ORIGINAL RESEARCH ARTICLE

Spatio-temporal coupling suitability of solar energy resources and distributed photovoltaic power generation projects in Beijing

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ABSTRACT

Distributed photovoltaic power generation projects contribute to the coordinated and sustainable development of "energy—economy—environment". The spatio-temporal coupling relationship between regional solar resources and distributed photovoltaic power generation projects is studied. Taking Beijing area as the research object, a variety of spatial analysis methods are proposed to explore the relationship between solar resources and distributed photovoltaic power generation projects from a new perspective of spatial geography. The spatio-temporal coupling suitability of regional solar energy resources and distributed photovoltaic power generation project development area was scientifically evaluated. The research results can provide suggestions and decision support for optimizing the timing of regional development of photovoltaic power generation, and also provide reference for planning and layout optimization of photovoltaic power generation projects in the Beijing-Tianjin-Hebei region and other regions.

Keywords: Solar Energy; Distributed Photovoltaic Power Generation Project; Spatio-Temporal Coupling; Suitability; Beijing

1. Introduction

Currently, distributed photovoltaic power generation projects based on the utilization of solar energy occupy a leading position in the field of distributed energy construction in China[1]. Beijing is a Class II solar resource region with good resource endowment, coupled with the high demand for low-carbon and safe energy in Beijing, it is therefore important to study the correlation between solar resources and distributed photovoltaic power generation projects in Beijing, to fully explore the potential of solar resource development and utilization in Beijing, and to develop and utilize clean energy resources in Beijing according to local conditions.

The current research on the resource–project–demand chain of distributed energy can be divided into three parts. (1) From the perspective of resources, Zhao and Fan[2] evaluates the abundance of energy resources in Beijing on the basis of solar energy, wind energy and biomass energy; Qi *et al.*[3] established an evaluation model for the development level of provincial renewable energy projects from the perspective of resource development and consumption. (2) From the project side, scholars at home and abroad have conducted comprehensive studies on the operation mode, risk assessment and economic benefits of distributed photovoltaic power generation projects. For example, Li *et al.*[4] discussed the operation mode and adaptability

of distributed photovoltaic power generation system in remote areas through feasibility analysis. Lu *et al.*[5] quantified the benefits of participants of distributed photovoltaic power generation projects adopting contract energy management mode from three perspectives: economy, environment and society. (3) From the perspective of demand side, researches mainly focus on demand response[6], virtual power plant[7], energy storage and integrated energy system[8]. Dynamic balance of energy supply chain can be maintained by adjusting flexible resources on the demand side, so as to optimize system resources and comprehensive benefits.

To sum up, this paper will focus on the "resource—project" association, and use a variety of spatial statistical methods to explore the suitability of solar resources and distributed photovoltaic power generation projects in Beijing from the perspective of the spatio-temporal coupling of resource endowment, in order to provide reference for distributed photovoltaic power generation projects in Beijing.

2. Research methods

Spatial statistical method is a method to study the geospatial relationship among various attribute factors, which is suitable for statistical analysis of data with spatial distribution characteristics[9]. This paper introduces kernel density estimation method, standard deviation ellipse method and bivariate spatial autocorrelation model to conduct an in-depth exploration of the static geospatial distribution law and dynamic spatio-temporal coupling relation-ship between solar resources and distributed photovoltaic power generation projects in Beijing.

2.1 Kernel density estimation method

Kernel density estimation is a spatial statistical method to simulate and explore the density and distribution characteristics around spatial points by fitting the observed data points with smooth peak kernel function.

Suppose the sample point is n, then the probability density function $f(x)$ can be expressed as:

$$f(x) = \frac{1}{n} \sum_{i=1}^{n} K_\mu (x - x_i)$$
$$= \frac{1}{n\mu} \sum_{i=1}^{n} K \frac{(x - x_i)}{\mu}$$

(1)

Where, x is the project point for which the estimated probability is to be obtained; μ is a smoothing parameter, that is, bandwidth, $\mu > 0$; x_i are other project points around the desired project point which are limited to μ, $i \in n \in$; K is the kernel density function, and the integral of $\int K(t)\, dt = 1$, where $t \geq 0$, when $0 \leq t \leq 1$, $K(t) = 1/2$; K_μ is the kernel density function of the μ bandwidth.

2.2 Standard deviation ellipse method

Standard deviation ellipse method adopts the deviation angle (long half-axis) to reflect the dominant direction of the pattern, which can be expressed as:

$$\begin{cases} SDE_X = \sqrt{\dfrac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n}} \\[4ex] SDE_Y = \sqrt{\dfrac{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}{n}} \end{cases}$$

(2)

$$\tan\theta = \frac{\left(\sum_{i=1}^{n}\tilde{X}_i^2 - \sum_{i=1}^{n}\tilde{Y}_i^2\right) + \sqrt{\left(\sum_{i=1}^{n}\tilde{X}_i^2 - \sum_{i=1}^{n}\tilde{Y}_i^2\right)^2 + 4\left(\sum_{i=1}^{n}\tilde{X}_i\tilde{Y}_i\right)^2}}{2\sum_{i=1}^{n}\tilde{X}_i\tilde{Y}_i}$$

(3)

In the formula, SDE_X and SDE_Y are the lengths of the short axis x and long axis x of the standard deviation ellipse, respectively, representing the major and minor development directions of the spatial distribution of project sites. θ is rotation Angle, $tan\theta$ is used to explain the development trend of the project site; X_i and Y_i are the coordinate points of the ith project site; $\bar{X}$ and $\bar{Y}$ are the center of gravity of all project points in the map; $\tilde{X}$ and $\tilde{Y}$ are the deviation between the coordinates and the center of gravity of the ith project points.

2.3 Bivariate spatial autocorrelation model

Bivariate spatial autocorrelation model is used to describe the coupling between multiple variables in space, which can be expressed as:

$$
\begin{cases}
I = \dfrac{m \sum\limits_{v=1}^{m} \sum\limits_{r=1}^{m} w_{vr} \left(c_v - \bar{c}\right)\left(c_r - \bar{c}\right)}{\left(\sum\limits_{v=1}^{m} \sum\limits_{r=1}^{m} w_{vr}\right) \sum\limits_{v=1}^{m} \left(c_v - \bar{c}\right)^2} \\[4mm]
z = \dfrac{1 - E(I)}{\sqrt{\mathrm{var}(I)}}
\end{cases}
\tag{4}
$$

Where, m is the number of object grids; w_{vr} is spatial weight matrix; c_v and c_r are grid specific values of elements v and r respectively, $v \in m$, $r \in m$; $\bar{c}$ is the mean value of all grid specific values; z is the test value; I is the correlation value; var (I) is the variance of I; E(I) is the expected value of I.

v and r grids are selected here to describe the spatial autocorrelation model of bivariate, namely:

$$
\begin{cases}
I_v = \dfrac{c_v - \bar{c}}{S^2} \sum\limits_{v}^{m} w_{vr} \left(c_v - \bar{c}\right) \\[3mm]
E(I_v) = -\dfrac{1}{m-1} \sum\limits_{r}^{m} w_{vr} \\[3mm]
z(I_v) = \dfrac{I_v - E(I_v)}{S(I_v)}
\end{cases}
\tag{5}
$$

$$
\begin{cases}
z_1^v = \dfrac{\beta_1^v - \overline{\beta}_1}{\sigma_1} \\[3mm]
z_G^r = \dfrac{\beta_G^r - \overline{\beta}_G}{\sigma_G} \\[3mm]
I_{1G}^v = z_1^v \sum\limits_{r=1}^{m} w_{vr}\, z_G^r
\end{cases}
\tag{6}
$$

Where, β_I^v is the attribute I value of v grid; $\overline{\beta}_I$ and $\overline{\beta}_G$ are the mean values of attribute I and attribute G, respectively. σ_I and σ_G are the variances of I and G, respectively. S is the discrete standard deviation of c_v; I_v is the correlation value of v; z_I^v is the test value of attribute I value of v grid. z_g^r is the test value of attribute G value of r grid. I_{IG}^v is the correlation value of I and G under v grid; β_I^v is attribute G value of r grid; when $|z| < 1.96$ and $v < 0.05$, it is spatially aggregated; otherwise, it is randomly distributed and has no spatial coupling relationship.

3. Distribution of distributed photovoltaic power generation projects in Beijing

Beijing is a typical temperate monsoon climate area. According to the classification of solar energy resources distribution in China, Beijing belongs to class II solar energy resource area, with rich resources. The annual total solar radiation is 1,393.9 ~ 1,463.3 kWh/m². In terms of spatial distribution of Beijing, the annual total solar radiation of Yanshan Mountains, Western Hills and the areas with relatively high altitude in the northwest direction is larger, which can reach more than 1,450 kWh/m². The average annual total solar radiation in the central and southeastern plains is less than 1,400 kWh/m².

In recent years, Beijing has developed a series of distributed photovoltaic power generation projects in batches. The distributed photovoltaic power generation projects published in *The Beijing Distributed photovoltaic Power Generation Project Award List* (hereinafter referred to as the Award List) from March 2016 to March 2020 are selected as the research objects. The Award List is divided into two parts: "legal entity" and "natural person", containing two batches each year. A total of 9 batches were selected for this study. The new annual grid-connected installed capacity and the number of new projects of distributed photovoltaic power generation in the Award List are shown in **Figure 1**.

As can be seen from **Figure 1**, from March 2016 to March 2020, the newly installed grid-connected capacity of distributed photovoltaic power generation projects in Beijing showed a trend of continuous growth. The number of new projects in that year showed a trend of rising first and then falling, among which, the number of new projects in 2018 was the largest, 6,423.
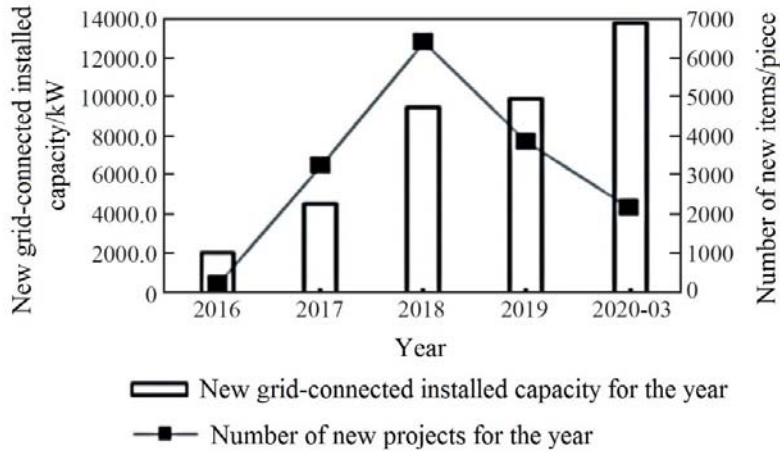
Figure 1. Change of annual newly grid-connected installed capacity and new projects number in *Award List.*

Among the above-mentioned 9 batches of projects, the area of newly added distributed photovoltaic power generation projects in Beijing has grown from 5 districts (Shunyi District, Haidian District, Changping District, Pinggu District, Tongzhou District) in March 2016 to 16 districts. The regional distribution has expanded, showing a trend from centralized development in some regions to decentralized development in multiple regions. At present, Beijing's distributed photovoltaic power generation projects are mostly distributed in Shunyi District, Tongzhou District and other areas around Beijing. According to different development speed, these areas can be divided into three categories: (1) decelerating development areas: Fangshan District, Daxing District, Changping District and Yanqing District, where the proportion of new projects is decreasing year by year. (2) Emerging development areas: including Shunyi District, Tongzhou District and Yizhuang Economic Development Zone, where the proportion of new projects is increasing year by year. (3) Traditional development areas: including Miyun District, Pinggu District and Huairou District, where the growth rate of new projects basically maintains a balanced state.

4. Spatio-temporal coupling relationship between solar energy resources and distributed photovoltaic power generation projects in Beijing

This study explores the multi-spatio-temporal coupling heterogeneity between solar energy resources and distributed photovoltaic power generation projects in Beijing from three aspects of the characteristics of circle, cluster and development. Considering the scale of distributed photovoltaic power generation project in Beijing and the availability and completeness of the relevant data, select 541 projects with legal entities as the main body from the *Award List*, whose total grid-connected installed capacity accounts for 65% of the nine batches of the *Reward List*, and therefore is representative.

The project data sources will query relevant enterprise information in the national Enterprise Credit Information Disclosure System (http://bj.gsxt.gov.cn/) through the enterprise information list of legal entities recorded in the *Award List*, delete the legal entities that have been revoked, expired or non-compliant as of 2020, and verify and supplement the legal entities whose information registration is unknown; then extract the spatial coordinates of the company name and address through the API development platform of Baidu Maps, and combined with AutoNavi map to supplement the spatial coordinate data.

4.1 Characteristics of the circle layer

Kriging interpolation is an optimal, linear and unbiased spatial interpolation method, which is widely used in geospatial isoline drawing[9]. In this study, total solar radiation (GHI) was used to measure solar resource margin, which was collected from Global GIS, and information of 10 points evenly distributed in 16 regions of Beijing was

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collected, namely 160 GHI data. The kriging interpolation method was used to assign weights based on the spatial relationship of GHI, and the weighted average interpolation results were used to divide Beijing into 9 layers with a resolution of about 2 km. Then the results were verified, 15% GHI samples were randomly selected and compared with the original results after fitting. Kriging interpolation rendering results and standardized error verification figure are shown in **Figure 2**.
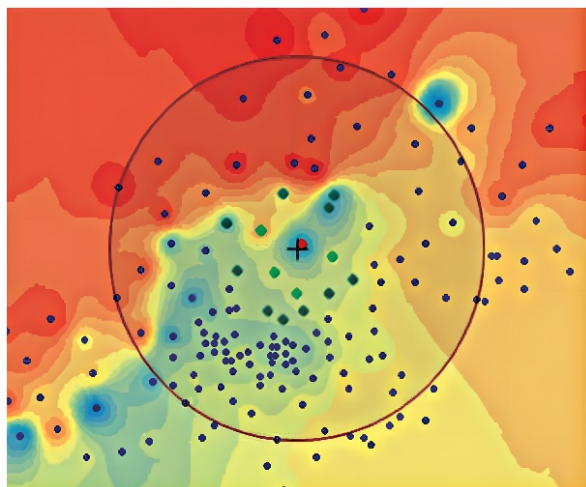
a. Kriging interpolation rendering results
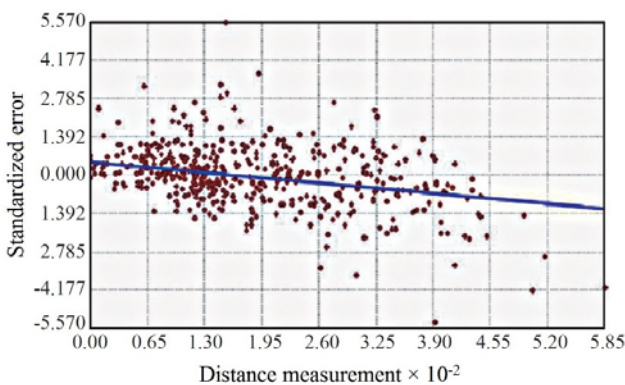
b. Verification of standardization error of Kriging interpolation method
Figure 2. Kriging interpolation method rendering results and standardized error verification chart.

It can be seen from **Figure 2** that the standardized error fitting curve is basically close to the horizontal, and the standardized error value fluctuates near the zero value, which indicates that the kriging interpolation method adopted is relatively ideal. The obvious circles and differences in the figure indicate that the spatial distribution of solar energy resources and distributed photovoltaic power generation projects in Beijing has significant circle differentiation and heterogeneity.

The kriging interpolation diagram is coupled with distributed photovoltaic power generation project sites in Beijing to obtain the circle layer distribution of distributed photovoltaic power generation projects in Beijing, as shown in **Figure 3**.

As can be seen from **Figure 3**, from the perspective of development sequence, distributed photovoltaic power generation projects in Beijing show a trend of developing from the middle resource valley area to the surrounding resource peak area, and their integration with the development of solar energy resources in Beijing gradually increases.

Considering the geographical location of Beijing, the first batch of distributed photovoltaic power generation projects are mainly distributed in the central region of Beijing. The second group is spread out across the city's central district; the third to fifth batch of projects were concentrated around the cluster area of the first and second batch of projects, showing a tendency of clustering in the middle. The sixth batch of projects keeps the development trend of centralization and gradually begins to expand outward. The seventh batch of projects shows obvious characteristics of development towards the southeast of the city; the number of projects in the eighth and ninth batches increased significantly and began to move toward the peak solar resource area around the city. According to the results of **Figure 3**, at present, distributed photovoltaic power generation projects in Beijing are still mostly concentrated in areas with relatively poor solar energy resources, and the spatial distribution of distributed photovoltaic power generation projects and solar energy resources is not balanced.

The solar energy resources in Beijing show a basin distribution. According to GHI value, the solar energy resources in Beijing can be divided into three grades: (1) the general resource area where the GHI value is 1,384.10 ~ 1,402.90 kWh/m^2; (2) the area with medium resource where the GHI value is 1,402.90 ~ 1,411.18 kWh/m^2; (3) the resource-rich region where the GHI value is 1,411.18 ~ 1,508.00 kWh/m^2. As can be seen from

Figure 3, 36.87% of the 9 batches of distributed photovoltaic power generation projects in Beijing are distributed in areas with general resources, namely Haidian District and Fengtai District in central Beijing. 38.48% of the projects are located in medium resource areas. 24.65% of the projects are located in resource-rich areas, namely Huairou District, Yanqing District and other surrounding areas of Beijing.
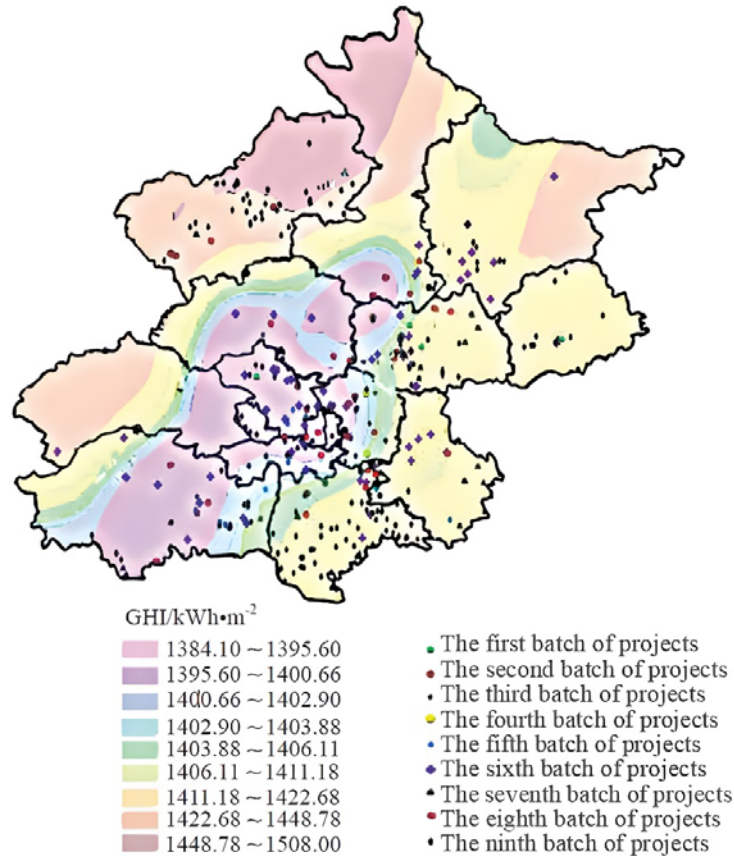

Figure 3. Circle distribution map of distributed PV power generation projects in Beijing.

To sum up, the spatial matching degree between solar resources and distributed photovoltaic power generation projects in Beijing is low at present, but the projects gradually begin to radiate to resource-rich areas with a positive development trend, and the spatial matching degree between energy utilization and project construction is gradually enhanced.

4.2 Agglomeration characteristics

A bivariate spatial autocorrelation model was established to analyze the spatial coupling between solar energy resources and distributed photovoltaic power generation projects in Beijing. There were two variables in the model: variable 1 was the geographical location of different projects, and variable 2 was GH value. In view of the total area and layer characteristics of Beijing, the grid function of ArcGIS software is used to divide Beijing into 6,043 grids of 1.5 km × 1.5 km. After linking and importing into GeoDa software, and several tests, the default distance threshold of 1.5 km was selected as the weight matrix of the bivariate spatial autocorrelation model.

After simulation, the value of Moran's I, which measures the spatial correlation index, is -0.30, indicating that there is a negative correlation between solar energy resources and distributed photovoltaic power generation projects in Beijing, which conforms to the distribution law of circle layer. According to the significant difference of spatial coupling relationship, the spatial coupling relationship between solar resources and distributed photovoltaic power generation projects in Beijing can be divided into four types: Low radiation–weak construction (L-L), low radiation–strong construction (L-H), high radiation–weak construction (H-L), and high

radiation–strong construction (H-H), the specific distribution is shown in **Figure 4**.

(1) Type 1: Low radiation–weak construction (L-L). This type refers to the regions with low GHI value and weak development of distributed photovoltaic power generation projects, which are distributed at both ends of the central belt region of Beijing and have 677 grids, accounting for 11.20% of the total grids, mainly including Mentougou District, Haidian District and the southern part of Pinggu District. The spatial distribution of solar resources and distributed photovoltaic power generation projects in this type of region does not show the characteristics of agglomeration, and the GHI value shows large horizontal change, and the utilization degree of solar resources of projects is not high. Affected by the level of economic development, user demand, geographical location and energy span, the development of photovoltaic power generation industry in this type of region is relatively weak.
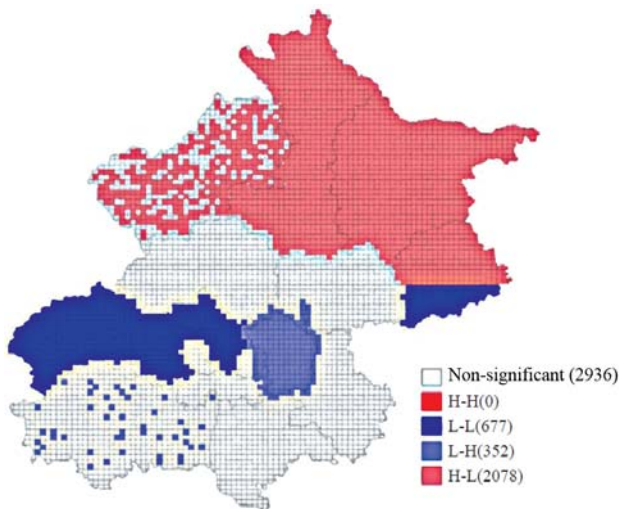

Figure 4. Spatial autocorrelation distribution of solar energy resources and distributed PV power generation projects in Beijing.

(2) Type 2: Low radiation–strong construction (L-H). This type refers to the region with low GHI value and agglomeration of distributed photovoltaic power generation projects, mainly distributed in Chaoyang District in central Beijing, with obvious agglomeration of projects and 352 grids, accounting for 5.82% of the total number of grids. The development of solar resources and distributed photovoltaic power generation projects in this type of region presents obvious heterogeneity characteristics, with less resource endowment but higher project development degree. Resource capacity lags behind project construction, that is, the adaptability of resource and project spatial distribution is poor. Due to the high level of economic development, the shortage of land resources and the large demand for energy on the user side in this type of region, the projects in this type of region are mostly rooftop distributed photovoltaic power generation projects, mainly utilizing roof resources, which is an application form of photoelectric architecture.

(3) Type 3: High radiation–weak construction (H-L). This type refers to the regions with high GHI value but weak development of distributed photovoltaic power generation projects, mainly distributed in the northern part of Beijing, with the Miyun area in the northeast having the most obvious agglomeration. The number of projects in this category is the largest, with 2,078 grids, accounting for 34.39% of the total grids. This type of region has a good resource endowment, but the agglomeration of projects is not obvious

On the one hand, the surrounding areas of the northern region of the city are mostly rural areas, and the distributed photovoltaic power generation projects are mostly dominated by natural people, while the projects dominated by legal entities are relatively few. On the other hand, the economic development of the surrounding rural areas in the northern region is relatively backward compared with that of the central region, with small energy demand from users and loose land resources use. As a result, a number of large-scale photovoltaic power generation projects are built, leading to weak clustering of distributed photovoltaic power generation projects. Therefore, there is significant spatial heterogeneity between the development and utilization of solar energy resources and distributed photovoltaic power generation projects in this type of region.

(4) Type 4: High radiation–strong construction (H-H). This type refers to the region with high GHI value and the agglomeration of distributed photovoltaic power generation projects. According to data analysis, there is no such area in Beijing.

To sum up, the spatial coupling relationship between solar resources and distributed photovoltaic power generation projects in Beijing mainly includes L-L, L-H and H-L, as well as areas with no significant autocorrelation of spatial distribution, and there are spatial differences between solar resources and distributed photovoltaic power generation projects, which is mainly reflected in the weak matching development between the north and the central region, and the development trend of the project shows a pattern of weak in the north and strong in the south.

4.3 Development characteristics

In order to explore the temporal and spatial development trend and evolution law of solar resources and distributed photovoltaic power generation projects, and to optimize the layout of future development and site selection of distributed photovoltaic power generation projects, this study uses standard deviation ellipse method to represent the trend development area of projects or solar energy resources. Two measurement indexes are introduced here, namely ellipticity and standard

centroid difference, and the calculation method is shown in equation (7).

$$\begin{cases} M = \sqrt{\left(\lambda_g - \lambda_D\right)^2 + \left(t_g - t_D\right)^2} \\ N = \dfrac{L}{T} \end{cases}$$

(7)

Where, M is the standard centroid difference; N is the ellipticity; λ_g and t_g are the horizontal and vertical coordinates of the center of mass of the standard deviation ellipse of each batch of project points, $g = 1, 2, 3..., 7, 8, 9$; L is the length of the long axis of the standard deviation ellipse; T is the length of the short axis of the standard deviation ellipse; λ_D and t_D are the horizontal and vertical coordinates of the center of mass of the GHI standard deviation ellipse.

The ellipse formed by GHI values shows the distribution of solar energy resources, and the ellipse formed by each batch of distributed photovoltaic project sites in Beijing shows the development trend of the batch of distributed photovoltaic power generation projects. The parameters of the standard deviation elliptic model are shown in **Table 1**.

Table 1. Parameter results of standard deviation ellipse model

Batch	Coordination of the center of mass		Long axis L	Short axis T	Ellipticity N	Standard centroid difference M	Rotation angle θ/(°)
	λ_g	t_g					
1	116.62	40.13	0.41	0.05	8.20	0.23	83.20
2	116.33	40.03	0.40	0.31	1.29	0.08	59.97
3	116.44	40.11	0.24	0.10	2.40	0.06	110.94
4	116.54	39.97	0.24	0.02	12.00	0.17	179.80
5	116.34	39.85	0.36	0.19	1.89	0.22	63.39
6	116.43	40.00	0.53	0.23	2.30	0.07	58.09
7	116.49	39.93	0.52	0.28	1.86	0.16	70.62
8	116.39	40.06	0.36	0.34	1.06	0.01	44.19
9	116.46	40.00	0.49	0.40	1.23	0.08	10.97
GHI	116.40	40.06	0.60	0.39	1.54	0.00	61.16

Note: Rotation angle can reflect the deviation degree of development.

As can be seen from **Table 1**, due to the small number of distributed photovoltaic power generation projects in batches 1 to 4, the indexes of these four batches have great changes. The center of mass of the first batch of projects falls in Shunyi District, and the difference between the ellipticity and standard center of mass is 8.20 and 0.23, respectively, which deviates greatly from the development trend of resources. The second and third batches of project agglomeration centroids are

shifted to the west, and compared with the first batch of projects, the standard centroid difference has decreased, and the adaptability to the resource development trend has improved. The fourth batch of project centroid gradually shifted to the southeast. The fifth to ninth batches of projects gradually mature, the centroid basically stable in Fengtai District and Chaoyang District. The ellipticity maintains at about 1.67, showing a development trend of gradual expansion of

development areas, gradual increasing of marginal projects, and gradual decreasing trend of standard centroid difference. The fluctuation range is much smaller than the first four batches. The increasing adaptability to resource development trend and the better development trend indicates that the development of distributed photovoltaic power generation projects in Beijing are taking the central region as the starting point and gradually expanding to surrounding areas. In future development, attention should be paid to the development of southwest and northeast regions to enhance the adaptability of resources and project development trend.

5. Evaluation of spatio-temporal coupling suitability between solar energy resources and distributed photovoltaic power generation projects in Beijing

At present, the construction of distributed photovoltaic power generation projects in Beijing is still in the exploratory stage. Optimization of regional industrial development pattern and rational distribution of distributed photovoltaic power generation projects are important measures to achieve green energy development in the capital. This study applies the method of spatial overlay analysis and the amount of information in each area of Beijing solar energy resources with a distributed photovoltaic power generation project, on the basis of the data of solar energy resources and the coupling of time and space of distributed photovoltaic power generation project suitability evaluation (evaluation results can be divided into five level), to exploit the development potential of the development of distributed photovoltaic project in Beijing.

5.1 Steps for evaluating the suitability of spatiotemporal coupling

The spatio-temporal coupling suitability of distributed photovoltaic power generation projects and solar energy resource utilization is taken as the evaluation object. The evaluation process is mainly divided into four steps: determining data sources,

quantitative classification of indicators, assignment of index weights, and calculation of spatio-temporal coupling suitability.

5.1.1 Identification of data sources

The data are mainly from the Global Solar Atlas, the National Center for Meteorological Science, and the 2019 Statistical yearbook of Solar resources and distributed photovoltaic power generation projects in Beijing. According to the principle of independence, relevance, feasibility and importance, 12 indexes are selected from the perspective of natural, social, industrial and project conditions, and the factors are quantified, standardized and rasterized, and rasterized with Beijing's geographic data, using the grid data with spatial data and factor attributes as the basic analysis unit.

5.1.2 Quantitative classification of indicators

Combined with the actual development of distributed photovoltaic power generation projects in Beijing and the advantages and disadvantages of the experimental results of multiple grades, each index is divided into five grades by using the re-classification tool in ArcGIS software and the natural discontinuous separation method, namely, very suitable, relatively suitable, medium suitable, less suitable and not suitable.

The circle characteristic index and agglomeration characteristic index are normalized as follows:

$$\begin{cases} A_h = \begin{pmatrix} a_1 & a_2 & \cdots & a_h \end{pmatrix} \\ \dot{A}_h = \begin{pmatrix} \dot{a}_1 & \dot{a}_2 & \cdots & \dot{a}_h \end{pmatrix} \\ \dot{B}_f = \begin{pmatrix} \dot{b}_1 & \dot{b}_2 & \cdots & \dot{b}_f \end{pmatrix} \end{cases}$$

(8)

In the equation, A_h is the actual quantity set of projects in the GHI equivalent area; $\dot{A}_h$ is the descending set of projects in the GHI equivalent regional; $\dot{B}_f$ is the descending set of projects in the GHI equivalent region; a_h is the number of items corresponding to h area in A_h set. $\dot{a}_h$ is the number of projects in h^{th} region of $\dot{A}_h$; $\dot{b}_f$ is the GHI value of fth region in $\dot{B}_f$.

$$\begin{cases} \eta_h = \dfrac{a_h}{\tilde{a}_h} \\ \tilde{a}_h = \dot{a}_h \\ \delta_h = \dfrac{1}{|1.54 - M_h| N_h} \end{cases}$$

(9)

In the formula, η_h and δ_h are the evaluation values of circle characteristics and agglomeration characteristics corresponding to h region, respectively. $\widetilde{a_h}$ is the optimal number of projects in region h; M_h and N_h are the standard centroid difference and ellipticity corresponding to h region, respectively.

$$\begin{cases} \phi_h = \dfrac{\eta_h - \eta_{\min}}{\eta_{\max} - \eta_{\min}} \\ \Omega_h = \dfrac{\delta_h - \delta_{\min}}{\delta_{\max} - \delta_{\min}} \end{cases}$$

(10)

In the formula, ϕ_h and Ω_h are the final evaluation values of the circle layer characteristics and agglomeration characteristics after the normalization of h region, respectively. η_{max} and η_{min} were the maximum and minimum values of circle characteristics, respectively. δ_{max} and δ_{min} are the maximum and minimum evaluation values of agglomeration characteristics, respectively.

5.1.3 Assigning index weights

The selection of different types of regions with sensitivity, that is, by using the information content method to calculate the weight of the index and the weight is obtained by measuring each single factor and its mean. The calculation formula of index weight is as follows:

$$\begin{cases} \sigma_p = \sqrt{\dfrac{\sum_{j=1}^{u} (C_{pj} - \overline{C}_{pj})^2}{u}} \\ k_q = \dfrac{\sum_{p=1}^{e} \sigma_p}{e} \\ H_q = \dfrac{k_q}{\sum_{q=1}^{e} k_q} \end{cases}$$

(9)

Where, σ_p is the global mean square error of p region at $u = 5$ levels. q is the qth evaluation factor;

k_q is the mean value of the overall mean square deviation of the qth evaluation factor in different grades. H_q is the normalized value, which is the weight value of the final evaluation factor. The weight value of each indicator is calculated by ArcGIS software. e is the number of factors affecting the development and utilization of distributed photovoltaic power generation projects, including 12 factors. C_{pj} is the single factor suitability of the jth level in the pth region. $\overline{C_{pi}}$ is the average value of C_{pj}.

5.1.4 Calculation of spatio-temporal coupling suitability

By superimposing and reclassifying different factors and geographic areas to obtain the distribution of each factor in geographic areas, and then using the raster calculation tool to construct the suitability calculation function and weight different factors, we can finally obtain the classification results of the spatial and temporal coupling suitability of solar energy resources and distributed photovoltaic power generation projects in Beijing.

The expression of spatio-temporal coupling suitability is:

$$F = \sum_{q=1}^{e} H_q \bullet GRID(q)$$

(12)

Where, F is the evaluation value of time-space coupling suitability; $GRID(q)$ represents the suitability of single factor, which is described by grids. The spatio-temporal coupling comprehensive evaluation indexes and their grades of solar resources and distributed photovoltaic power generation projects in Beijing are shown in **Table 2**.

5.2 Comprehensive evaluation results

The spatio-temporal coupling comprehensive evaluation results of solar resources and distributed photovoltaic power generation projects in Beijing are shown in **Figure 5**. The spatio-temporal coupling of solar resources and distributed photovoltaic power generation projects presents five suitability types, among which, the very suitable development region, the relatively suitable development region and the moderately suitable

development region can all be considered as the preferred site selection and encouraged development region of distributed photovoltaic power generation projects. These regions can reach a relatively balanced level with the development of distributed photovoltaic power generation projects in terms of resource endowment and energy demand, and can rely on the distributed photovoltaic power generation projects originally gathered in the regions to reduce technical costs, improve the economic output value and benefits of enterprises, and thus optimize the layout. However, other energy sources should be considered for less suitable development areas and unsuitable development areas, so as to make use of energy according to local conditions.

As can be seen from **Figure 5**:

(1) For area very suitable for development, the evaluation value of the space-time coupling suitability is 118.95 ~ 131.83. This kind of area is mainly distributed in Daxing District, with abundant solar energy resources and moderate

Table 2. Comprehensive evaluation indexes and classification of space-time coupling between solar energy resources and distributed PV power generation projects in Beijing

| Primary index | Secondary index | Grade scale | | | | | Weight |
		Very suitable	Generally suitable	Suitable	Less suitable	Not suitable	
Resource side	Natural conditions (A)	GHI(A_1)/kWh·m^{-2}	≥1,422.68	1,406.11 ~ 1,422.68	1,402.90 ~ 1,406.11	1,395.60 ~ 1,402.90	<1,395.60	0.07
		Average annual temperature (A_2)/°C	≥12.00	11.50 ~ 12.00	11.00 ~ 11.50	8.00 ~ 11.00	<8.00	0.05
		Average annual sunshine hours (A_3)/h	≥2,764.0	2,588.6 ~ 2,764.0	2,519.0 ~ 2,588.6	2,384.3 ~ 2,519.0	<2,384.3	0.04
	Social conditions (B)	Population density (B_1)/person·km^{-2}	≥19,618	6,881 ~ 19,618	598 ~ 6,881	229 ~ 598	<229	0.06
		Per capita GDP (B_2)/ten thousand yuan·person^{-1}	≥29.51	9.90 ~ 29.51	5.29 ~ 9.90	4.36 ~ 5.29	3.90 ~ 4.36	0.04
		Proportion of urban population (B_3)/%	≥100.00	89.12 ~ 100.00	70.05 ~ 89.12	58.33 ~ 70.05	<58.83	0.05
		Proportion of tertiary industry (B_4)/%	≥91.20	80.00 ~ 91.20	56.06 ~ 80.00	45.81 ~ 56.06	<45.81	0.05
	Industry conditions (C)	Total power generation in the power industry (C_1)/100 million kWh	≥102.81	70.45 ~ 102.81	17.37 ~ 70.45	11.86 ~ 17.37	<11.86	0.17
		Administrative area power load (C_2)/100 million kWh	≥83.15	70.93 ~ 83.15	21.58 ~ 70.93	12.54 ~ 21.58	<12.54	0.15
Project side	Item condition (D)	Circle characteristics (D_1)	≥0.23	0.19 ~ 0.23	0.11 ~ 0.19	0.03 ~ 0.11	<0.03	0.07
		Agglomeration characteristics (D_2)	H-H	H-L	L-H	L-L	uncorrelated	0.13
		Development characteristics (D_3)	≥1.00	0.98 ~ 1.00	0.96 ~ 0.98	0.14 ~ 0.96	<0.14	0.12
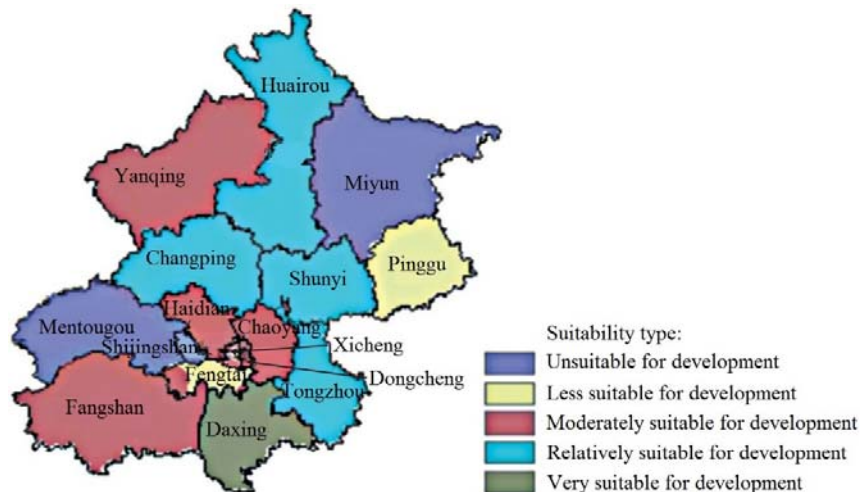
Figure 5. Comprehensive evaluation results of space-time coupling between solar energy resources and distributed PV power generation projects and in Beijing.

power demand. Since the 9th batch of projects, distributed photovoltaic power generation projects in Daxing District have gradually started to develop, and the distribution density has increased. Such areas are suitable for developing large-scale distributed photovoltaic power generation projects and improving the utilization level of solar energy resources by combining the advantages of local resources, power demand and existing power grids and projects.

(2) For areas relatively suitable for development, the evaluation value of the suitability of the space-time coupling is 114.20 ~ 118.95. Such areas are mainly distributed in Huairou District, Changping District, Shunyi District and Tongzhou District. Previously, the distribution density of distributed photovoltaic power generation projects in Huairou District was small, but since the 8th batch of projects, the development of the projects has gradually increased, showing a new development trend. Changping District, Shunyi District and Tongzhou District are rich in solar energy resources, with large user demand. Distributed photovoltaic power generation projects are not saturated, and the distribution of projects is relatively uniform. In the past, such areas had a certain foundation of project clusters, and in the future, it is necessary to promote the development of new projects on the basis of ensuring the development of existing projects.

(3) For areas moderately suitable development, the evaluation value of the suitability of spatial-temporal coupling is 108.26 ~ 114.20. This type of area is the most widely distributed, including Yanqing District, Haidian District, Dongcheng District, Xicheng District, Chaoyang District and Fangshan District. Among them, Yanqing District and Fangshan District are dominated by abundant solar energy resources, but the demand for electricity in these areas is relatively low, and the demand for distributed photovoltaic power generation is also relatively low. The solar energy resources in Haidian District, Dongcheng District, Xicheng District and Chaoyang District are relatively small, but there is a large demand for electricity. The distribution density of distributed photovoltaic power generation projects that have been built in moderately developed areas is relatively balanced, and local resources such as energy, roof and power grid are abundant, which can maintain the current growth trend and continue to develop in the future.

(4) For areas less suitable for development, the evaluation value of the spatial-temporal coupling suitability of this area is 104.20 ~ 108.26. This type of area is mainly distributed in Pinggu District, Fengtai District, and its common characteristics are that the foundation of the original distributed photovoltaic power generation project is weak, the distribution density of the project is small, and the population density and power load pressure are relatively small. Therefore, such areas are not suitable for large-scale concentrated development of distributed photovoltaic power generation projects, and future planning should consider developing small and medium-sized distributed photovoltaic power generation projects on the basis of accurate site selection.

(5) For areas unsuitable for development, the evaluation value of the suitability of space-time coupling is 98.86 ~ 104.20. This kind of area is mainly distributed in Mentougou District and Miyun District. Among them, Mentougou District has a good advantage in solar energy resources, but its users' energy demand and supporting facilities for the development of distributed photovoltaic power generation projects are few. Therefore, the next step in this area should be to integrate supporting facilities such as roofs and power grids, and carry out appropriate planning and development. The foundation of the original distributed photovoltaic power generation projects in Miyun District is weak, which is more suitable for developing smaller-scale distributed photovoltaic power generation projects.

6. Conclusion

This paper takes Beijing as an example, innovatively put forward the evaluation system of spatial-temporal coupling suitability of resources and projects by using spatial analysis methods such as nuclear density analysis and standard deviation ellipse method from the perspective of spatial-temporal coupling between regional solar

energy resources and distributed photovoltaic power generation projects to explore the spatial-temporal coupling relationship between regional solar energy resources and related distributed photovoltaic power generation projects, and scientifically evaluate the regional suitability of their development. The results show that:

(1) The spatial matching degree between solar energy resources and distributed photovoltaic power generation projects in Beijing is still low, and the spatial matching development between the northern region and the central region is weak, and the development trend is characterized by expanding from the central region to the surrounding regions.

(2) The development of solar energy resources and distributed photovoltaic power generation projects in Daxing District and other districts has reached a relatively balanced level; Miyun District, Mentougou District and other districts are no longer suitable for developing large-scale distributed photovoltaic power generation projects. In the future, other green energy development modes should be considered and optimized.

The research results can provide important reference for resource utilization, project layout and development planning of regional distributed photovoltaic power generation projects.

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Conflict of interest

The authors declared no conflict of interest.

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