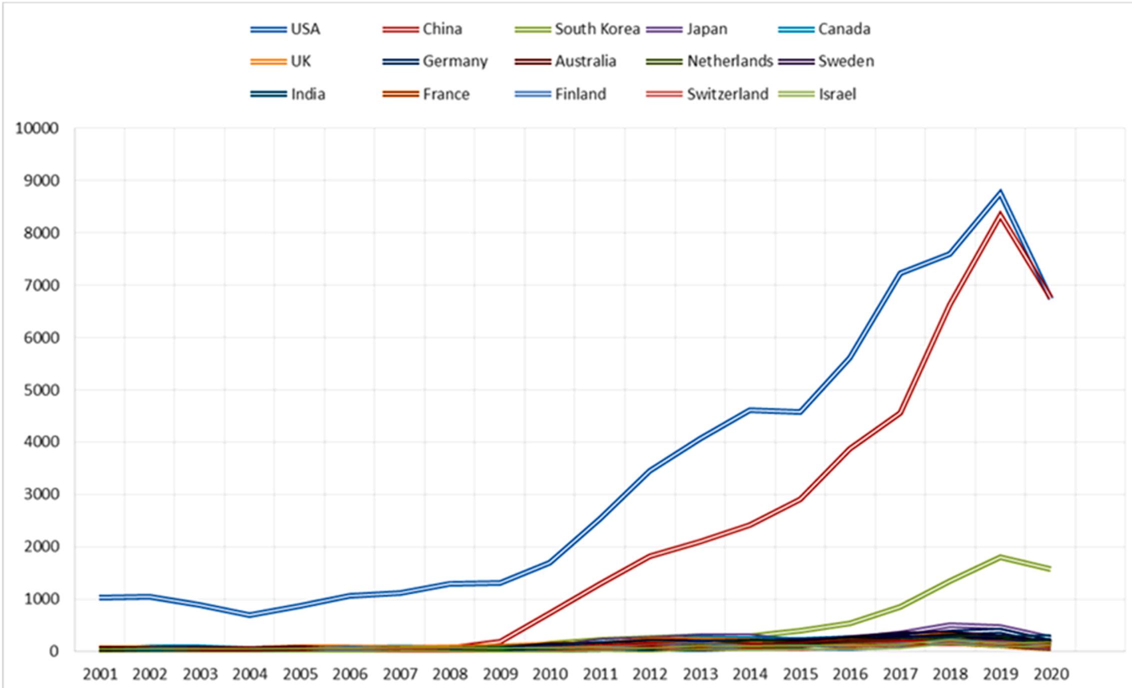


Fig. 1. Global innovation trends in smart grid technology 2001–2020.

Among which,

$$q = 1 - \frac{1}{N\sigma^2}\sum_{h=1}^{L} N_h \sigma_h^2 100 \times q\% \tag{5}$$

$$SE = \frac{0.26136}{\sqrt{n^2/A}} \tag{6}$$

If *ANN* is greater than 1, then the agglomeration pattern tends to be discrete. If *ANN* is less than 1, that means it tends to cluster, and the smaller *ANN* is, the more clustered it is.

(1) Spatial Autocorrelation

From the perspective of spatial econometrics, the innovation level of each city is related to its neighbors in space [43,51]. At present, spatial autocorrelation analysis in spatial econometric analysis is divided into global and local spatial autocorrelation analysis. Global correlation analysis is used to measure the overall spatial correlation degree, which is usually represented by positive and negative Moran's I Index and its size [52]. Global spatial autocorrelation is also considered to be the description of spatial features of attribute values of geographical elements in the whole region [53]. Therefore, the global spatial autocorrelation is adopted to analyze overall smart grid industrial innovation through Moran's I, so as to reflect the spatial distribution law of the technological innovation level. According to Feng et al. [44], the expression is as follows:

$$M = \frac{N}{S_0}\cdot\frac{\sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}\left(X_i - \overline{X}\right)\left(X_j - \overline{X}\right)}{\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^2} \tag{7}$$

Where, X represents the output value of innovation carriers in the province (region);

W_{ij} represents the distance coefficient based on Euclidean distance. In this paper, the sum of the squares of the inverse distance is chosen as the spatial weight, and the power value is 1. X represents the average value of the output value of innovation carriers; $S_0 = \sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}$.

(1) Geographic concentration index

Geographic concentration index refers to the degree of concentration of a certain element in a region [54]. Because it can not only reveal the spatial distribution characteristics of elements, but also represent the status and function of small regions of the same level in a large region, it is often used to evaluate the innovation concentration degree of each local region [55–57]. Combined with the results of global spatial autocorrelation, spatial agglomeration can be explained more specifically. The geographical concentration index is therefore used to measure the spatial agglomeration degree of smart grid innovation carriers in different regions. The formula based on Sun [45] is as follows:

$$G = 100\sqrt{\sum_{i=1}^{n}\left(\frac{x_i}{T}\right)^2} \tag{8}$$

Where: G is the geographic concentration index of innovation carriers in different administrative regions;

x_i is the number of units of innovation carriers in the administrative region;

T is the sum of the number of innovation carriers within the administrative region.

The closer G value is to 100, the more concentrated the spatial layout of innovation carriers is.

On the contrary, the smaller G value is, the more dispersed the spatial layout of innovation carriers will be.

(1) Spatial standard deviation ellipse

The spatial standard deviation ellipse (SDE) method reveals the multi-dimensional overall pattern and spatial aggregation characteristics of the discrete patent space composed of several cities (points) by using the spatial ellipse with center, long axis, short axis and azimuth angle as the basic parameters. SDE can well describe the centrality, distribution, directionality and spatial morphology of the spatial

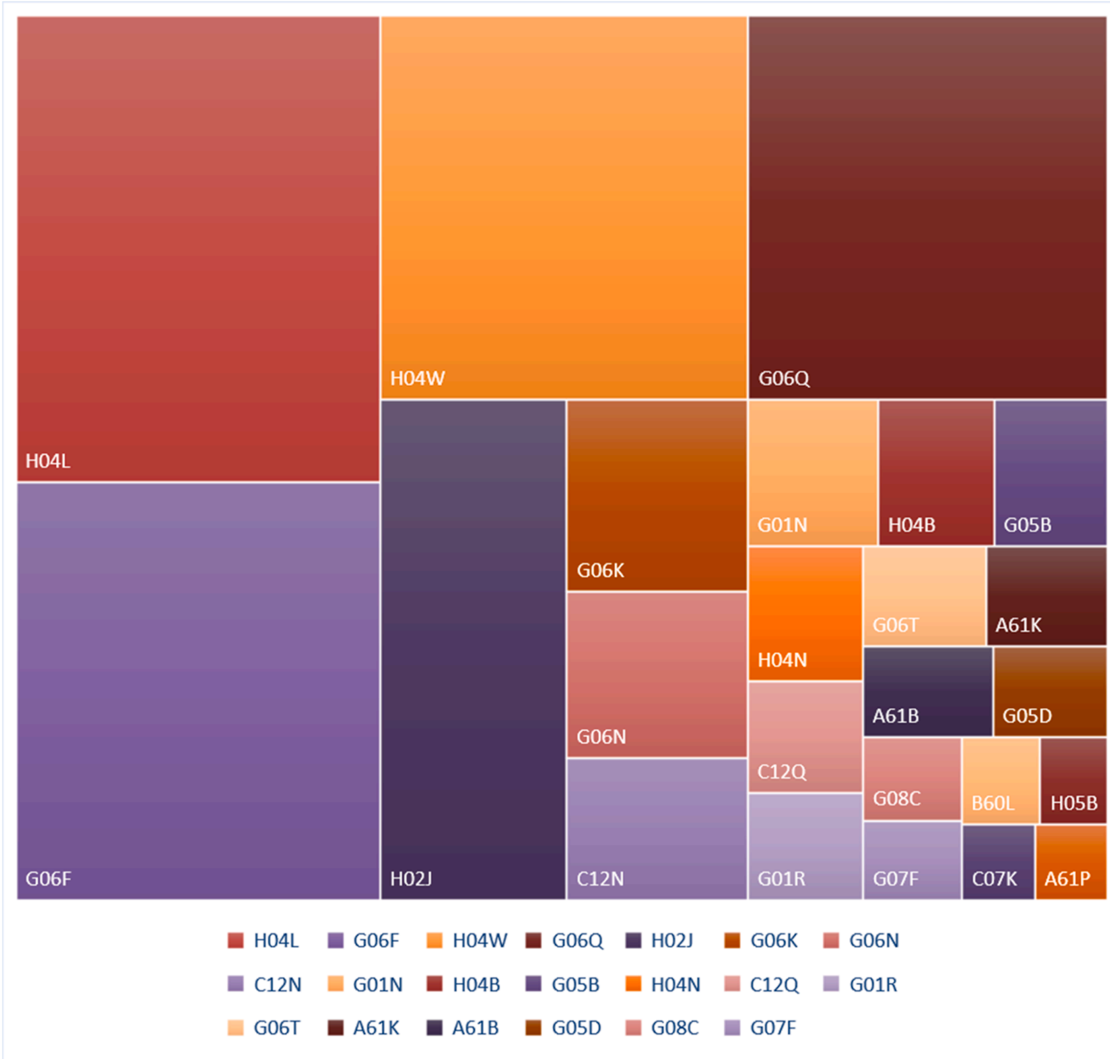


Fig. 2. Global research hotspots of smart grid patent technologies.

Table 3
Top 5 Global Hotspots of Smart Grid Patent Technologies.

Patent Classification	Meaning	Patent Number
H04L	The transmission of digital information, such as telegraph communication	24,773
G06F	Electrical digital data processing	22,155
H04W	Wireless communication network	20,599
G06Q	Data processing systems or methods specially adapted for administrative, commercial, financial, managerial, supervisory, or forecasting purposes; Processing systems or methods not covered by any other category that are specifically suitable for administrative, commercial, financial, managerial, supervisory or forecasting purposes	20,077
H02J	Electrical devices or systems for supplying or distributing electricity; Electrical energy storage system	13,582

distribution of geographical elements [59], so it is usually selected to analyze the directionality of the spatial distribution of innovation activities [58]. Since the standard deviation ellipse is calculated based on spatial location and spatial structure, we can further analyze the factors influencing the evolution of the spatial pattern of smart grid patents in combination with the changes of urban patent spatial differentiation. Based on Yang and Grigorescu [46], the basic parameter calculation formula is as follows:

Center

$$\overline{X_w} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}; \overline{Y_w} = \frac{\sum_{i=1}^{n} w_i y_i}{\sum_{i=1}^{n} w_i} \tag{9}$$

Azimuth Angle:

$$\tan\theta = \frac{\sum_{i=1}^{n} w_i^2 \widetilde{x}_i^2 - \sum_{i=1}^{n} w_i^2 y_i^2 + \sqrt{\left(\sum_{i=1}^{n} w_i^2 \widetilde{x}_i^2 - \sum_{i=1}^{n} w_i^2 \widetilde{y}_i^2\right)^2 + 4\sum_{i=1}^{n} w_i^2 \widetilde{x}_i^2 \widetilde{y}^2}}{2\sum_{i=1}^{n} w_i^2 \widetilde{x}_i^2 \widetilde{y}^2} \tag{10}$$

X-axis standard deviation:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n} \left(w_i \widetilde{x}_i \cos\theta - w_i \widetilde{y}_i \sin\theta\right)^2}{\sum_{i=1}^{n} w_i^2}} \tag{11}$$

Y-axis standard deviation:

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n} \left(w_i \widetilde{x}_i \cos\theta - w_i \widetilde{y}_i \sin\theta\right)^2}{\sum_{i=1}^{n} w_i^2}} \tag{12}$$

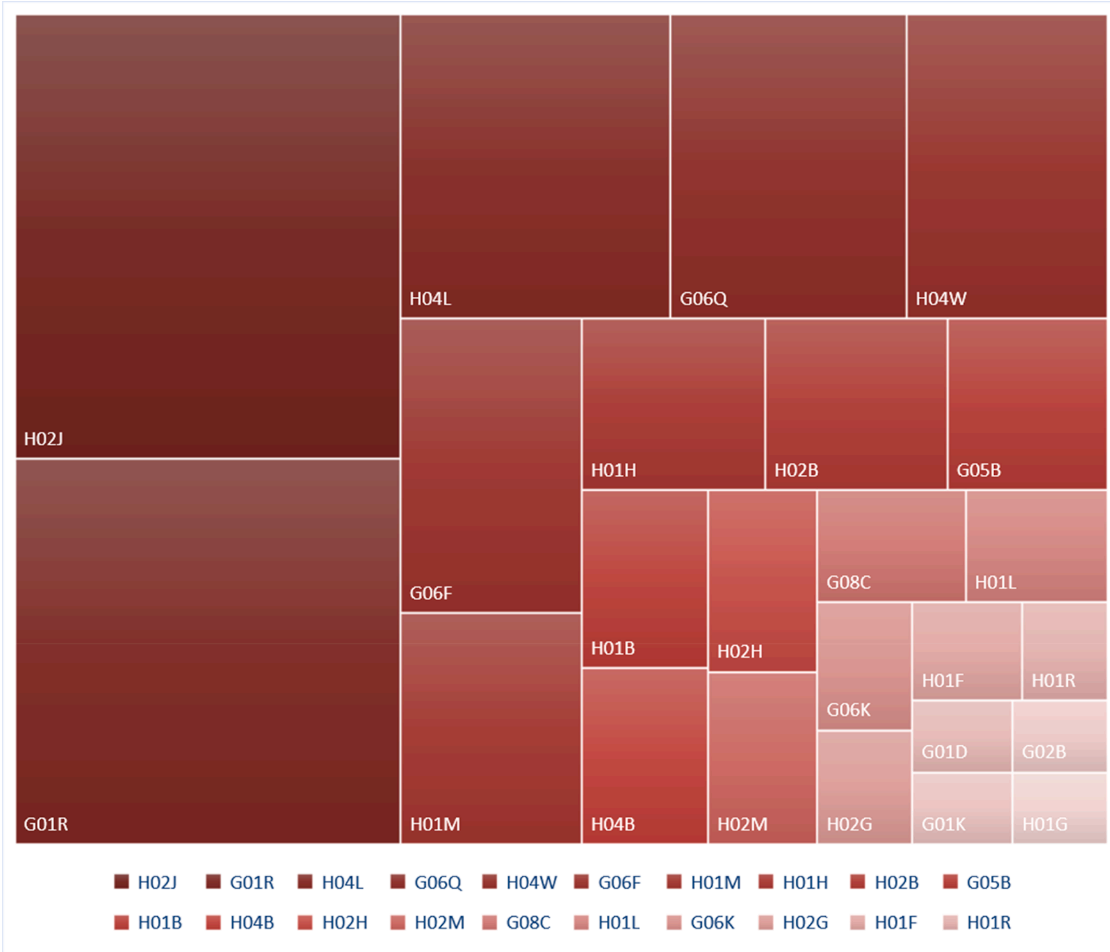


Fig. 3. China's research hotspots of smart grid patent technologies.

Table 4
Top 5 hotspots of smart grid patent technologies in China.

Patent Classification	Meaning	Patent Number
H02J	Electrical devices or systems for supplying or distributing electricity; Electrical energy storage system	6016
G01R	Device or method for measuring electrical variables; Device or method for measuring magnetic variables	5194
H04L	The transmission of digital information, such as telegraph communication	2874
G06Q	Data processing systems or methods specially adapted for administrative, commercial, financial, managerial, supervisory, or forecasting purposes; Processing systems or methods not covered by any other category that are specifically suitable for administrative, commercial, financial, managerial, supervisory or forecasting purposes	2513
H04W	Wireless communication network	2143

Where (x_i, y_i) ($i = 1, 2, \dots, n$) represents the location of urban unit i; w_i represents the weight, and is represented by the number of smart grid patent applications in city i; $(\overline{X_w Y_w})$ represents the weighted average center, and θ represents the azimuth angle of the ellipse, which is the included angle formed by clockwise rotation from due north to the long axis of the ellipse. $\tilde{x}_i, \tilde{y}_i$ respectively represent the coordinate deviation from the location of city i to the average center; σ_x, σ_y is the standard deviation along the x axis and the y axis.

3. Results

3.1. 3.1 global innovation trends in smart grid technology

From the perspective of patent applications for smart grid in the past 20 years, there is an obvious upward trend. Before 2009, the number of patent applications per year was small. During this period, traditional power grid technologies were dominant, and the relevant smart grid technologies were mainly led by the United States. Since 2009, smart grid technology has entered a period of rapid development [10]. The number of patent applications in both China and the United States has seen explosive growth. In 2019, the number of patent applications in China has reached a peak of 8338. Since there is an 18-month lag period for the disclosure of invention patent applications, there is a lag period for the publication of patent application data. The data in Fig. 1 from 2019 to 2020 will be smaller than the actual data. This period is only for reference, and patent applications may not show a downward trend.

In view of China's outstanding performance in the field of smart grid, this paper takes China as the research subject. In 2009, the State Grid Corporation of China divided the construction of China's "strong smart grid" into three stages: pilot planning, comprehensive construction and leading and upgrading. Since then, China has introduced a series of policies to support and guide the development of smart grid. The National Development and Reform Commission and the Energy Administration proposed in the Guidance on Promoting the Development of Smart Grid that a smart grid system that is safe, efficient, intelligent,

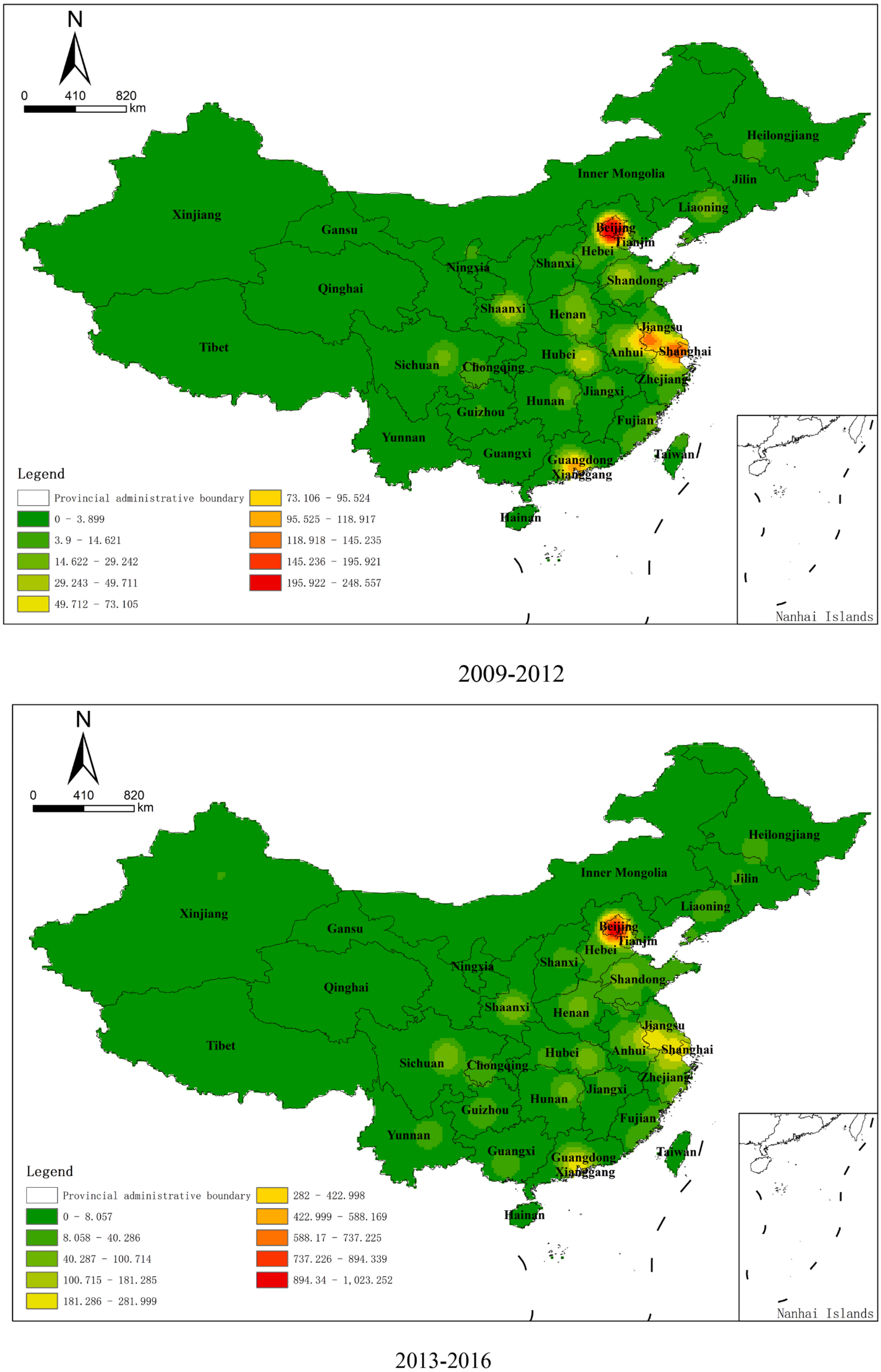
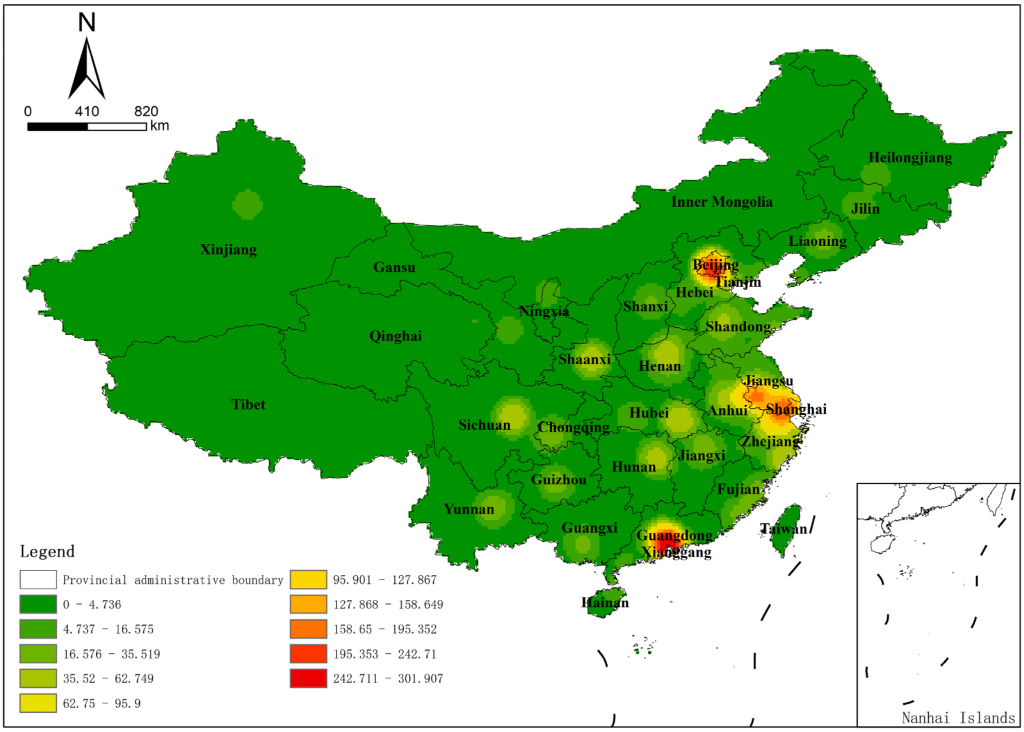


Fig. 4. Kernel density estimation of smart grid innovation.

compatible, energy saving and environmental protection, and interactive between supply and demand should be established by 2020. As can be seen from Fig. 1, innovation in China's smart grid field has made rapid progress since 2009, therefore, the time span of this study is set as 2009 to 2020.



2017-2020

Fig. 4. (*continued*).

Table 5
Mean distance to nearest neighbour.

	2009–2012	2013–2016	2017–2020
Nearest Neighbour Index (NNI)	0.074127	0.079961	0.104597
Z-Score	−103.569502	−166.68976	−130.590715
P Value	0	0	0

3.2. 3.2 distribution of hot spots

According to IPC classification and coding, the research hotspots of global smart grid patent technologies are shown in Fig. 2. H04L, G06F, H04W, G06Q and H02J are the top five hot areas. The corresponding classification explanation is shown in Table 3. As can be seen from Table 3, global smart grid has the largest innovation output in the fields of digital information transmission, electrical digital data processing and wireless communication network, and a important reason for this situation is that the United States has invested a lot in the fields of digital information transmission and wireless communication network technology. Different from the global situation, Fig. 3 shows the distribution of smart grid patented technologies in China. As shown in Fig. 3 and Table 4, the IPC classification of smart grid technologies in China mainly focuses on five categories: H02J, G01R, H04L, G06Q and H04W. Among them, H02J is mainly about the construction of power supply and distribution system of smart grid, and H04L patent is mainly about the communication between local or external parts of smart grid. The patents of G01R and G08C related to smart grid mainly relate to operation monitoring and fault alarm of various components in the system. Operating condition and fault monitoring play an important role in the stable operation of the system. China has a considerable number of patent innovations throughout the whole industry chain of smart grids, of which it is worth noting that the patent layout of circuit devices or systems for power supply or distribution and energy storage systems is far ahead of other countries.

3.3. Spatial distribution of smart grid innovation

In order to study the overall spatial distribution of innovation activities in China's smart grid industry, this study summarized and analyzed the total number of innovation patents in China's regional smart grid industry and the overall spatial distribution in each province and city during 2009–2012, 2013–2016, and 2017–2020. The results are shown in Fig. 4 and Table 5.

The above results indicate that the overall technological innovation of China's smart grid industry presents a spatial distribution characteristic of "concentrated in Beijing-Tianjin-Hebei" during 2009–2012, and this trend continues during 2013–2016. However, during 2017–2020, the proportion of the Pearl River Delta region increases significantly, while that of the Yangtze River Delta region also increases during the same period. As can be seen from Table 5, the indexes of 2009–2012 and 2013–2016 are all less than 0.1, indicating that the innovation activities of China's smart grid industry are spatially concentrated and distributed. The index from 2013 to 2016 is greater than that from 2009 to 2012, indicating that the agglomeration degree of innovation activities in China's smart grid industry is gradually weakening with the change of time, especially during the period from 2017 to 2020, the nearest neighbor index exceeds 0.1. The spatial distribution of innovation activities representing China's smart grid industry has approached the distribution pattern of normal innovation industries, which tends to be discrete or competitive.

Economic geographers argues that the spatial distribution of innovation within a region is greatly influenced by geospatial factors such as capital/technology externalities and increasing spatial returns. On the one hand, the enterprise's choice of regional settlement is likely to be the result of the random decision of the enterprise, but due to the industrial connection and technology spillover, the spatial return increases and the production cost decreases, which will attract other enterprises to continue to settle in, forming the circular accumulation of innovation activities agglomeration, and constantly polarization into the "center". On the other hand, with the excessive agglomeration of innovation

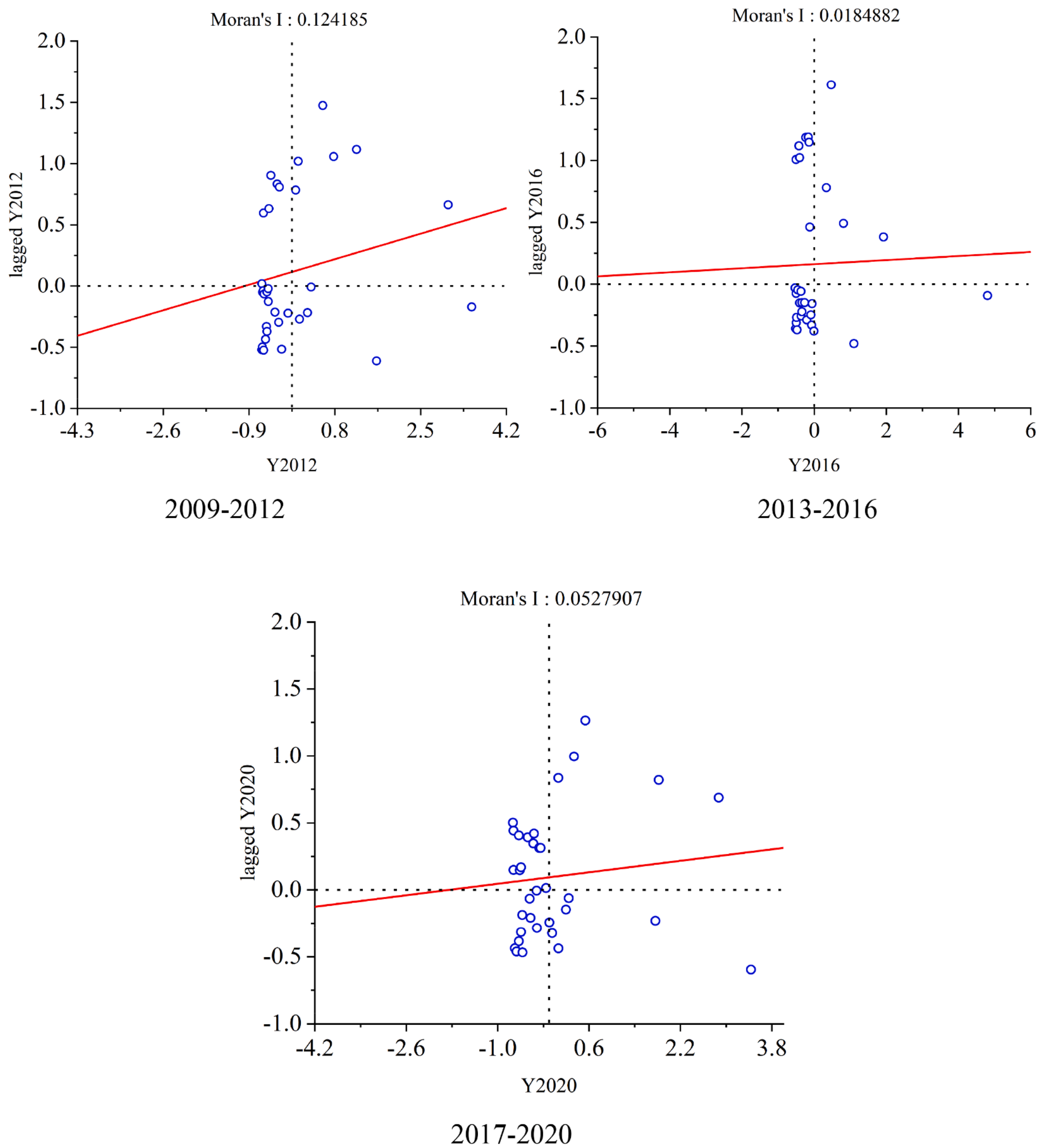


Fig. 5. Global autocorrelation analysis of smart grid innovation space.

activities in the same region, the price of production factors will rise, and the polarized region will continue to export economic activities to the surrounding areas through a series of linkage mechanisms, generating diffusion effect and forming "periphery". According to the results of global autocorrelation analysis, China's smart grid innovation space has obvious agglomeration characteristics, showing a trend of gradual decline from the center to the periphery, and the diffusion effect has initially appeared, as shown in Fig. 5.

According to Eq. (8), Table 6 shows that the spatial geographic concentration index of smart grid innovation carriers in different provinces in China is different. In terms of innovation carriers, the geographic concentration index of Macao Special Administrative Region, Shanghai, Tianjin and Chongqing is low, while the geographic concentration index of Tibet Autonomous Region and Shaanxi Province is the highest. The agglomeration effect of innovation carriers in Tibet Autonomous Region and Shaanxi Province is obvious. Through data screening and analysis, it can be seen that the smart grid innovation carriers in Shaanxi Province are basically only distributed in Xi 'an, the capital of Shaanxi Province, so the agglomeration effect is prominent. The agglomeration causes of innovation carriers in Tibet Autonomous Region are basically the same as those in Shaanxi Province. In terms of hot technological innovation space, Heilongjiang Province and Shaanxi Province have the most concentrated hot technological innovation space, which is basically consistent with the composition of the above-mentioned agglomeration effect of innovation carriers. Macao Special Administrative Region has the least geographical concentration of hot technological innovation space. Under the influence of more institutions of higher education and research, Hubei province has more hot spots of technological innovation relying on institutions of higher learning and research, which has promoted the development of Hubei province.

According to the patent statistics and patent spatial ellipse parameter analysis in Table 7 and Table 8 of China's smart grid, China's smart grid patent space center is located at the junction of Xinyang City of Henan Province, Huanggang City of Hubei Province and Lu 'an City of Anhui Province. From 2009 to 2020, it has a spatial shift of 208 km to the southwest, among which, it moves 87 km to the west. It moved 191 km to the south; The main area of spatial aggregation increased by 23 km^2 to 2.1 million km^2, and the long axis and short axis continued to grow synchronously. The shape of space ellipse is gradually rounded; The azimuth angle continues to increase, that is, the long axis appears clockwise rotation. From the perspective of the evolution of urban patent spatial differentiation, the cities with the most significant increase in

Table 6
Geographical concentration index of smart grid innovation carriers.

Provinces (Regions)	G Value of Innovation Carrier	Provinces (Regions)	G Value of Hotpot Technology Innovation
Anhui	0.612	Anhui	0.675
Macao Special Administrative Region	0.000	Macao Special Administrative Region	0.000
Fujian	0.562	Fujian	0.581
Gansu	0.740	Gansu	0.789
Guangdong	0.526	Guangdong	0.564
Guangxi Zhuang Autonomous Region	0.689	Guangxi Zhuang Autonomous Region	0.718
Guizhou	0.849	Guizhou	0.855
Hainan	0.805	Hainan	0.751
Hebei	0.478	Hebei	0.560
Henan	0.446	Henan	0.461
Heilongjiang	0.885	Heilongjiang	0.927
Hubei	0.788	Hubei	0.806
Hunan	0.722	Hunan	0.776
Jilin	0.648	Jilin	0.652
Jiangsu	0.483	Jiangsu	0.558
Jiangxi	0.644	Jiangxi	0.821
Liaoning	0.564	Liaoning	0.643
Inner Mongolia Autonomous Region	0.537	Inner Mongolia Autonomous Region	0.653
Ningxia Hui Autonomous Region	0.683	Ningxia Hui Autonomous Region	0.762
Qinghai	0.815	Qinghai	0.711
Shandong	0.425	Shandong	0.455
Shanxi	0.685	Shanxi	0.714
Shaanxi	0.947	Shaanxi	0.974
Sichuan	0.817	Sichuan	0.821
Tibet Autonomous Region	1.000	Tibet Autonomous Region	0.000
Xinjiang Uygur Autonomous Region	0.614	Xinjiang Uygur Autonomous Region	0.682
Yunnan	0.758	Yunnan	0.783
Zhejiang	0.491	Zhejiang	0.571
Beijing	0.592	Beijing	0.604
Shanghai	0.362	Shanghai	0.387
Tianjin	0.398	Tianjin	0.414
Chongqing	0.361	Chongqing	0.395

the proportion of patent filings in the national total are mainly distributed in the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei, while the cities with the most significant decrease in the proportion of the national total are mainly distributed in Shanghai, Beijing, Pearl River Delta. On the whole, the central typical region of the patent space ellipse has an increasing influence on the national patent space, while the influence of Beijing and the Pearl River Delta region on the national patent space is relatively decreased. As a result, the patent space ellipse in China moves toward the center, the space shrinks, the long axis shortening and the short axis increasing. From the perspective of spatial differentiation evolution of urban invention patents, the cities with the most significant increase in the proportion of invention patents in the national total are mainly distributed in the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei and Wuhan, and the cities with the most significant decrease in the proportion of invention patents in the national total are mainly distributed in Chengdu-Chongqing, Changsha, Jinan. Therefore, the spatial ellipse of invention patents in China moves to the southeast, and the long and short axes increase at the same time, but the growth range of the long axis is smaller than that of the short axis.

Although the evolution trend of China's patent invention space during 2009–2012, 2013–2016 and 2017–2020 is consistent, each stage still has different spatial differentiation and evolution characteristics. From 2013 to 2016, the long axis of China's invention patent space has a larger growth range and a larger area. From 2017 to 2020, the short axis of China's invention patent space has a larger growth range, a more significant westward movement and a greater increase in rotation angle. According to calculations, from 2013 to 2016, the cities with the most significant increase in the proportion of invention patents in China are Beijing (26.69%), Nanjing (6.00%), Shanghai (4.88%), Shenzhen (3.31%), Hangzhou (3.00%), Guangzhou (2.92%), Xi'an (2.49%), Chengdu (2.46%), Tianjin (2.15%) and Suzhou (2.11)%); The cities with the most significant decrease in the proportion of the country are mainly Hanzhong, Baiyin, Tianshui, Zhangye, Pingliang, Wuzhong, Guyuan, Hami and other cities in the northwest of China. These cities are in the regions with relatively backward economic and technological development, and the proportion of these cities is not more than 0.01%. During 2017–2020, the cities with the most significant increase in the proportion of invention patents in China were Beijing (10.05%), Shenzhen (6.14%), Guangzhou (5.82%), Nanjing (5.63%), Shanghai (5.09%), Hangzhou (3.68%), Chengdu (2.63%), Wuhan (2.60%), Xi 'an (2.55%) and Wenzhou (2.34%). In addition to the changes in the overall innovation pattern, this paper also lists the two most popular innovation fields H02J and G01R in Table 7 and Table 8 as references. It is found that in the past decade, Beijing's position as the most important innovation center has not changed and has been continuously consolidated. Besides, Guangzhou showed a more obvious upward trend. These two findings are consistent with previous research on urban innovation. In

Table 7
China smart grid patent statistics.

Category	Year	Range	Median	Mean Value	Number of Cities above Mean Value	Top 10 Cities
Overall	2009–2012	649	0	9.215633423	49	Beijing, Shanghai, Nanjing, Shenzhen, Wuhan, Xi 'an, Hangzhou, Guangzhou, Jinan, Hefei
	2013–2016	2663	1	24.17520216	47	Beijing, Nanjing, Shanghai, Shenzhen, Hangzhou, Guangzhou, Xi 'an, Chengdu, Tianjin, Suzhou
	2017–2020	584	2	15.66576819	58	Beijing, Shenzhen, Guangzhou, Nanjing, Shanghai, Hangzhou, Chengdu, Wuhan, Xi 'an, Wenzhou
H02J	2009–2012	187	0	2.520215633	49	Beijing, Shanghai, Nanjing, Guangzhou, Zhumadian, Jinan, Hangzhou, Shenzhen, Hefei, Xi 'an
	2013–2016	595	0	5.60916442	49	Beijing, Nanjing, Shanghai, Guangzhou, Tianjin, Shenzhen, Hangzhou, Jinan, Chengdu, Xi 'an
	2017–2020	122	0	2.811320755	70	Beijing, Nanjing, Guangzhou, Shanghai, Hangzhou, Shenzhen, Wuhan, Zhuhai, Tianjin, Ji 'nan
G01R	2009–2012	121	0	1.706199461	61	Beijing, Shanghai, Nanjing, Xi 'an, Shenzhen, Wuhan, Hangzhou, Ji 'nan, Hefei, Zhenjiang
	2013–2016	518	0	4.471698113	50	Beijing, Hangzhou, Shanghai, Nanjing, Chengdu, Wenzhou, Xi 'an, Wuhan, Shenzhen, Guangzhou
	2017–2020	109	0	3.336927224	57	Beijing, Shanghai, Guangzhou, Shenzhen, Nanjing, Hangzhou, Xi 'an, Chengdu, Wuhan, Changsha

Table 8
Spatial Ellipse Parameters of Smart Grid Patents.

Category	Year	Center of Inertia (COI)	Long half axis/km	Short half axis/km	Rotation Angle/°	Short axis/Long axis
Overall	2009–2012	116.645223, 32.963635	7.996	5.999	15.626	0.750
	2013–2016	116.204685, 33.825952	8.541	6.190	20.118	0.725
	2017–2020	115.547648, 31.314265	8.792	7.251	36.433	0.825
H02J	2009–2012	116.775195, 33.142578	7.824	5.336	15.239	0.682
	2013–2016	116.052343, 33.732651	8.591	6.226	19.636	0.725
	2017–2020	115.526725, 31.808186	9.186	7.453	38.053	0.811
G01R	2009–2012	116.389958, 33.24285	7.989	5.922	18.509	0.741
	2013–2016	115.98778, 34.030729	8.596	6.489	26.972	0.755
	2017–2020	115.370187, 31.334816	8.978	7.616	44.143	0.848

Beijing, state-owned enterprises are the dominant force in technological innovation, and the production and supply of electricity and heat, as the pillar industry, accounts for 23%. Some scholars believe the innovation ability of Guangzhou come from its own "innovation" gene in previous studies [61]. In the ranking of intellectual property ownership of enterprises in Guangzhou, intermediary agencies, rather than technology companies, rank first, which is considered to be the main reason for its growth [62]. However, we also find that Shanghai's innovation ability is declining both as a whole and in H02J and G01R. The reasons for this trend may be the dominant position of Shanghai's financial industry and the lack of inputs in research. In the intellectual property evaluation, some scholars found that the innovation subjects in Shanghai lacks cooperation compares with Beijing [60].

4. Conclusion

Based on the perspective of smart grid patent, this study uses big data method to crawls the global smart grid patent application and authorization data from 2009 to 2020, and extracts the hot spots of innovation space in different development stages. By mining the patent network, this paper identifies the current hot innovation fields of smart grid in China and the world, and selects classifications of H02J, G01R and H04L as the main hot smart grid technologies for innovation space analysis.

In further study, kernel density estimation, spatial nearest neighbor index, global autocorrelation analysis, geographical concentration and spatial statistical standard deviation ellipse are used to comprehensively analyze the spatial distribution of smart grid innovation and patent spatial differentiation and evolution characteristics in China from 2009 to 2020, taking cities at prefecture level and above as research units. The following conclusions are drawn:

1) The average Nearest Neighbor Index (NNI) of 2009–2012 and 2013–2016 are 0.074127 and 0.079961. Both values are less than 0.1, indicating that innovation activities of China's smart grid industry are spatially agglomerated. The mean value of NNI from 2013 to 2016 is greater than that from 2009 to 2012, indicating that the agglomeration degree of innovation activities in China's smart grid industry gradually weakens with the change of time. However, during 2017–2020, the value exceeds 0.1 and reached 0.104597. Such spatial distribution representing China's smart grid industry has approached the distribution pattern of normal innovation industries.
2) According to the results of global autocorrelation analysis, China's smart grid innovation space has obvious agglomeration characteristics, showing a trend of gradual decline from the center to the periphery, and the diffusion effect has initially appeared. Through the analysis of geographical concentration, it can be found that the regions with high agglomeration degree of smart grid innovation carriers in China are in Shaanxi, Guizhou, Hainan and Heilongjiang provinces with few scientific and technological innovation enterprises, and smart grid innovation carriers are mainly distributed in provincial capitals in these provinces. Therefore, the concentration of these provinces is higher than that of the Yangtze River Delta, Pearl River Delta and Beijing-Tianjin-Hebei regions, which have a large number of smart grid innovation carriers and greater diffusion.
3) Finally, the smart grid patent statistics and the spatial ellipse parameters of smart grid patents intuitively present the characteristics of China's smart grid projects in terms of the evolution of the spatial differentiation of patents during 2009–2012, 2013–2016, and 2017–2020. Although each stage has different characteristics, with the evolution, the cities with the most significant increase are mainly distributed in the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei and Wuhan. Therefore, the spatial ellipse of smart grid innovation in China moves to the southeast, and the long and short axes increase at the same time, but the growth range of the long axis is smaller than that of the short axis.

CRediT authorship contribution statement

Yang Bai: Conceptualization, Methodology, Software. **Lichen Chou:** Validation, Supervision. **Wanhao Zhang:** Formal analysis, Writing – original draft.

Declaration of Competing Interest

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

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