Spatiotemporal Distribution Characteristics and Regionalization of Solar Energy Resources in Southern Xinjiang: Postprint

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Date: 2021-12-14T00:00:00+00:00

Abstract

Based on the China Regional High Spatiotemporal Resolution Ground Meteorological Elements Driving Dataset (ITPCAS) from 1980–2015 and monthly sunshine data from 30 meteorological observation stations, this study employs trend analysis, rescaled range analysis, wavelet analysis, and solar-thermal resource evaluation index assessment methods to analyze and evaluate the spatiotemporal distribution variation patterns of total solar radiation and solar energy resources in the Southern Xinjiang region from 1980–2015; and constructs a hierarchical indicator system for regional solar energy resource zoning by incorporating factors such as frequency of sand-dust weather, population abundance, and land traffic accessibility, to explore the utilization zoning of solar energy resources in Southern Xinjiang. The results indicate that total solar radiation in the Southern Xinjiang region exhibits significant interannual variation characteristics, with an overall increasing trend and fluctuations occurring every 10–15 years. Solar energy resources are more abundant in the south than in the north, and at the same latitude, mountainous areas have more resources than plains; among these, the Kunlun Mountains region has the most abundant and relatively stable solar energy resources. The entire region' s solar energy resources are divided into three zones: Aksu, Kashgar, Hotan, and other areas have abundant solar energy resources with high utilization value and relatively less sand-dust weather, classified as Grade I utilizable zones, which are optimal areas for integrated photovoltaic and photobiomass energy utilization; the Tarim Basin and its fringe areas, which experience frequent sand-dust weather and have moderate land traffic accessibility, are designated as Grade II utilizable zones, where applications such as agricultural greenhouses and solar heating can be promoted; the Ruoqiang area is classified as a Grade III utilizable zone, which is significantly affected by sand-dust weather and has poor population and basic transportation infrastructure conditions, where the development of

distributed photovoltaic power stations and independent microgrids can be vigorously promoted.

Full Text

Spatial and Temporal Distribution Characteristics and Zoning of Solar Energy Resources in Southern Xinjiang

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Abstract: This study analyzes and evaluates the spatial and temporal distribution characteristics of total solar radiation and solar energy resources in southern Xinjiang from 1980 to 2015, using the ITPCAS (China' s regional high spatiotemporal resolution surface meteorological element driven dataset) and monthly sunshine data from 30 meteorological observation stations. The regionalization of solar energy resource utilization is further explored through trend analysis, rescaled range analysis, wavelet analysis, and photothermal resource evaluation indicators. The results reveal that total solar radiation in southern Xinjiang exhibits clear interannual variability with an overall increasing trend, fluctuating once every 10–15 years. Solar resources are more abundant in the south than in the north, and at the same latitude, mountainous areas have more resources than plains. The Kunlun Mountains region has the most abundant and stable solar resources. Based on factors including sand-dust weather frequency, population abundance, and land transportation accessibility, the region' s solar resources are classified into three zones: Aksu, Kashgar, and Hotan are identified as Grade I available areas with abundant resources, high utilization value, and relatively less dust weather—the optimal region for comprehensive photoelectric and photobiological energy utilization. The Tarim Basin and its marginal areas, affected by frequent dust weather and moderate transportation accessibility, are designated as Grade II available areas suitable for agricultural greenhouses and solar heating applications. The Ruoqiang area, classified as Grade III available area, is significantly impacted by dust weather and has poor population and infrastructure conditions, making it ideal for distributed photovoltaic power stations and independent microgrid construction.

Keywords: solar energy resources; spatial and temporal distribution characteristics; zoning research; southern Xinjiang

Introduction

With the escalating energy crisis and environmental pollution in recent decades, alongside rising energy demands, numerous countries have intensified their development and utilization of renewable energy. In China, rapid economic development has created an imbalance between supply and demand for traditional energy sources, making the energy crisis a global concern. Establishing a sustainable energy system centered on renewable clean energy (including solar, wind, biomass, ocean, and other forms) represents a crucial pathway to addressing energy shortages and environmental security issues. Since wind, hydro, biomass, ocean thermal, and tidal energies all originate from the sun, solar energy is internationally recognized as one of the most competitive new energy sources for the future. Consequently, scholars worldwide have conducted extensive research on solar radiation distribution patterns and influencing factors.

Early studies on China' s solar radiation spatial distribution characteristics include Zuo Dakang et al., who produced monthly and annual total radiation distribution maps for China. Ma Jinyu et al. analyzed long-term variation trends, decadal anomalies, cycles, and mutation points of surface solar radiation across China and various regions using nearly half a century of ground solar radiation observation data from 716 meteorological stations. Huang Jiamin et al. analyzed Xinjiang' s solar radiation spatiotemporal variation trends from 1984 to 2007 using GEWEX data. Research has also shown that aerosols, sand-dust, cloud cover, and other factors affect total solar radiation to varying degrees.

Xinjiang is located in northwestern China between 73°40 -96°18 E and 34°25 - 48°10 N, with annual sunshine hours of 2300–3300 and sunshine percentage of 60%–80%, ranking second nationally after the Tibetan Plateau. Surrounded by mountains and located deep inland, Xinjiang has a unique temperate continental climate characterized by large temperature differences and low precipitation, causing all solar radiation reaching the surface to be influenced by climatic conditions and atmospheric underlying surface characteristics. Xinjiang' s solar resources are more abundant than North and Northeast China at the same latitude and exceed those of the lower-latitude Yangtze River middle-lower reaches and South China. Southern Xinjiang is particularly rich in these resources. However, sparse solar radiation observation stations and lack of total solar radiation data have limited understanding of regional solar resource distribution and available areas. Therefore, this study analyzes the spatiotemporal variation patterns of total solar radiation in southern Xinjiang and proposes zoning recommendations for solar resource utilization, aiming to clarify radiation trends and available spatial distribution patterns to provide theoretical support for low-cost ecological utilization technology integration and engineering applications.

1. Data Sources and Accuracy Analysis

Solar total radiation data were obtained from the ITPCAS (China' s regional high spatiotemporal resolution surface meteorological element driven dataset) developed by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. This dataset integrates ERA-40 and ERA-Interim reanalysis data, GEWEX radiation data, and Princeton precipitation data with China surface meteorological observation data, offering temporal resolution and spatial resolution for the period 1979–2015. Meteorological data include China' s monthly sunshine and wind speed grid dataset and daily radiation basic elements dataset from the China Meteorological Data Network. Auxiliary data comprise China' s population spatial distribution kilometer grid dataset, land use status remote sensing monitoring data, and Xinjiang county-level administrative boundary vectors from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences.

To verify data applicability, we compared ITPCAS annual and daily total solar radiation data with corresponding ground measurements from 6 radiation stations in the study area. Annual data comparison covered 2001–2010 (Table 1), while daily data randomly selected 365 days from each quarter for 2010. The results show correlation coefficients between ITPCAS annual total solar radiation and station measurements exceeding 0.9, with daily correlations above 0.85 for all 6 stations (Figure 1). This indicates good correlation and consistency between the radiation dataset and station measurements, confirming that the dataset can effectively reflect regional annual variation patterns and meet requirements for analyzing spatiotemporal distribution characteristics and evaluating solar energy resources in southern Xinjiang.

2. Methods

2.1.1 Trend Analysis Linear regression is commonly used to analyze long-term trends in solar radiation. This study calculated multi-year trends for each grid cell in the time series to obtain fitted regression line slopes representing change trends at each pixel. A positive slope indicates increasing total solar radiation, with larger values indicating more significant increases, while negative slopes indicate decreases. The method reflects spatiotemporal distribution characteristics across different periods:

$$slope = \frac{n\sum_{i=1}^{n} x_{it}i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} t_i}{n\sum_{i=1}^{n} t_i^2 - (\sum_{i=1}^{n} t_i)^2}$$

where *slope* is the trend line slope ($\mathrm{MJ \cdot m^{-2} \cdot yr^{-1}}$), x_i is the annual total solar radiation in year i ($\mathrm{MJ \cdot m^{-2}}$), t_i is year i, and n is the study period length (years).

2.1.2 Rescaled Range (R/S) Analysis R/S analysis is a long-term sequence memory analysis method. For a given time series $\{x(t)\}$, $t = 1, 2, ..., \tau$, the mean sequence is defined as:

$$\overline{x}_\tau = \frac{1}{\tau}\sum_{t=1}^{\tau} x(t)$$

The cumulative deviation is:

$$X(t,\tau) = \sum_{t=1}^{\tau}(x(t) - \overline{x}_\tau)$$

The range is:

$$R(\tau) = \max_{1\le t\le \tau} X(t,\tau) - \min_{1\le t\le \tau} X(t,\tau)$$

The standard deviation is:

$$S(\tau) = \sqrt{\frac{1}{\tau}\sum_{t=1}^{\tau}(x(t) - \overline{x}_\tau)^2}$$

If $R/S \propto \tau^H$, the time series exhibits Hurst phenomenon, where H is the Hurst index. When $H = 0.5$, the series is independent. When $H > 0.5$, the series shows positive correlation with persistent long-term characteristics—past trends continue into the future. When $H < 0.5$, the series shows negative correlation—past trends reverse in the future.

To understand persistence in southern Xinjiang's solar radiation trends, we overlaid change rate maps with Hurst index distribution maps to obtain persistence characteristics. Classification standards were determined based on percentage 突变点 of different Hurst values, combined with change rates (Table 2).

2.1.3 Wavelet Analysis Wavelet analysis is a time-frequency multi-resolution method that extracts information from signals through scaling and translation operations. To identify periodic components and their temporal distribution, we used Morlet wavelet analysis on ground solar radiation:

$$\psi(t) = \frac{1}{\sqrt{\pi f_b}} e^{2\pi i f_c t} e^{-\frac{t^2}{f_b}}$$

where $W_f(a,b)$ are wavelet transform coefficients; $f(t)$ is a signal or square-integrable function; t is time scale; R is real numbers; a is scale parameter; b is time position parameter; ψ is the wavelet function; i is imaginary unit; c is constant.

2.2.1 Construction of Zoning Index System Solar energy development feasibility, scale, and intensity result from comprehensive influences of resource-environment and socio-economic systems. Considering southern Xinjiang's characteristics and data availability, we selected solar resource abundance, stability, utilization value, total radiation change trend, sand-dust weather frequency, population abundance, land transportation accessibility, and land use to construct a zoning index system. Each indicator was classified according to different grading standards, then spatially overlaid for regionalization (Table 3).

2.2.2 Solar Energy Resource Evaluation Indicators **Abundance:** Based on annual total solar radiation (Table 4).

Stability: Calculated as the ratio of maximum to minimum monthly sunshine hours, with $K > 12$ indicating instability (Table 5):

$$K = \frac{\max(D_i)}{\min(D_i)}$$

where K is stability index and D_i is sunshine hours in month i.

Utilization Value: Evaluated using days with monthly sunshine hours >6 h/day (Table 6). We calculated average days >6 h/day at 30 stations and classified them according to southern Xinjiang' s specific conditions.

Other Indicators: Include sand-dust weather frequency, population abundance, transportation accessibility, and land use.

Sand-dust Weather Frequency: Based on Bagnold' s critical threshold velocity formula and supercritical sand velocity days, which correlate with observed dust days at $r > 0.8$ (Figure 2, Table 7).

Population Abundance: Adjusted classification standards for Xinjiang' s low population density (Table 8).

Transportation Accessibility: Adopted from Liu Hailong et al.' s Xinjiang accessibility research.

Land Use: Using 2015 land use data, farmland and protected areas were designated as restricted zones, while urban, industrial, mining, residential, and unused land were designated as priority development zones.

3. Results

3.1 Spatiotemporal Distribution of Solar Radiation in Southern Xinjiang From 1980–2015, annual total solar radiation showed a fluctuating upward trend (Figure 4) at a rate of 15.23 $\mathrm{MJ \cdot m^{-2} \cdot yr^{-1}}$, peaking in 2009 (6444.75 $\mathrm{MJ \cdot m^{-2}}$) and reaching minimum in 1993 (5893.49 $\mathrm{MJ \cdot m^{-2}}$). This aligns with research showing China' s surface solar radiation transitioning from "dimming" to "brightening" around 1990. Wavelet analysis revealed periodic fluctuations:

a 10-15 year cycle with weak negative and strong positive anomalies. The first cycle (1980-1995) showed weak negative anomalies; the second (1995-2010) showed transition from negative to positive with dense closed lines indicating significant fluctuations; post-2010 suggests a new negative anomaly cycle forming. Although showing an upward trend, the rate has slowed.

Hurst index analysis reveals spatial persistence characteristics (Figure 5). Areas with persistent increase account for 58.63% (average $H = 0.68$), concentrated in the Taklamakan Desert hinterland, Karakoram Mountains, and Hotan/Kashgar oases. Persistently and significantly increasing areas occupy 38.10%, while persistently and slightly increasing areas occupy 20.53%, primarily influenced by continuous temperature rise. Persistently decreasing areas (22.88%) concentrate in Ruoqiang, Taxkorgan County, and the upper Kongque River basin. Ruoqiang' s decrease is mainly due to dust weather weakening radiation through aerosol scattering and absorption. Taxkorgan and upper Kongque River areas are significantly affected by cloud cover, with increasing precipitation. Stable areas (0.88%) are scattered in the middle Yarkant River. Non-persistent change areas are limited: increase-to-decrease transition occupies 11.82% (Qiemod and central Yarkant River basin), while decrease-to-increase transition occupies 5.79% (desert-oasis boundaries).

3.2 Solar Energy Resource Evaluation Evaluation results for abundance, stability, and utilization value (Figure 6) show "extremely abundant" resources along the Kunlun Mountains, with other areas classified as "abundant." This reflects southern Xinjiang' s unique geographic and climatic conditions: arid climate with low cloud cover, frequent sandstorms, alternating mountains and basins, and deserts surrounding oases. The terrain slopes high-west to low-east and high-south to low-north, preventing low-level airflow from directly reaching the Tarim Basin and creating more clouds/precipitation in the northwest that weakens radiation, while the southeast with less cloud cover receives more radiation.

"Stable" resources concentrate in central-southern areas (36.3%), with "relatively stable" areas occupying 46.2% and "unstable" areas 17.5%. Utilization periods are long throughout southern Xinjiang, with "extremely long utilization" in the southeast. Average days with sunshine >6 h/day range from 310 days (Ruoqiang) to 213 days (Tazhong station), indicating high potential utilization value.

3.3 Solar Energy Resource Utilization Zoning Zoning aims to reflect functional differences in solar resource development systems and guide exploration direction, sequence, and priorities. Based on the index system (Table 3) and strategic plans like the "Three Bases and One Channel" construction and Xinjiang' s regional development/poverty alleviation plans, southern Xinjiang' s solar resources are divided into three grades (Figure 7):

Grade I Available Area: Includes Aksu, Kashgar, Hotan, and Korla. With annual total radiation >5200 $MJ \cdot m^{-2}$ and sunshine hours of 240–280 days, these areas show persistent increasing trends. Located in the Tarim Basin and margins with frequent dust weather but moderate transportation accessibility, these newly-poverty-alleviated areas are major fruit-vegetable production zones and green agricultural product bases—optimal for solar utilization. Applications include agricultural greenhouses, solar heating, and water heaters. These ecologically fragile desert vegetation areas with scarce surface water can use photovoltaic power for groundwater extraction to support vegetation conservation and restoration.

Grade II Available Area: The most widely distributed zone, covering most of southern Xinjiang' s central region. With radiation of 5800–6500 $MJ \cdot m^{-2}$ and stable sunshine hours averaging 295 days, this area has good resource endowment but is constrained by nature reserves, high winds, poor population/transportation conditions. High winds may affect panel safety and reduce support structure corrosion resistance. These areas can combine wind and photovoltaic power, prioritizing wind power in high-wind zones while promoting distributed photovoltaic stations and independent microgrids elsewhere to solve energy shortages in grid-inconvenient regions.

Grade III Available Area: Includes Ruoqiang and other areas. Despite abundant annual radiation and long sunshine hours, poor population/infrastructure conditions and large nature reserves limit development. Distributed photovoltaic stations and independent microgrid construction should be vigorously promoted.

4. Conclusions

1) Southern Xinjiang' s solar resources show two major characteristics: (a) Clear interannual variation with overall increasing trend, fluctuating once every 10–15 years within normal ranges; (b) Abundant and stable resources with good utilization value, showing spatial patterns of more in south/less in north, and more in mountains/less in plains at same latitude. The Kunlun Mountains region has the most abundant and stable resources.

2) Based on national solar resource zoning and southern Xinjiang' s radiation patterns, combined with sand-dust frequency, population, and transportation accessibility, the region is divided into three zones: Aksu, Kashgar, and Hotan as Grade I; Tarim Basin and margins as Grade II; Ruoqiang as Grade III.

3) Grade I areas have excellent resource endowment with favorable dust, population, and infrastructure conditions—optimal for comprehensive photoelectric and photobiological utilization. Grade II areas have moderate conditions suitable for agricultural greenhouses and solar heating. Grade III areas, despite resource potential, face constraints from nature reserves, high winds, and poor infrastructure, making them suitable for distributed photovoltaic and independent microgrid development.

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Note: Figure translations are in progress. See original paper for figures.