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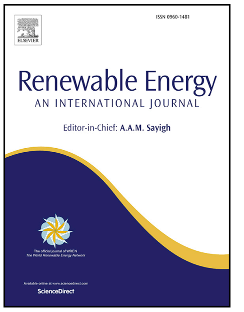

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Solar energy potential assessment: A framework to integrate geographic, technological, and economic indices for a potential analysis

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Solar energy potential assessment: A framework to integrate geographic, technological, and economic indices for a potential analysis

Abstract: To develop solar energy as a primary source of electricity supply in China, it is imperative to also develop an overall and complete solar energy potential analysis. Such an analysis technique would be a substantial contribution to solar power generation development both nationally and regionally. This study analyzes the spatial and temporal distribution of solar energy in China and estimates the solar energy potential from three aspects: geography, technology, and economy. The results of this research showed that the solar energy resource in China is substantially rich and stable, but also has notable spatial heterogeneity. A potential estimation indicated that Xinjiang Province was the most optimal site for large-scale photovoltaic station construction, displaying the highest values for all three potentials. It was also found that solar energy potential in western China is greater, while the eastern region is less suitable for solar photovoltaic development. These results can provide support for the large-scale development and utilization of solar energy resources in the future.

Keywords: solar energy potential; temporal and spatial analysis; constraint analysis; China

1. Introduction

In the light of ensuring a sustainable future and addressing the increasingly serious impacts of climate change, especially global warming, developing countries are urgently seeking to switch from traditional energy to renewable energy [1–5]. Solar energy is abundant, free, and non-polluting; hence, it is considered one of the most competitive choices of all the renewable energy choices [4,6]. The global solar PV market has rapidly grown by 50% over the past decade [7]. The International Energy Agency (IEA) expects that the share of global electricity from photovoltaic (PV) systems will reach 16% by 2050 (IEA, 2010). In particular, China is playing an increasingly immense role in the PV electricity supply. Due to the guidance of the 13th Five-Year Plan in China, more than 110 million kilowatts of solar power is planned to be installed by 2020 [9]. It has also been estimated that nearly 40% of the global installed PV capacity will be held by China by 2023 [10]. According to the CHINESE RENEWABLE ENERGY DEVELOPMENT REPORT (2018) [11], solar energy and wind power remain the two primary pillars of electricity generation in China. A critical step in the process of utilizing this tremendous solar energy resource is to identify and prioritize optimal sites for PV power stations [12,13]. Furthermore, to find suitable places for solar energy exploitation, it is imperative to first estimate the actual solar energy potential on the ground [3].

The estimation of solar energy potential depends on multi-dimensional indicators. These include but are not limited to local solar energy resources, land cover, technological development, the economics of solar products, and the governmental policies. All of these factors exert significant impacts on the development of the solar energy market [14]. Land cover is a major factor in the selection of a suitable area for solar PV generation installation [15]. Technological development directly determines the efficiency of the solar power transition [16], which could influence the economic feasibility of solar power generation. In addition, governmental policy has already been confirmed to play an indispensable role in solar PV generation operation [17]. Due to these factors, a comprehensive solar energy potential analysis should be based on not only the solar energy resource but also the technological potential, economic potential, and other factors. A complete evaluation of solar energy should identify successful installation factors while minimizing construction and operational costs [18].

In the last decade, considerable efforts have been made to evaluate the global and regional solar energy potential, both on the ground and on building rooftops. However, most studies have only estimated direct solar resources; namely, naturally obtained solar radiation, without considering the impacts of technological transition efficiency, let alone the economic feasibility. For example, Fillol et al. (2017) evaluated the potential for solar energy based on the Diffuse Horizontal Irradiance (GHI), the Direct Normal Irradiance (DNI), as well as the inter-variability of radiation in the Guiana Shield. Jung et al. (2019) proposed a computational method that estimated the solar energy potential on national highway slopes that referred to simply solar radiation. Huang et al. (2018) successfully identified suitable areas for large-scale PV station operation but failed to perform a complete solar energy potential estimation. Additionally, urban solar energy potential estimations, particularly rooftop solar energy, have also been focused on. Still, a majority of the studies have explored methodologies for solar radiation evaluations [21–24]. Recently, a considerable number of studies have focused on the technological feasibility and economic feasibility of solar power PV generation by integrating these factors into solar energy potential analyses. Hoogwijk (2004) presented a comprehensive analysis framework to assess the geographical, technical, and economic potential of all renewable energy. Mahtta et al. (2014) considered land-use factors and the solar to electric conversion efficiency of PV modules to map the solar power potential of India. Polo et al. (2015) mapped the theoretical and technical potential of Vietnam and the solar potential for concentrating solar power (CSP) and for grid-connected photovoltaic (PV) technology. Sun et al. (2013) evaluated the comprehensive potential analysis of solar PV generation for the Fujian Province of China from the perspectives of the geographical potential, technological potential, and economic feasibility. Li et al. (2015) investigated the solar potential of urban residential buildings by considering the resource, technological, and economic potentials from the perspective of increasing solar energy potentials.

Solar potential studies in China are still in their infancy, and the studies are limited. To our greatest knowledge, only Huang et al. (2018) have evaluated China's entire solar energy potential, yet they also only considered the geographic constraints and mapped the GHI nationally. They did not consider technological and economic factors. In order to develop the enormous solar PV generation potential of China, it is urgent for China to perform an overall and complete solar energy potential analysis. Such a comprehensive analysis will make a substantial contribution to solar power generation development.

Thus, by referring to the evaluation model of Hoogwijk (2004) and Gómez et al. (2010), a complete solar energy potential analysis for the installation of large-scale photovoltaic (LS-PV) stations in China is performed in this study. This knowledge is vital for over-coming problems in the development of solar energy production projects. Section 2 details the methodology utilized for the estimation of the solar energy potential. Section 3 details the results and contains the discussion as well. Finally, section 4 outlines the primary conclusions and provides policy recommendations.

2. Methodology and data

Figure 1 shows a summary of the study methodology flow. Prior to the solar energy potential analysis, the spatio-temporal distribution of solar radiation was analyzed to determine the characteristics of solar radiation resources in China. Then, a constraint analysis was performed to exclude the unsuitable lands for LS-PV stations. This was based on the above two portions of the study that were conducted in advance. The geographical potential, technological potential, and economic potential were also progressively estimated. Finally, the optimal sites for solar energy exploitation were selected based on the results of the previous work.

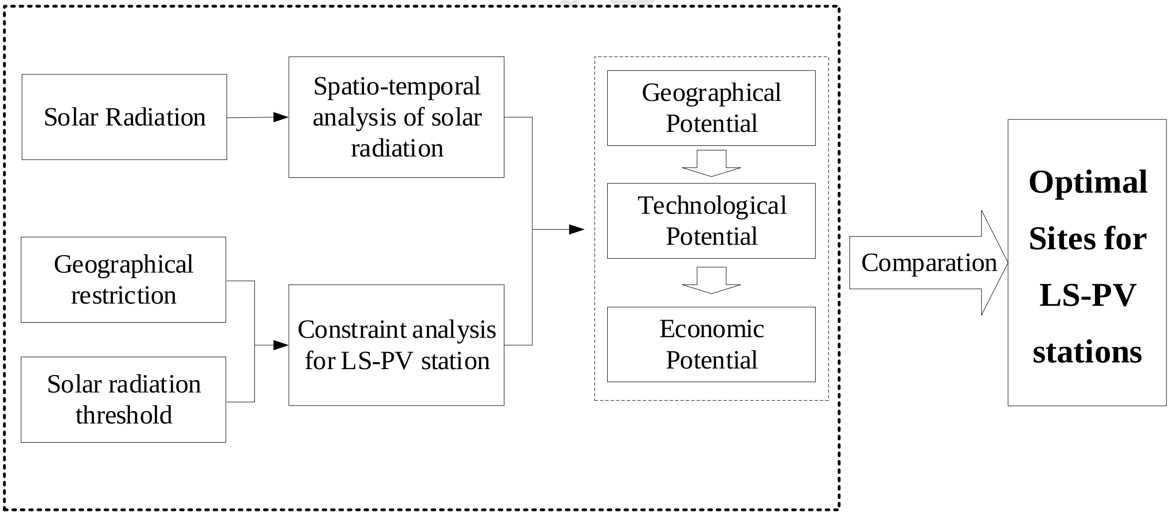


Figure 1: Study methodology flow

2.1 Constraint analysis

The potential analysis was established based on land areas suitable for the construction of LS-PV stations that excluded geographic constraints and the solar radiation threshold. It was essential to identify and eliminate all of the unsuitable areas prior to the potential evaluation, thus avoiding unsuitable lands that could influence the potential results. Based on previous studies, constraint factors for the LS-PV station typically referred to geographical restrictions and the solar radiation threshold. Among these, the geographical restriction consisted of three types of land areas: protected areas, unsuitable land use areas, and land with slopes of more than 5º. In terms of the solar radiation threshold, areas with solar radiation below 5400 MJ/m^2 were generally considered unsuitable areas. ArcGIS software was used to merge and reclassify all the constraint factor layers and then compound the maps for LS-PV stations construction. The two constraint factors are detailed below.

2.1.1 Geographical restriction

The construction of LS-PV stations has strict geographical land limitations. According to previous research [28–30], six land use patterns, including protected areas, water bodies, cultivated land, forest land, high-coverage grasslands, and construction lands, are not suitable for the construction of LS-PV power stations. In addition, steep land is also a geographical restriction, which would make LS-PV generation construction projects maintenance expensive. Some studies have shown that the maximum acceptable surface slope for photovoltaic construction varies from 3° to 5.2° [31–34], and most studies have used 5° as the reference. Therefore, areas where the surface slope exceeded 5° were excluded.

2.1.2 Solar radiation threshold

The abundance of the solar energy resource is obviously the primary factor that influences PV power generation. Adequate solar radiation is very important for the development and utilization of solar energy and economic feasibility. There has been no consensus regarding the minimum acceptable radiation for solar photovoltaic systems. In this study, 5400 MJ/m^2 was chosen as the baseline.

2.2 Solar potential estimation

In this study, the solar energy potential was examined using three aspects: geography, technology, and economy, as proposed by Hoogwijk (2004) and Gómez et al. (2010) [14].

The principle is similar to that published by the World Energy Council [35]. All three potentials were calculated for the provinces on an annual basis, and ArcGIS was employed to map the solar energy potential. By using ArcGIS, the potential of every grid was first estimated. Then the average potential data of every province were calculated. According to previous studies [14,25,27,36] and the available dataset, the definition of geographic potential, technological potential, and economic potential was as follows:

- **Geographic potential**: the amount of the total annual solar radiation per unit area, excluding geographically restricted areas.
- **Technological potential**: the amount of the total electric energy that can be translated considering the technological limitations of conversion efficiency and suitable land areas.
- **Economic potential**: the costs of PV power generation per unit of electricity with competitiveness at the cost level.

The three solar energy potentials are detailed in the following sections.

2.2.1 Geographical potential

Based on the constraint analysis, the geographical potential for the suitable area was calculated by averaging the amount of solar radiation in the remaining areas.

2.2.2 Technical potential

Solar photovoltaic technology is based on photovoltaic cells that can directly convert solar radiation into electrical energy. From the technical and economic point of view, the current photovoltaic power generation technology is considered a mature technology [37]. Photovoltaic power generation technology can be divided into the following categories [37]: (1) Photovoltaic cells that include crystalline silicon materials such as monocrystalline silicon, polycrystalline silicon, and gallium arsenide; (2) thin film solar cells based on amorphous silicon, cadmium telluride, cadmium sulfide, or copper indium gallium selenide/copper indium selenium materials; (3) organic polymer solar cells; (4) hybrid solar cells; (5) dye-sensitized solar cells; and (6) photovoltaic technology based on nanotechnology. These technologies differ in efficiency and costs of photovoltaic modules.

Currently, crystalline silicon materials occupy a dominant position in the market [37], and single crystal materials account for approximately 80% of the total photovoltaic market [38].

In recent years, the efficiency of photovoltaic power generation technology has been significantly improved. According to research by (Tyagi et al., 2013), the efficiency of monocrystalline silicon solar cells was approximately 15% in the 1950s, and it has now increased to 28%. In addition, the efficiency of polycrystalline solar cells has reached 19.8% [39]. However, commercially available photovoltaic cells and modules are less efficient. According to research by (Razykov et al., 2011), the efficiencies of single crystal photovoltaic cells sold on the market are now between 15% and 22%.

By considering both the efficiency and suitable land areas, the technological potential (total electricity converted) was calculated using Equation (1) [30,40]:

$$E_i = SR \times CA \times AF \times \eta \ , \quad (1)$$

where SR is the geographical solar radiation; CA is the appropriate total land area; AF is the area factor, indicating that the solar panel can cover that portion of the calculation area; and η is the photovoltaic system efficiency. According to the maximum footprint of the photovoltaic panel, AF=70% was selected due to the minimal shadowing effect [30]. The efficiency of single crystal photovoltaic cells ranges from 15% to 22%, and this was calculated as $\eta = 22\%$ in this study.

2.2.3 Economic potential

The electricity cost, C_{el}, of a solar power plant operating in solar mode depends primarily on its investment cost, I, the annual operating cost of operation and maintenance, $C_{O\&M}$, the economic life cycle, n, the average capital interest rate, i, and the annual net solar power generation at the corresponding location. The following equation was used to calculate the cost [41]:

$$C_{el} = \frac{\frac{i\cdot(1+i)^n}{(1+i)^n-1}\cdot I + C_{O\&M}}{E_i} \quad . \quad (2)$$

To simplify the evaluation process, the average investment cost per unit grid, I=420 USD, was used in this study. This figure was calculated in reference to the Chinese PV market and (Sun et al., 2013). The average capital interest rate is 9%, the economic life cycle is 25 years, and the annual operating cost of operation and maintenance, $C_{O\&M,}$ is assumed to be a constant value during the life cycle, which is 3% of the investment cost.

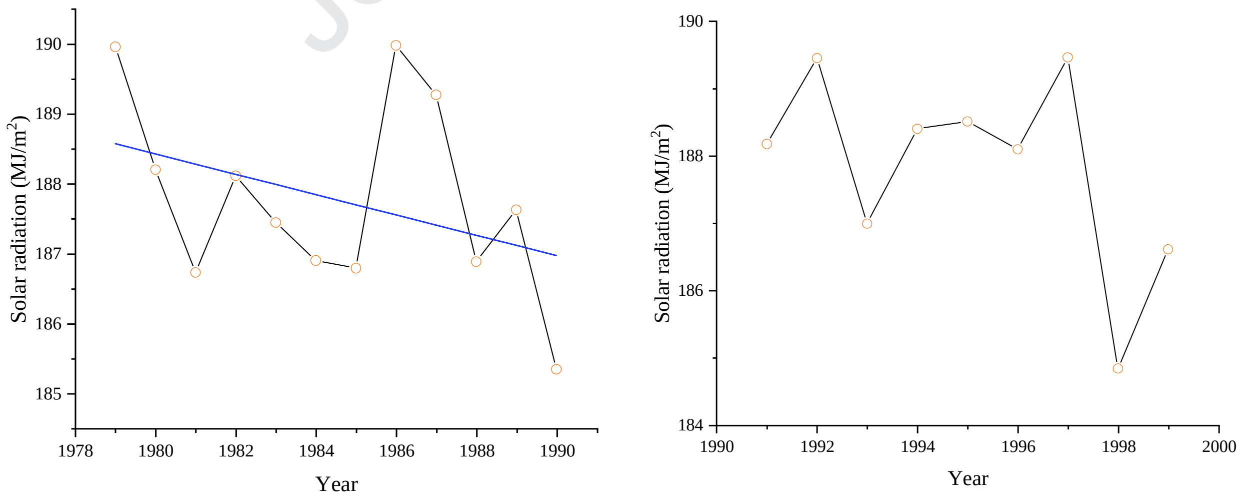
2.3 Data source

The solar radiation dataset used in this study is the ERA-Interim meteorological reanalysis data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). This study selected the dataset that covered all of China from January 1, 1979, to December 31, 2017, with a spatial resolution of 0.75°×0.75° and a temporal resolution of the monthly total [42,43] in order to simplify the calculation process. The World Database on Protected Areas (WDPA) derived from UNEP and the World Conservation Union (IUCN) was used to extract the protected areas. In addition, the 2015 land use/cover data provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn), were used to extract the unsuitable area.

3. Results and discussion

3.1 Solar radiation estimation

3.1.1 Temporal distribution



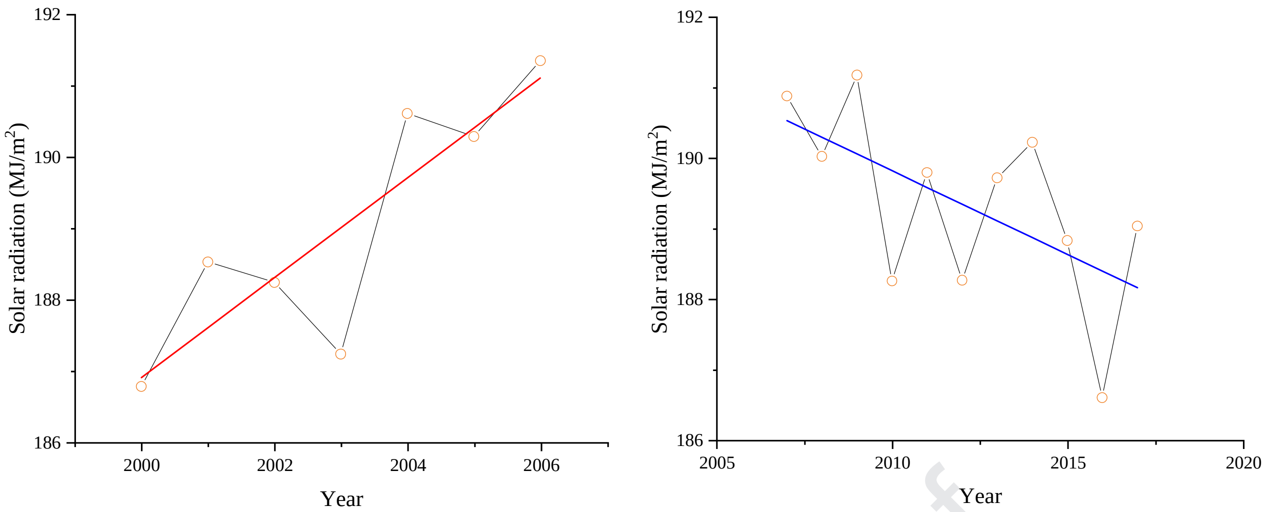


Figure 2: Trends in solar radiation from 1979 to 2017

Figure 2 shows the long-term trend of solar radiation in China from 1979 to 2017, and the red line is the 39-year trend fitting line of solar radiation. The solar radiation value in China ranged from 5486.82 MJ/m^2 to 5776.70 MJ/m^2, and the variation trend of the solar radiation over the years was 2.54 MJ/m^2/yr. The solar radiation increased overall during the period from 1979 to 2017. However, it showed a decreasing trend from 1979 to 1990, and it stabilized after 1990. At the beginning of the 21st century, it displayed an increasing trend, and after 2007, it displayed a downward trend. Yet, the solar energy resource in China was still abundant and stable.

Studies have shown that since the 1950s, solar radiation on the surface has generally decreased, and the world is in a dark period [44–49]. In 2005, Martin Weald [50] published an article entitled “From Darkening to Lighting: Interdecadal Variation of Solar Radiation on the Earth’s Surface” in the journal *Science*. In this article, he pointed out that the solar radiation on the surface had a significant downward trend in many observational records up to 1990, but this trend did not last after the 1990s. According to the fourth IPCC (Intergovernmental Panel on Climate Change) report, “global dimming” will not continue after 1990 [51,52]. The results in Figure 4 are basically consistent with the process from darkening to brightening.

3.1.2 Spatial distribution

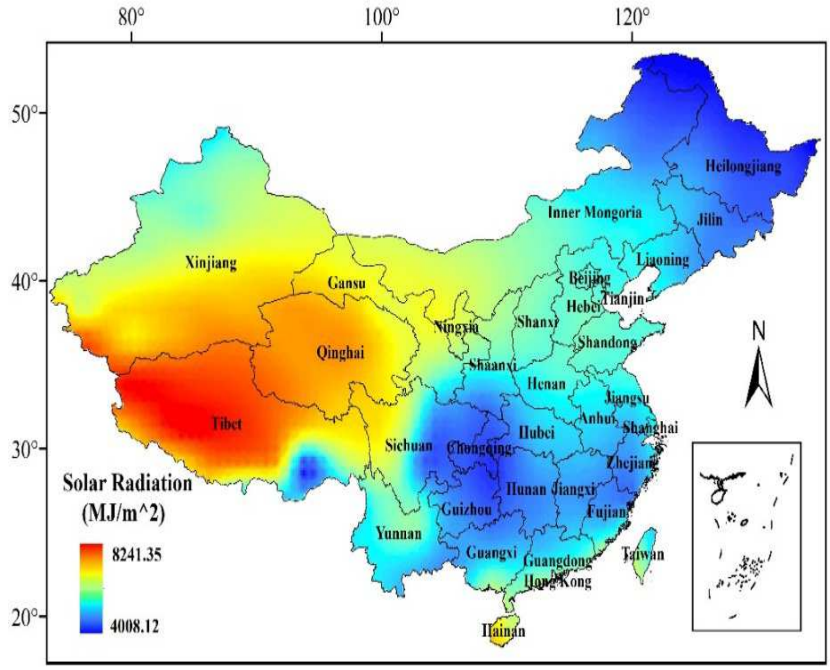


Figure 3: Spatial distribution map of the annual average solar radiation

As can be seen in Figure 3, China's solar radiation is generally high in the western region and low in the eastern region. The average annual solar radiation is bounded by the east side of the Inner Mongolia Plateau, Taihang Mountain, Qinling, the west side of the Sichuan Basin, and the border between Yunnan and Guizhou. Solar radiation is relatively weak in the east and south of the boundary and stronger in the west and north. Tibet in the southwestern region has the strongest solar radiation, reaching 7347.55 MJ/m^2. Higher provinces also include Qinghai, Xinjiang, Gansu in the northwest, and Hainan in central southern China. The provinces with low solar radiation are Chongqing and Guizhou in the eastern part of southwest China and Heilongjiang in northeast China. By comparing the solar energy resources of each province, the southwest and northwest regions with higher altitudes are richer, and the eastern regions are less. The western provinces, such as Tibet, Qinghai, Xinjiang, and Gansu, are rich in solar radiation. Chongqing, which has lower altitudes, and Heilongjiang, which has higher latitudes, are poorer in solar resources. Tibet, with abundant solar resources, and Chongqing, with poor solar energy resources, are in southwest China. The two provinces are at the same latitude, but Tibet has a higher altitude, thin air, and strong solar radiation. Chongqing is in the Sichuan Basin, with a lower terrain, more clouds, more rain, and less solar radiation.

3.2 Constraint analysis

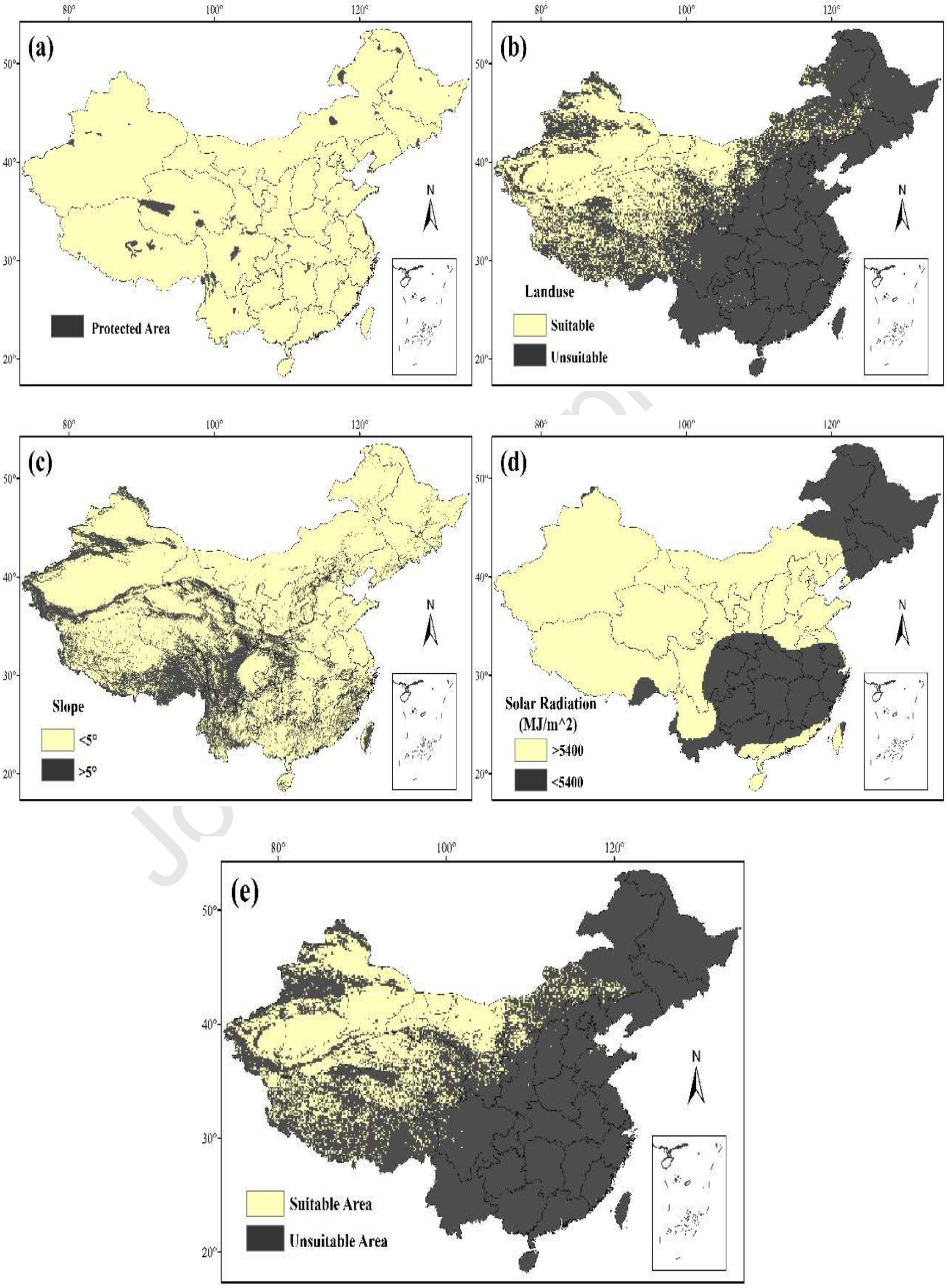


Figure 4: Screening process of areas suitable for solar energy resource development

Figure 4(a) shows the protected areas in China. Figure 4(b) depicts the land cover suitable for the construction of photovoltaic power plants in China. It is worth noting that most areas have been excluded, except northwest China. This is because these excluded lands are covered by agricultural land, construction land, forests, and other land use types not suitable for PV plant construction. As shown in Figure 4(c), areas with slopes greater than 5° are excluded, primarily because the steep land would make construction difficult. Figure 4(d) shows the areas where the annual average solar radiation is less than 5400 MJ/m^2. Large areas of eastern China, northeast China, and south-central China are economically infeasible for the development of photovoltaic power plants. According to all the exclusion criteria, a photovoltaic adaptability map of China was drawn. As shown in Figure 4(e), the conclusion of the exclusion process is that the land suitable for the development of large-scale photovoltaic power plants is primarily concentrated in the northwest of China.

Table 1: Suitable areas in each province

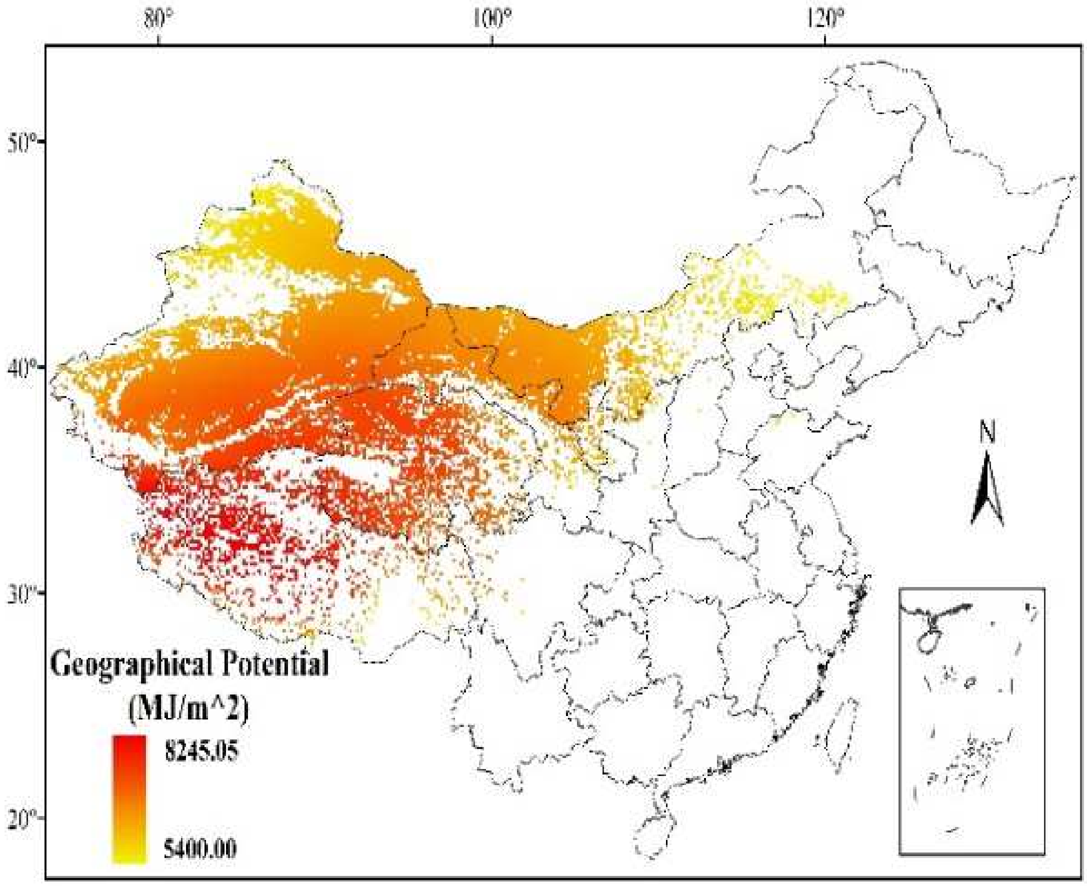
Physical Geographic Division	Province	Total areas (10^4 km^2)	Suitable area (10^4 km^2)	Proportion of Suitable Area to Each Province (%)	Proportion of Suitable Area to the Whole Country (%)
Northwest China	Xinjiang	176.22	116.29	65.99	12.08
	Gansu	41.41	19.07	46.05	1.98
	Qinghai	71.53	36.72	51.33	3.81
	Ningxia	5.21	1.60	30.77	0.17
	Shaanxi	20.41	0.52	2.55	0.05
North China	Inner Mongolia	135.07	39.30	30.54	4.08
	Hebei	19.79	0.06	0.3	0.01
	Shanxi	16.02	0.08	0.5	0.01
East China	Shandong	15.64	0.12	0.77	0.01
	Fujian	11.15	0.02	0.18	0
Southwest China	Tibet	113.94	28.01	24.59	2.91
	Sichuan	45.44	0.78	1.72	0.08

As shown in Table 1, among the provinces, Xinjiang has the largest area suitable for developing and utilizing solar energy resources. The exploitable area accounts for 65.99% of the total area of Xinjiang, accounting for 12.08% of the total area of the country. This area is followed by Inner Mongolia, the Qinghai Province, Tibet, and the Gansu Province, whose exploitable areas account for 30.54%, 51.33%, 24.59%, and 46.05%, respectively, of the total area of each province and account for 4.08%, 3.81%, 2.91%, and 1.98%, respectively, of the total area of the country. The exploitable area of Ningxia accounts for 0.17% of the total area of the entire country. The total area of Ningxia is relatively small, although the exploitable area is much smaller than that of Tibet and Inner Mongolia, and the exploitable area accounts for 30.77% of the total area of Ningxia. The area of solar energy resources that can be developed in Sichuan Province and Shanxi Province is small, and the exploitable area accounts for 1.72% and 2.55% of Sichuan Province and Shanxi Province, respectively, and accounts for 0.08% and 0.05%, respectively, of the total area of the country. Shandong, Shanxi, Hebei, and Fujian have very few exploitable areas, the least of which is Fujian. The area suitable for developing solar energy resources only accounts for 0.18% of the total area of Fujian Province.

The constraint analysis results can be explained as follows. Extensive areas in eastern China were invalid for large-scale PV generation, which is related to high-speed urbanization. The provinces in eastern China are well-known for prosperous economies and flourishing industries. This has also accelerated urban expansion [53–55], increased construction land, and reduced suitable areas for large-scale solar PV stations. Due to China's urbanization effort, construction has nearly never stopped. Therefore, Hebei and Shanxi in northern China and Shandong and Fujian in eastern China have lost massive amounts of available land according to the constraint analysis. Furthermore, large agricultural planting areas are another critical reason for the lack of suitable land areas for LS-PV stations in central and eastern China, particularly in the Yangtze and Yellow River basins [56]. Sichuan, Shandong, Fujian, and other areas are important agricultural production provinces [57]. The Three-North Shelter Forest Program (TNSFP) is the world's largest ecological afforestation program and has been in operation for 30 years in China [58]. Shanxi, Shaanxi, Hebei, and other provinces have implemented the TNSFP

[59]. Large-scale cultivated land in these provinces has led to few suitable lands for LS-PV station construction. Certainly, in addition to the accelerated urbanization and large areas of agricultural lands, an increase in forest land has also restricted the development and utilization of solar energy resources. Therefore, suitable land area is a critical limiting factor for large-scale solar PV development.

3.3 Solar energy potential



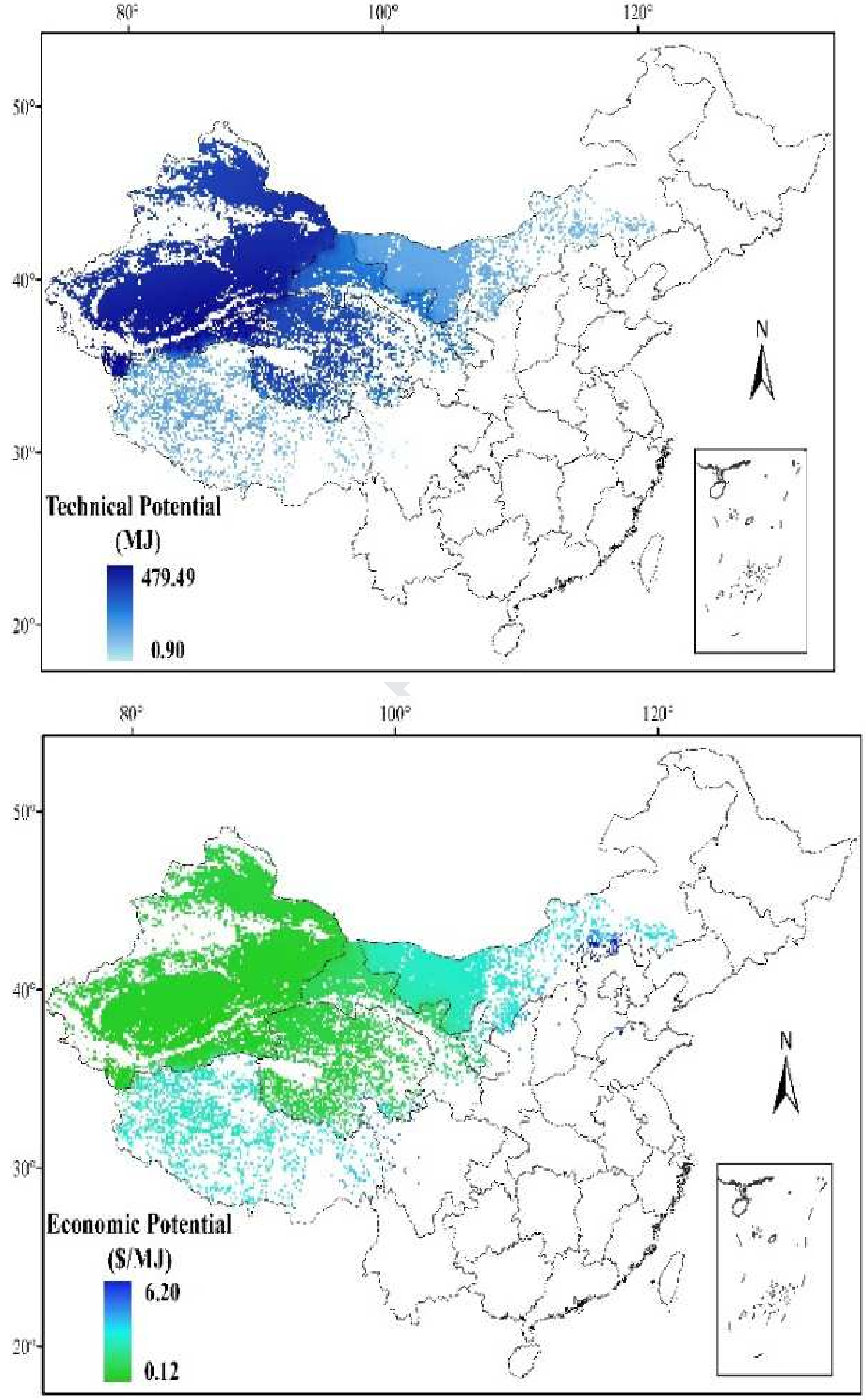


Figure 5: Solar energy potential in China

The areas with high potential for solar energy in China are located primarily in the northwest, southwest, and small parts of eastern China. Figure 5 shows the geographic potential, technical potential, and economic potential of solar energy resources.

The geographical potential of solar energy resources is between 5400.00 MJ/m^2 and 8245.05 MJ/m^2, with an average value of 6429.05 MJ/m^2. The geographical potential of the Qinghai-Tibet Plateau is relatively large, and the eastern China region has the smallest potential.

The technical potential is between 0.90 MJ and 479.49 MJ, and the average value is 147.94 MJ. The maximum and minimum values are quite different. The Xinjiang region is larger, and the eastern China region is small. It is suitable land areas that significantly determine the technological potential. According to Figure 5 and Table 1, eastern China is evidently scarce in suitable land areas for large-scale PV station operation, while in northwest China, land sources are abundant.

The economic potential is between 0.12\$/MJ and 6.20\$/MJ, with an average of 1.25\$/MJ. The lower the value, the higher the economic potential. As such, the largest economic potential is in the northwest, while in the eastern portion of northern China and eastern China, the economic potential is small.

3.4 Optimal site selection

Table 2: Solar energy potential of each province

Physical Geographic Division	Province	Geographical Potential (MJ/m^2)	Technical Potential (MJ)	Economic Potential (\$/MJ)
Northwest China	Xinjiang	6683.27	395.28	0.14
	Gansu	6697	280.63	0.20
	Qinghai	7302.86	331.39	0.17
	Ningxia	6393.23	191.82	0.30
	Shaanxi	6071.42	60.68	0.37
North China	Inner Mongolia	6297.25	178.19	0.33

	Hebei	5615.54	28.21	3.11
	Shanxi	5787.29	35.33	1.77
East China	Shandong	5705.35	3.18	1.93
	Fujian	5718.61	0.92	5.90
Southwest China	Tibet	7753.71	182.91	0.32
	Sichuan	6811.13	60.68	0.48
Acentric factor		0.1012	0.8884	1.3308

Table 2 summarizes the potential of solar energy resources in each province. It is apparent that China possesses rich solar energy resources, yet there exists substantial spatial heterogeneity. The provinces suitable for developing and utilizing solar energy primarily include 12 provinces, which are Xinjiang, Gansu, Qinghai, Ningxia, Shanxi, Inner Mongolia, Hebei, Shanxi, Shandong, Fujian, Tibet, and Sichuan, and most of these provinces are in the western region. The province with the highest geographical potential is Tibet, with a value of 7753.71 MJ/m^2, and the smallest is Shandong Province, with a value of 5705.35 MJ/m^2. The largest technical potential is 395.28 MJ in Xinjiang, and the smallest is that of the Fujian Province, which is only 0.92 MJ. The economic potential is represented by the cost of electricity, so the smaller the value, the greater the economic potential. The province with the greatest economic potential is Xinjiang, and the smallest potential is located in the Fujian Province, with the electricity cost reaching 5.90$/MJ. Notably, the acentric factor of three potential values denoted that the technological and economic desperation degrees were significantly higher than the geographical factor, which was 0.8884, while the acentric factor of the geographical potential was only 0.1012. The high disparity in the 12 provinces’ technical potential was primarily attributed to the strong distinction in their suitable land areas for LS-PV stations, which is detailed in section 3.2.

In summary, the province with the greatest potential for solar energy development was the Xinjiang autonomous region, which had the greatest of all three potentials and was the most optimal option for LS-PV station operations. Qinghai Province, Gansu Province, the Inner Mongolia autonomous region, and the Tibet autonomous region, which are concentrated in the western region, were also suitable. However, the eastern region was not suitable for the development and utilization of solar energy resources. In fact, the demand of the eastern region for electricity was higher than that for western China. Therefore, the electricity supply balance is the key problem that needs to be solved. It is highly recommended that governmental policies support solar grid connections and strengthen the West-to-East Power Transmission Project.

5. Conclusions and policy implications

To evaluate the solar energy potential in China, initially the spatial-temporal distribution of solar energy resources was examined, and then the constraint factors were excluded. Then the geographic, technological, and economic potentials were then estimated. The conclusions are as follows:

(1) Solar energy resources in China are affluent and relatively stable, and they range from 5486.82 MJ/m^2 to 5776.70 MJ/m^2.

(2) Solar radiation in China also has substantial spatial heterogeneity, which is stronger in the western and northern regions. The Tibet, Qinghai, Xinjiang, and Gansu provinces possess abundant solar energy resources.

(3) There are few suitable land areas for LS-PV power stations. Suitable land areas for LS-PV stations in China account for only 25.19% of the total land area, while areas with abundant solar energy resources (solar radiation >5400 MJ/m^2) are approximately 65.48% of the total land area of China.

(4) The technological potential and economic potential in China display distinctive spatial heterogeneity, while a small difference exists in the geographic potential. The acentric factor of the technological potential and economic potential was 0.8884 and 1.3308, respectively, while the acentric factor of geographic potential was only 0.1012.

(5) Twelve provinces were selected as optimal sites for LS-PV stations: Xinjiang, Gansu, Qinghai, Ningxia, Shanxi, Inner Mongolia, Hebei, Shanxi, Shandong, Fujian, Tibet, and Sichuan. Among these, Xinjiang Province was the best option for LS-PV generation development. The eastern region is less suitable for the development and utilization of solar energy resources due to scarce suitable lands.

On the basis of the substantial spatial heterogeneity and the severe regional imbalances in China, some policy recommendations are provided that also refer to the previous studies that have been conducted [53–57]. With finite suitable lands for large-scale solar PV operation, eastern China can take full advantage of solar thermal technology by installing solar collectors on the roofs and exterior walls of buildings without restrictions on land use [55]. For areas with affluent lands for construction, likely in northwestern China, large-scale PV generation is preferred to alleviate energy shortages and make full use of solar energy resources. In addition, strengthening network connectivity would be conducive to reduce photoelectric losses.

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References:

[1] T. Muneer, M. Asif, S. Munawwar, Sustainable production of solar electricity with particular reference to the Indian economy, Renewable and Sustainable Energy Reviews. 9 (2005) 444–473. doi:10.1016/j.rser.2004.03.004.

[2] N.K. Sharma, P.K. Tiwari, Y.R. Sood, Solar energy in India: Strategies, policies, perspectives and future potential, Renewable and Sustainable Energy Reviews. 16 (2012) 933–941. doi:10.1016/j.rser.2011.09.014.

[3] R. Mahtta, P.K. Joshi, A.K. Jindal, Solar power potential mapping in India using

remote sensing inputs and environmental parameters, Renewable Energy. 71 (2014) 255–262. doi:10.1016/J.RENENE.2014.05.037.

[4] H. Fang, J. Li, W. Song, Sustainable site selection for photovoltaic power plant: An integrated approach based on prospect theory, Energy Conversion and Management. 174 (2018) 755–768. doi:10.1016/J.ENCONMAN.2018.08.092.

[5] S. Grassi, N. Chokani, R.S. Abhari, Large scale technical and economical assessment of wind energy potential with a GIS tool: Case study Iowa, Energy Policy. 45 (2012) 73–85. doi:10.1016/j.enpol.2012.01.061.

[6] Y. Wu, B. Zhang, C. Wu, T. Zhang, F. Liu, Optimal site selection for parabolic trough concentrating solar power plant using extended PROMETHEE method: A case in China, Renewable Energy. 143 (2019) 1910–1927. doi:10.1016/J.RENENE.2019.05.131.

[7] H. Lu, W. Zhao, Effects of particle sizes and tilt angles on dust deposition characteristics of a ground-mounted solar photovoltaic system, Applied Energy. 220 (2018) 514–526. doi:10.1016/j.apenergy.2018.03.095.

[8] international energy agency (IEA), Technology Roadmap: Solar Photovoltaic Energy, OECD Publishing, 2010. doi:10.1787/9789264088047-en.

[9] National Energy Administration, Solar energy developmentof the 13th Five-Year Plan, (2016). http://zfxxgk.nea.gov.cn/auto87/201612/t20161216_2358.htm.

[10] IEA, Renewables 2018, OECD, 2018. doi:10.1787/re_mar-2018-en.

[11] NDRC, Energy Research Institute of China Academy of Macroeconomic, China National Renewable Energy Centre, China Renewable Energy Outlook 2018, 2019.

[12] M. Vafaeipour, S. Hashemkhani Zolfani, M.H. Morshed Varzandeh, A. Derakhti, M. Keshavarz Eshkalag, Assessment of regions priority for implementation of solar projects in Iran: New application of a hybrid multi-criteria decision making approach, Energy Conversion and Management. 86 (2014) 653–663. doi:10.1016/j.enconman.2014.05.083.

[13] I. Gunderson, S. Goyette, A. Gago-Silva, L. Quiquerez, A. Lehmann, Climate and land-use change impacts on potential solar photovoltaic power generation in the Black Sea region, Environmental Science and Policy. 46 (2015) 70–81. doi:10.1016/j.envsci.2014.04.013.

[14] Y. Sun, A. Hof, R. Wang, J. Liu, Y. Lin, D. Yang, GIS-based approach for potential analysis of solar PV generation at the regional scale: A case study of Fujian Province, Energy Policy. 58 (2013) 248–259. doi:10.1016/J.ENPOL.2013.03.002.

[15] E. Fillol, T. Albarelo, A. Primerose, L. Wald, L. Linguet, Spatiotemporal indicators of solar energy potential in the Guiana Shield using GOES images, Renewable Energy. 111 (2017) 11–25. doi:10.1016/J.RENENE.2017.03.081.

[16] D. Li, G. Liu, S. Liao, Solar potential in urban residential buildings, Solar Energy. 111 (2015) 225–235. doi:10.1016/J.SOLENER.2014.10.045.

[17] P. Aragonés-Beltrán, F. Chaparro-González, J.-P. Pastor-Ferrando, A. Pla-Rubio, An AHP (Analytic Hierarchy Process)/ANP (Analytic Network Process)-based multi-criteria decision approach for the selection of solar-thermal power plant investment projects, Energy. 66 (2014) 222–238. doi:10.1016/J.ENERGY.2013.12.016.

[18] I.R. Pillai, R. Banerjee, Methodology for estimation of potential for solar water heating in a target area, Solar Energy. 81 (2007) 162–172. doi:10.1016/j.solener.2006.04.009.

[19] J. Jung, S. Han, B. Kim, Digital numerical map-oriented estimation of solar energy potential for site selection of photovoltaic solar panels on national highway slopes, Applied Energy. 242 (2019) 57–68. doi:10.1016/J.APENERGY.2019.03.101.

[20] T. Huang, S. Wang, Q. Yang, J. Li, A GIS-based assessment of large-scale PV potential in China, Energy Procedia. 152 (2018) 1079–1084. doi:10.1016/J.EGYPRO.2018.09.126.

[21] D. Groppi, L. de Santoli, F. Cumo, D. Astiaso Garcia, A GIS-based model to assess

buildings energy consumption and usable solar energy potential in urban areas, Sustainable Cities and Society. 40 (2018) 546–558. doi:10.1016/J.SCS.2018.05.005.

[22] J.B. Kodysh, O.A. Omitaomu, B.L. Bhaduri, B.S. Neish, Methodology for estimating solar potential on multiple building rooftops for photovoltaic systems, Sustainable Cities and Society. 8 (2013) 31–41. doi:10.1016/J.SCS.2013.01.002.

[23] K.K.-L. Lau, F. Lindberg, E. Johansson, M.I. Rasmussen, S. Thorsson, Investigating solar energy potential in tropical urban environment: A case study of Dar es Salaam, Tanzania, Sustainable Cities and Society. 30 (2017) 118–127. doi:10.1016/J.SCS.2017.01.010.

[24] Z. Huang, T. Mendis, S. Xu, Urban solar utilization potential mapping via deep learning technology: A case study of Wuhan, China, Applied Energy. 250 (2019) 283–291. doi:10.1016/J.APENERGY.2019.04.113.

[25] M.M. Hoogwijk, On the global and regional potential of renewable energy sources, 2004. http://np-net.pbworks.com/f/Hoogwijk+(2004)+Global+and+regional+potential+of+renewable+energy+sources+(Thesis+Utrecht).pdf.

[26] J. Polo, A. Bernardos, A.A. Navarro, C.M. Fernandez-Peruchena, L. Ramírez, M. V. Guisado, S. Martínez, Solar resources and power potential mapping in Vietnam using satellite-derived and GIS-based information, Energy Conversion and Management. 98 (2015) 348–358. doi:10.1016/J.ENCONMAN.2015.04.016.

[27] A. Gómez, M. Rodrigues, C. Montañés, C. Dopazo, N. Fueyo, The potential for electricity generation from crop and forestry residues in Spain, Biomass and Bioenergy. 34 (2010) 703–719. doi:10.1016/j.biombioe.2010.01.013.

[28] R. Djebbar, D. Belanger, D. Boutin, E. Weterings, M. Poirier, SolarPACES 2013 potential of concentrating solar power in Canada, Energy Procedia. 49 (2013) 2303–2312. doi:10.1016/j.egypro.2014.03.244.

[29] T.P. Fluri, The potential of concentrating solar power in South Africa, Energy Policy. 37 (2009) 5075–5080. doi:10.1016/j.enpol.2009.07.017.

[30] A. Gastli, Y. Charabi, Siting of large PV farms in Al-Batinah region of Oman, 2010 IEEE International Energy Conference and Exhibition, EnergyCon 2010. (2010) 548–552. doi:10.1109/ENERGYCON.2010.5771742.

[31] H.Z. Al Garni, A. Awasthi, Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia, Applied Energy. 206 (2017) 1225–1240. doi:10.1016/J.APENERGY.2017.10.024.

[32] A.A. Merrouni, A. Mezrhab, A. Mezrhab, PV sites suitability analysis in the Eastern region of Morocco, Sustainable Energy Technologies and Assessments. 18 (2016) 6–15. doi:10.1016/j.seta.2016.09.006.

[33] Y. Charabi, A. Gastli, PV site suitability analysis using GIS-based spatial fuzzy multi-criteria evaluation, Renewable Energy. 36 (2011) 2554–2561. doi:10.1016/J.RENENE.2010.10.037.

[34] M. Uyan, GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region Konya/Turkey, Renewable and Sustainable Energy Reviews. 28 (2013) 11–17. doi:10.1016/j.rser.2013.07.042.

[35] J. Darnell, J. M, New renewable energy resources - a guide to the future, 1995.

[36] A. Yushchenko, A. de Bono, B. Chatenoux, M.K. Patel, N. Ray, GIS-based assessment of photovoltaic (PV) and concentrated solar power (CSP) generation potential in West Africa, Renewable and Sustainable Energy Reviews. 81 (2018) 2088–2103. doi:10.1016/j.rser.2017.06.021.

[37] V. V. Tyagi, N.A.A. Rahim, N.A. Rahim, J.A.L. Selvaraj, Progress in solar PV technology: Research and achievement, Renewable and Sustainable Energy Reviews. 20 (2013) 443–461. doi:10.1016/j.rser.2012.09.028.

[38] L. El Chaar, L.A. Lamont, N. El Zein, Review of photovoltaic technologies, Renewable and Sustainable Energy Reviews. 15 (2011) 2165–2175.

doi:10.1016/j.rser.2011.01.004.

[39] T.M. Razykov, C.S. Ferekides, D. Morel, E. Stefanakos, H.S. Ullal, H.M. Upadhyaya, Solar photovoltaic electricity: Current status and future prospects, Solar Energy. 85 (2011) 1580–1608. doi:10.1016/j.solener.2010.12.002.

[40] S.R. Ghazanfar Khan, Optimal Site Selection for Solar PV Power Plant in an Indian State Using Geographical Information System (GIS), Technology, International Journal of Emerging Engineering Research. 2 (2014) 260–266.

[41] H. Broesamle, H. Mannstein, C. Schillings, F. Trieb, Assessment of solar electricity potentials in North Africa based on satellite data and a geographic information system, Solar Energy. 70 (2001) 1–12. doi:10.1016/S0038-092X(00)00126-2.

[42] P. Berrisford, D.P. Dee, P. Poli, R. Brugge, K. Fielding, M. Fuentes, P.W. Kållberg, S. Kobayashi, S. Uppala, A. Simmons, The ERA-Interim archive Version 2.0, ERA Report Series, ERA Report Series. (2011) 23. http://www.ecmwf.int/sites/default/files/elibrary/2011/8174-era-interim-archive-version-20.pdf.

[43] D.P. Dee, S.M. Uppala, A.J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M.A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A.C.M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A.J. Geer, L. Haimberger, S.B. Healy, H. Hersbach, E. V. Hólm, L. Isaksen, P. Kållberg, M. Köhler, M. Matricardi, A.P. Mcnally, B.M. Monge-Sanz, J.J. Morcrette, B.K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.N. Thépaut, F. Vitart, The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society. 137 (2011) 553–597. doi:10.1002/qj.828.

[44] H.D. Kambezidis, D.G. Kaskaoutis, G.K. Kalliampakos, A. Rashki, M. Wild, The solar dimming/brightening effect over the Mediterranean Basin in the period 1979–2012, Journal of Atmospheric and Solar-Terrestrial Physics. 150–151 (2016) 31–46.

doi:10.1016/j.jastp.2016.10.006.

[45] B.G. Liepert, Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990, Geophysical Research Letters. 29 (2002) 61-1-61–4. doi:10.1029/2002gl014910.

[46] B. Müller, M. Wild, A. Driesse, K. Behrens, Rethinking solar resource assessments in the context of global dimming and brightening, Solar Energy. 99 (2014) 272–282. doi:10.1016/j.solener.2013.11.013.

[47] V.K. Soni, G. Pandithurai, D.S. Pai, Is there a transition of solar radiation from dimming to brightening over India?, Atmospheric Research. 169 (2016) 209–224. doi:10.1016/j.atmosres.2015.10.010.

[48] G. Stanhill, S. Cohen, <global_dimming_AFM2001.pdf>, 107 (2001) 255–278.

[49] Y. Wang, M. Wild, A new look at solar dimming and brightening in China, Geophysical Research Letters. 43 (2016) 11,777-11,785. doi:10.1002/2016GL071009.

[50] M. Wild, H. Gilgen, A. Roesch, A. Ohmura, C.N. Long, E.C. Dutton, B. Forgan, A. Kallis, V. Russak, A. Tsvetkov, From dimming to brightening: Decadal changes in solar radiation at earth's surface, Science. 308 (2005) 847–850. doi:10.1126/science.1103215.

[51] O. Angélil, S. Perkins-Kirkpatrick, L. V. Alexander, D. Stone, M.G. Donat, M. Wehner, H. Shiogama, A. Ciavarella, N. Christidis, Comparing regional precipitation and temperature extremes in climate model and reanalysis products, Weather and Climate Extremes. 13 (2016) 35–43. doi:10.1016/J.WACE.2016.07.001.

[52] H.Z. Che, G.Y. Shi, X.Y. Zhang, R. Arimoto, J.Q. Zhao, L. Xu, B. Wang, Z.H. Chen, Analysis of 40 years of solar radiation data from China, 1961-2000, Geophysical Research Letters. 32 (2005) 1–5. doi:10.1029/2004GL022322.

[53] L. Bird, D. Lew, M. Milligan, E.M. Carlini, A. Estanqueiro, D. Flynn, E.

Gomez-Lazaro, H. Holttinen, N. Menemenlis, A. Orths, P.B. Eriksen, J.C. Smith, L. Soder, P. Sorensen, A. Altiparmakis, Y. Yasuda, J. Miller, Wind and solar energy curtailment: A review of international experience, Renewable and Sustainable Energy Reviews. 65 (2016) 577–586. doi:10.1016/j.rser.2016.06.082.

[54] C. Li, H. Shi, Y. Cao, J. Wang, Y. Kuang, Y. Tan, J. Wei, Comprehensive review of renewable energy curtailment and avoidance: A specific example in China, Renewable and Sustainable Energy Reviews. 41 (2015) 1067–1079. doi:10.1016/j.rser.2014.09.009.

[55] G. Liu, Y. Zhou, Z. Wan, Q. Ge, W. Wu, E. Dai, a Gis Method for Assessing Roof-Mounted Solar Energy Potential: a Case Study in Jiangsu, China, Environmental Engineering and Management Journal. 10 (2018) 843–848. doi:10.30638/eemj.2011.117.

[56] N. Tang, Y. Zhang, Y. Niu, X. Du, Solar energy curtailment in China: Status quo, reasons and solutions, Renewable and Sustainable Energy Reviews. 97 (2018) 509–528. doi:10.1016/j.rser.2018.07.021.

[57] P. Liu, P. Chu, Wind power and photovoltaic power: How to improve the accommodation capability of renewable electricity generation in China?, International Journal of Energy Research. 42 (2018) 2320–2343. doi:10.1002/er.4013.

Highlights:

- Chinese solar energy resources are stable and has notable spatial heterogeneity
- Northwestern China was with higher potential than the east
- Xinjiang Province was the most optimal option for PV station operation
- Land use remained critical for large-scale PV generation

Declaration of Interest Statement:

The authors declare no conflict of interest.

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