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An environmental evaluation of potentially optimal regions for solar plant construction in China

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Abstract. Owing to the huge environmental costs and socioeconomic losses caused by burning fossil fuels, renewable energy has become a heated topic for researchers to investigate on. Accordingly, solar energy (e.g., photovoltaic energy or PV energy), renowned for being an eco-friendly power source, emerges as a crucial subject for investigation, particularly within the context of global warming and net-zero carbon economy targets. To expedite the production of PV power in China, this study aims to assess the environmental suitability of potential regions optimal for the construction of solar plants within the country. By collecting data in different regions of China based on various factors (including environmental and socioeconomic factors), innovative evaluation metrics are developed, which produce a score for each region's suitableness for constructing solar power plants. According to the evaluation framework for solar plant construction, each region can be ranked easily according to those scores. The results suggest that Tibet is the optimal province for PV power production, with Gar identified as the most favorable area within Tibet; meanwhile, Chongqing exhibits the lowest potential for solar plant construction among all evaluated regions. The insights derived from this study can provide a vital reference for corporations and government entities in making informed decisions on the location for the development of large-scale solar power installations.

Keywords: Environmental Evaluation, Solar Plant, Optimal Regions/Location Selection, China.

1. Introduction

Energy serves as the foundation of human advancement, with fossil fuel combustion being a primary method for its generation. The consumption of fossil fuels has persistently remained high and experienced a continuous growth since the onset of the first industrial revolution [1]. Global energy consumption exceeded 120,000 TWh (terawatt-hour) in 2022, and such a high level of fossil fuel consumption generates substantial negative environmental impacts, such as the emission of excessive carbon dioxide, a major contributor to global warming. The negative impacts of fossil fuels were assessed across various dimensions, including humans, animals, ecosystems, buildings, air quality, and global warming. The total environmental damage from fossil fuels, excluding human discomfort and potential climate change, amounted to $2360 billion annually in 1990 [2]. There is no doubt that this figure will be much higher in 2023, given the increased consumption of fossil fuels compared to 1990. This immense environmental toll has prompted scientists to explore alternative energy sources to replace fossil fuels. Consequently, various forms of renewable energy have emerged as promising alternatives to fossil fuels. Typical examples of renewable energy sources include solar power, geothermal, biomass, wind power, and hydropower, etc. Many regions of the world have taken steps to make the transition from consuming fossil fuel to renewable energy. For example, The State Council in China issued the 14th Five-Year Plan for energy conservation and emission reduction. To that end, the Chinese government is going to accelerate the application of wind, solar, biomass, and other renewable energy sources [3].

Among all the renewable energy, solar power has become one of the primary sources in recent years and we have seen an increase in electricity generation from solar power in recent decades; Yet, there are many challenges to obtaining solar energy. Solar energy needs to be captured, converted, and stored effectively to counteract the diurnal cycle and intermittency of the Earth's solar resources. The best way to reach that goal is through the production of cheap solar fuel, in the form of chemical bonds. However, significant advances in basic science are needed to realize the full potential of the technology. More efficient materials must be created to capture and convert solar energy, and more efficient catalysts are needed to make the required conversion of chemical bonds [4]. Furthermore, it is mentioned in a research, which assesses the environmental impact of generating solar energy, that some of the emerging wafer-based and thin-film technologies such as GaAs (Gallium Arsenide), CZTS (Copper Zinc Tin Sulfide), OPVs (Organic Photovoltaic), DSSCs (Dye-Sensitized Solar Cell), and QDPVs (Colloidal Quantum Dot Photovoltaics) require further technical and environmental attention [5]. Besides, the uncertainty about the amount of solar energy generation is a big problem because the weather changes from day to day, and the energy generation will fluctuate in the short run.

Notably, choosing the optimal location for constructing the solar plants is full of challenges because of the complexity it contains. There are plenty of environmental factors potentially affecting the amount of energy generated by solar. For example, daylight duration, surface solar irradiation, and precipitation are crucial factors. Generally, extended daylight hours, increased solar irradiation, and minimal precipitation will optimize the energy output of solar panels. However, determining the energy production for different locations becomes complex when combining all these factors. Additionally, other considerations, such as population size, influence the feasibility of constructing a large solar plant. Specifically, a smaller population size implies greater availability of space for constructing a solar power plant.

The primary objective of this research is to identify the potentially optimal location of solar plant construction in different spatial scales in China. To achieve this objective, a new evaluation metric has been developed, considering both environmental and socioeconomic factors, which assigns a score to each region's suitability for constructing solar power plants. Based on this evaluation framework for solar plant construction, regions can be easily ranked according to their respective scores. This study will potentially shed light on the most viable locations for solar plant development, guiding policymakers and investors in making informed decisions that balance ecological preservation with sustainable energy production.

2. Materials and Methods

2.1. Research area

This research focuses mainly on different regions in China (provincial capitals of each province of China; (Figure 1). To ensure the accuracy of this research, because Tibet and Xinjiang are two provinces with relatively huge area, this research also choose a few cities other than the provincial capitals as subjects of this research. To obtain regional results from a larger spatial scale, China is divided into four major regions, namely: Qinghai-Tibet Plateau, Northwest China, North China, and South China (Figure 2). In the diagram, the light green area is the Qinghai-Tibet Plateau. The dark green area, which is the temperate continental climate zone in the diagram, represents the Northwest China region. North China includes the yellow area in the diagram, which is shown as a temperate monsoon climate zone in the diagram. The red and orange areas, which are tropical and subtropical climate zones respectively in the diagram, together represent the South China region. After evaluating all the data in each region, this research can also determine the suitability of solar plant construction in each region in China.

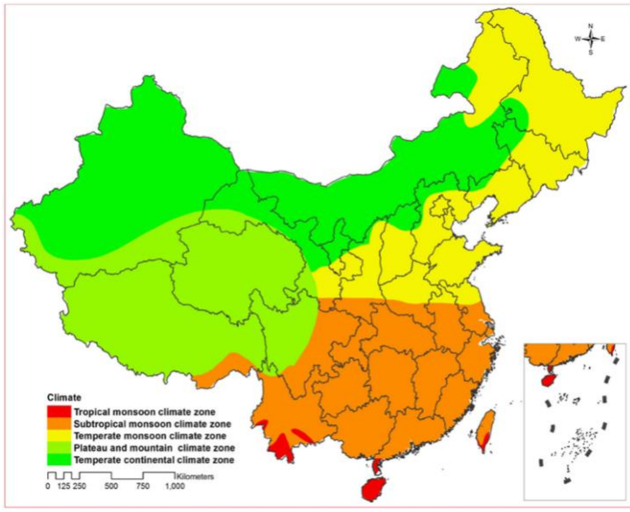

Figure 1. China's map with major cities [6].

Figure 2. China's map with different regions [7].

2.2. Data

Different sets of data related to the solar energy production of China's major cities are collected: total annual sunshine hours of those cities [8]; population density in those cities counted in the number of people per square kilometer [9]; annual precipitation of major cities [10]; major topography of different regions in China [11]; GHI (ground horizontal irradiation) of different regions in China [12]. All data are available on the website at: https://zenodo.org/record/8298163.

2.3. PV power plant construction Ranking

Total score (max 100)=GHI score (max 35)+average sunshine score (max 25)
+population score (max 15)+topography score (max 15)+precipitation acore (max 10)

This research aims to provide each major city in China with a score that represents the suitability for the construction of solar plants in that area. During this hierarchy process, factors like the total annual sunshine hours, population density, topography, and GHI all contribute to this score but different proportions are involved. The basic logic for this score includes: the higher the sunshine hours are, the higher PV production, and therefore the score is higher; the higher the population is, the possibility of constructing the large power plant is than lower, so the score is lower; the higher the precipitation, the fewer solar energy can be collected, so the score is lower; the higher the GHI is, the more irradiation that it can absorb, and thus the score is higher; the higher the craggedness is, the more difficult to construct the solar plant, so the score is lower. As a result, sunshine hours, GHI, and average elevation have a positive relationship with the PV power plant construction score. Other factors like population density, craggedness, and annual precipitation have a negative relationship with the PV power plant construction score. To rank cities properly, different weightings should be given to each different factor. To simplify this process, all data in different factors will be given a different total score, corresponding to their importance. The most two important factors that contribute to this score are GHI and sunshine hours, which have a total score of 35 and 25. Then, both the topography and population have 15 total scores. The precipitation has 10 total scores. As regards GHI, a 0 score is given to 2.5 kilowatts per square meter per day, 1 score is added for each 0.1 more kilowatts per square meter per day, and a 35 score is given to GHI more than 6 kilowatts per square meter per day. As for sunshine hours, a 0 score is given to sunshine hours between 40- 50 hours per month, and 1 more score is awarded for every 10 hours added. A score of 25 will be given to sunshine hours more than 290 hours per month. For Annual precipitation, a score of 10 is given to annual precipitation from 0-400 mm, and each 1 mark is deducted for every 400 millimeters added from 0. A zero score is given to annual precipitation that is more than

4,000 millimeters. As for topography, a score of 12 is given to a province if the plateau counts for more than 20 percent of the total area. A score of 9 is given to a province if plain counts for more than 20 percent of the total area. A score of 6 would be given to a province if hills count for more than 20 percent of the total area. A score of 3 would be given to a province if it is mountainous for more than 20 percent of the total area. If the province has more than one terrain more than 20 percent of the area, the mark is the highest one among those different scores of different terrains.

3. Results and Discussion

3.1. Comparison of Change in Solar Power between China and the USA

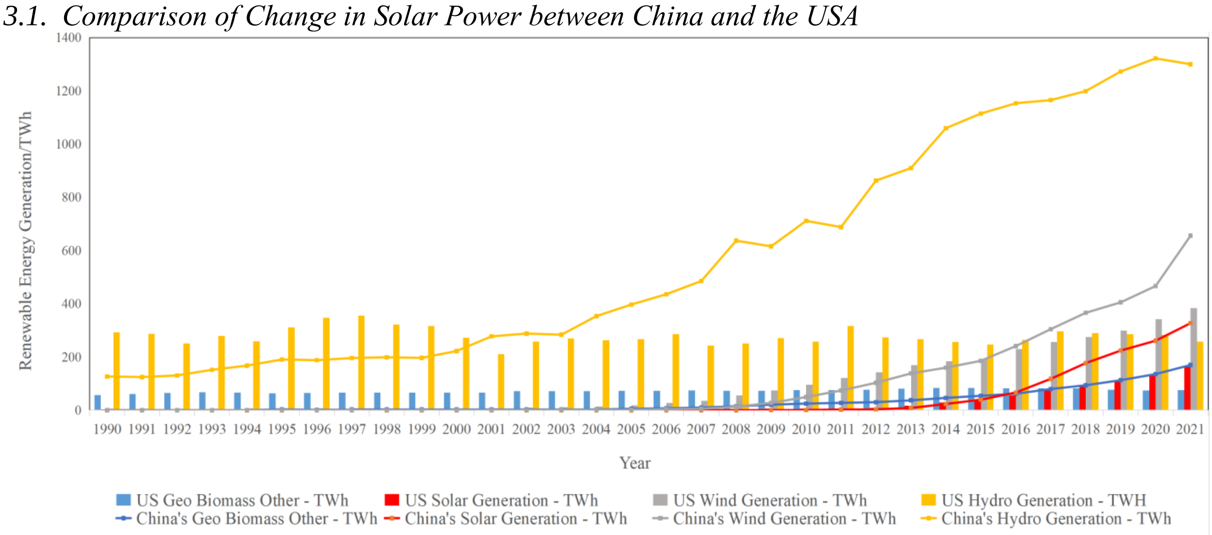

Figure 3. Renewable energy generation in the USA from 1990 to 2021. Renewable energy includes solar, wind, hydro, Geo, Biomass, and others [13].

In Figure 3, China's hydrogen energy generation has generally continued to increase since 2003 and is extremely high among all renewable energy generation. However, the trend of this is slowing down. For the US's hydro-generation, the amount of energy is nearly unchanged for thirty years. Concerning wind energy generation, both countries have shown an increasing generation trend since 2009, and the increasing rate is growing these years. As for solar energy generation, the output of energy has been increasing since 2014, and the increasing rate is also increasing these years, which has a high potential for future development. The amount of China's solar energy generation is more than that of the US. For, geo biomass generation, the energy output remains nearly the same and at a low level for thirty years both for US and China. As a result, both wind energy and solar energy have a high potential for future development.

3.2. History of PV development in China

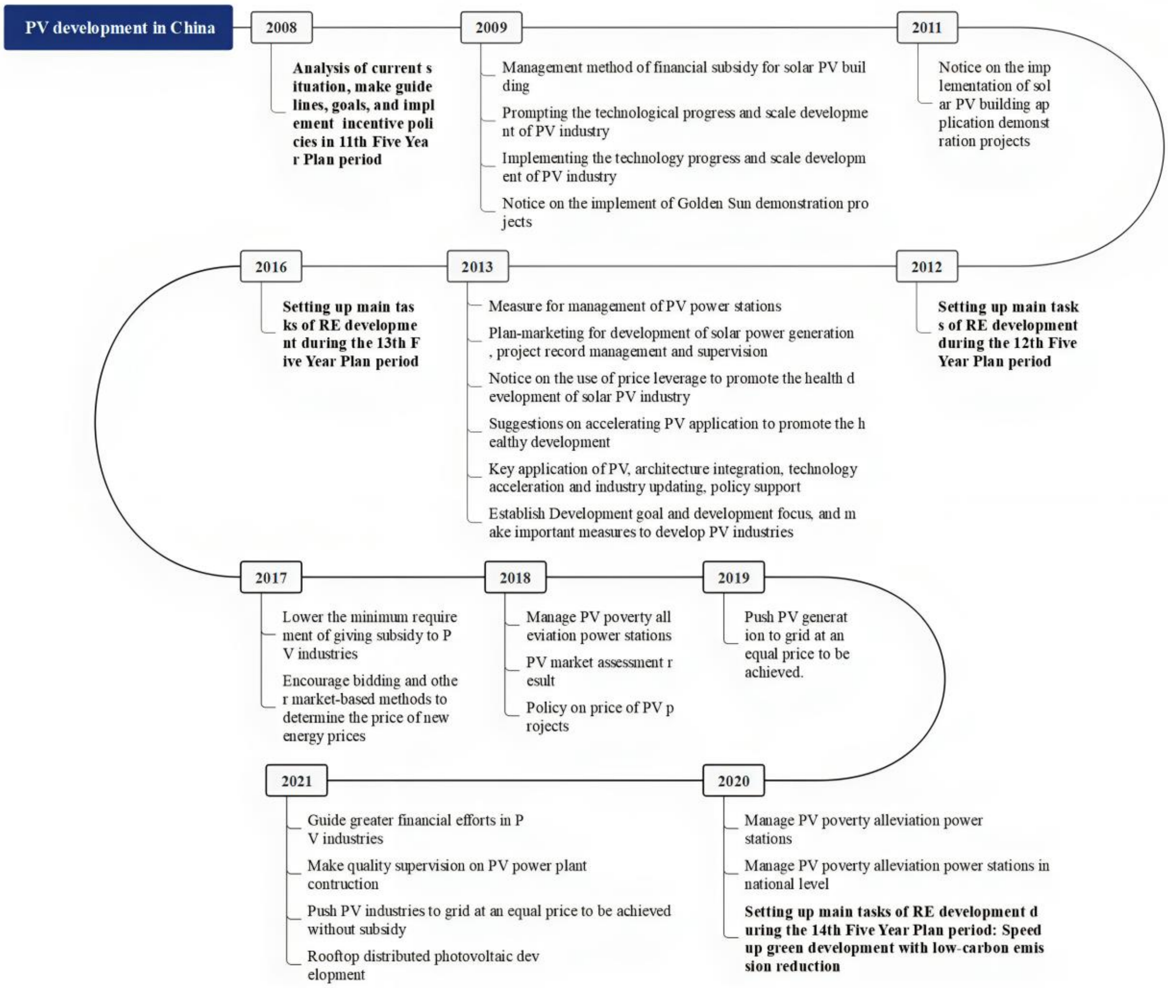

Figure 4. China's history of solar development from 2008 to 2021 [3, 14].

China's history of solar development can be divided into three main stages. The first stage is the preparation stage, from 2008 to 2012, in which the Chinese government made many policies to remove the obstacles in the PV industry. The main purpose of those policies in the preparation phase was to reduce the financial burden on the PV industry and promote the development of PV technology. Therefore, in this stage, the energy production of the PV industry was very low, which is shown in Figure 3. The second stage is the low-rate growing stage, from 2012 to 2016. In this stage, most of the fundamental problems had been solved, so the main purpose of the policies made in these years was to accelerate development. Thus, the Chinese government did marketing and promoted the application of PV energy generation. The third stage is the fast-growing stage, from 2016 to 2021. In this stage, most policies were about encouraging marketing activities in the PV industry and lowering the cost of production to attract more firms to enter this industry. Therefore, PV production in China has grown at a high rate with that much effort done by the Chinese government.

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3.3. *Environmental factors*

3.3.1. *Overall examination of the total score for different regions of China.*

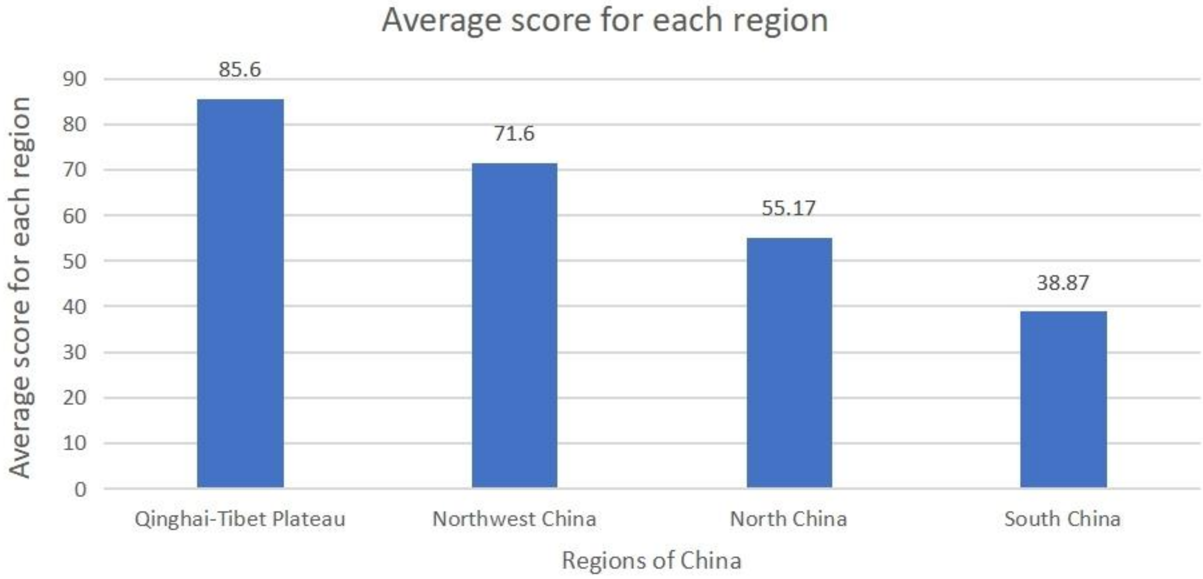

Figure 5. Average score for each major region in China, including Qinghai-Tibet Plateau, Northwest China, North China, and South China.

The results of the scores in four regions in China show a clear gap between those scores. Qinghai- Tibet Plateau region has the highest score among these regions, which has a score of 85.6. Moreover, the difference in score between the first place and second place is 14, which is relatively a huge gap. Accordingly, this shows that the Qinghai-Tibet Plateau region gains a dominant advantage in building solar plants over other regions in China. The following region is Northwest China. Having a score of 71.6, this region also has a high potential for future development of PV production, although the potential is not as high as that of the Qinghai- Tibet Plateau. The last two regions, which are South China and North China, have relatively low scores for constructing solar plants.

3.3.2. Overall examination of the Total score for different cities in China

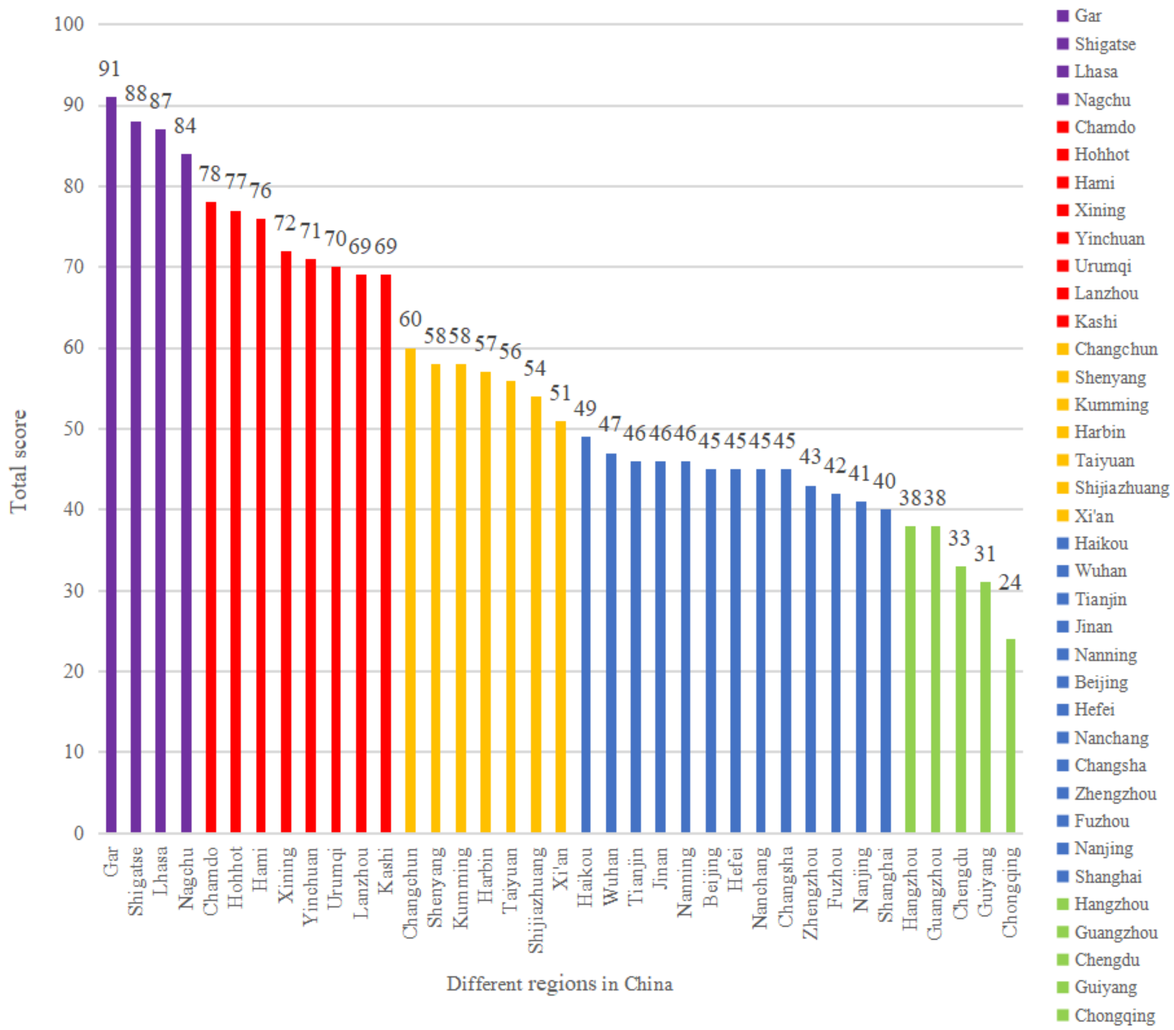

Figure 6. Total score for different cities in China.

Figure 6 shows the score for different cities in China. The first five cities are all in the Tibet area, indicating that Tibet has a preferable environment for developing the PV industry. Among these cities, Gar has the highest score of 91, indicating its conditions are the most hospitable for building solar plants. By contrast, Chongqing has the lowest score of 24, indicating that it is not suitable for constructing a solar plant. Furthermore, Figure 6 marks different columns with different colors. The purple color represents areas with a total score of more than 80, indicating that they have extremely high potential for developing PV production. The red color represents areas with a total score between 60 and 80 (including 80), indicating that they have a relatively high potential for developing PV production. Yellow columns represent areas with a total score between 50 and 60 (including 60), meaning that these areas have medium potential in developing PV industries. Blue columns represent areas with a total score between 40 and 50 (including 40 and 50), meaning that these areas have relatively low potential in developing PV industries. Green areas have a score lower than 40, indicating little potential for constructing large solar plants to produce solar energy. Accordingly, Tibet, Inner Mongolia, Qinghai, Ningxia, Gansu, and Xinjiang are six provinces that have high or relatively high potential for developing solar plants.

3.3.3. GHI (ground horizontal irradiation)

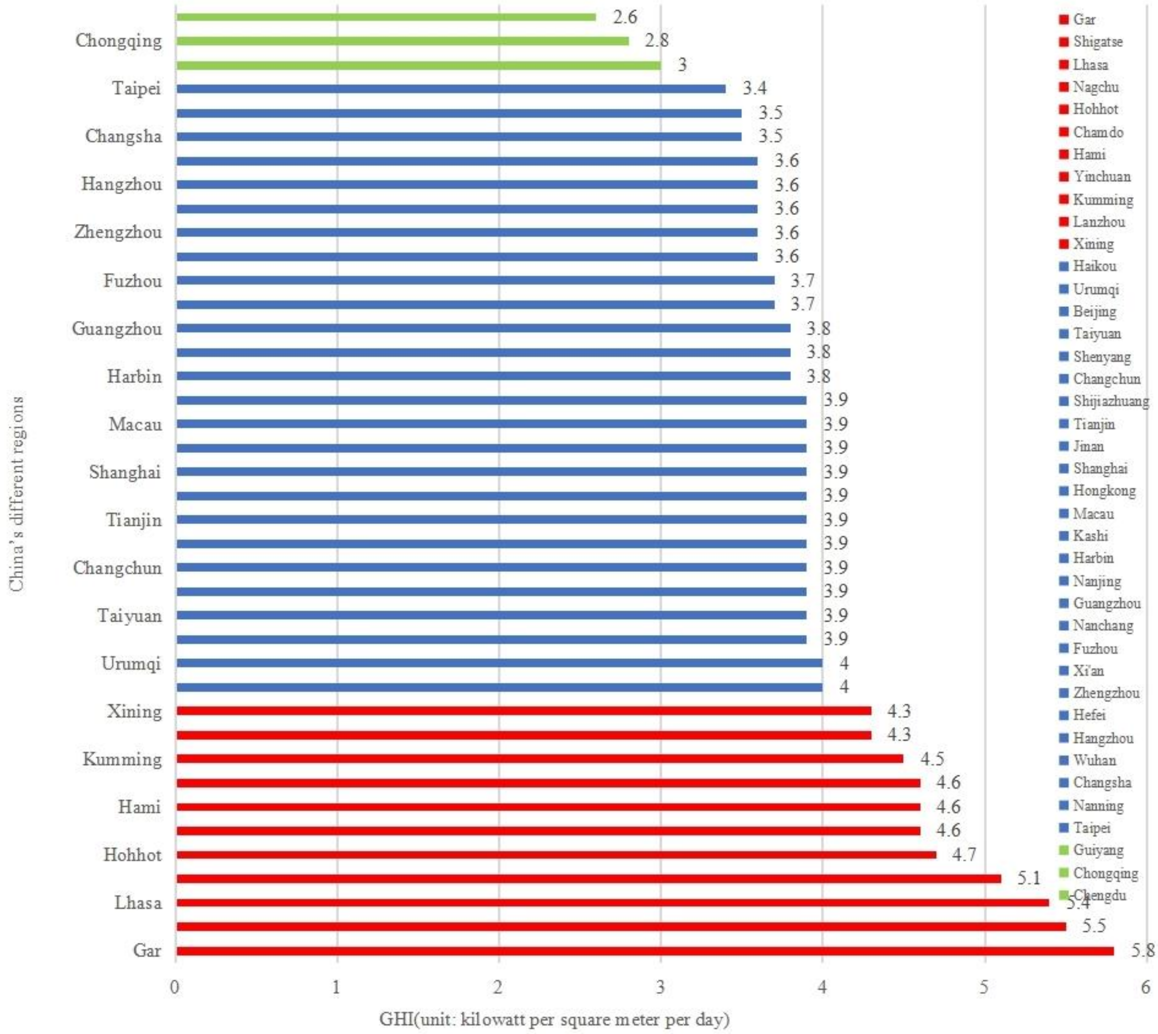

Figure 7. GHI for different regions in China.

In Figure 7, the first four cities with the highest GHI are also from Tibet, and their GHI is much higher than the fifth one. This shows that the solar plants there can generate huge amounts of energy. In contrast, the region with the lowest GHI in Chengdu has a value of less than half of the highest value. This shows that solar plants in Chengdu can absorb much less energy from irradiation. Figure7 marks different columns with different colors. Red color represents areas with a GHI higher than 4 (include 4), indicating that solar plants there can absorb high amount of energy from the irradiation. Blue columns represent areas with a GHI between 3 and 4, meaning that solar plants there can absorb medium amount of energy from the irradiation. Green areas have GHI lower than 3, indicating that solar plants there can absorb a small amount of energy from the irradiation. Accordingly, Inner Mongolia, Tibet, Xinjiang, Ningxia, Yunnan, Gansu, and Qinghai, are seven provinces that have high levels of irradiation for the solar panels to absorb.

3.3.4. Average Annual Sunshine Hours.

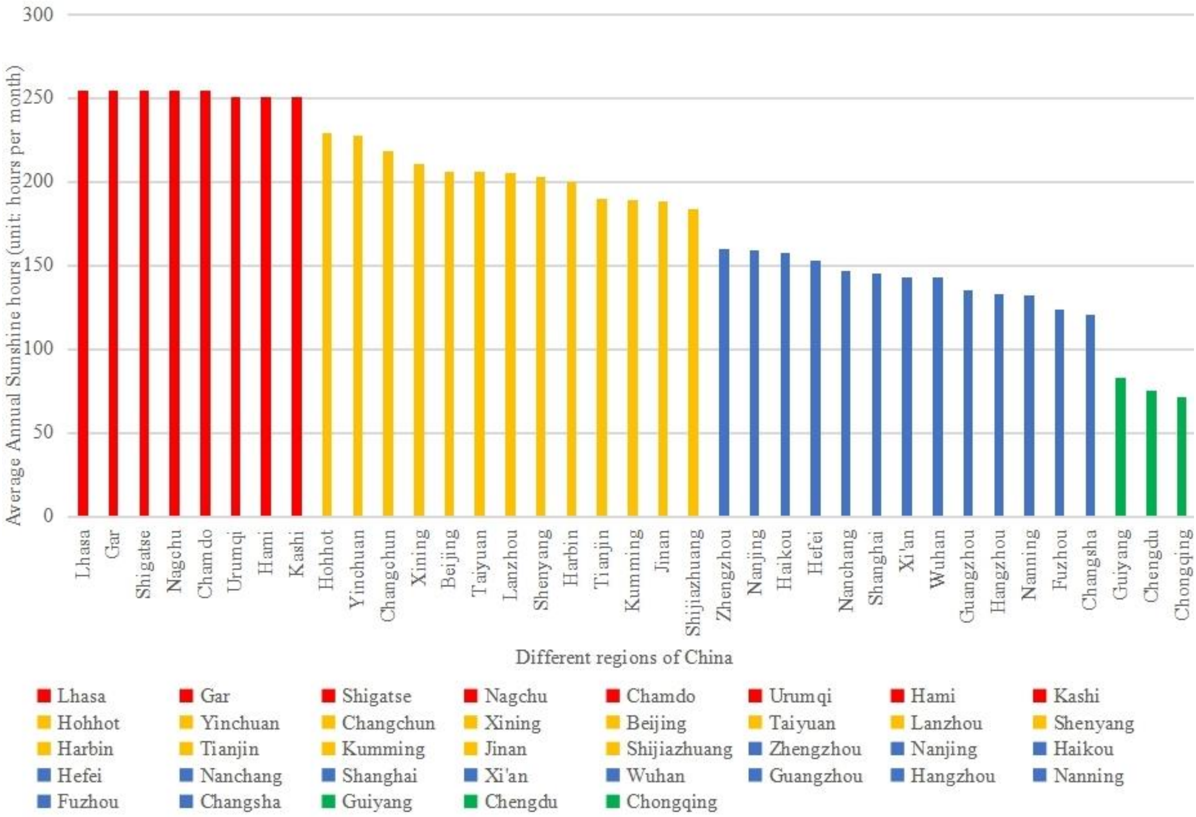

Figure 8. Average annual sunshine hours for different regions in China.

As shown in Figure 8, the first five cities with the highest average annual sunshine hours are all from Tibet, which shows that the solar plants there can absorb irradiation from the sun for relatively a long time. In contrast, the region with the lowest GHI, which is Chongqing, has a value of less than one-third of the highest value. This shows that solar plants in Chengdu can absorb much less time from the sun. Furthermore, the color red denotes regions with an average of over 250 hours of sunshine per month, signifying prolonged sunlight exposure. The color yellow is used for regions averaging between 175 and 250 hours of sunshine monthly, indicating a relatively long duration of sunlight exposure. Blue is assigned to regions with monthly sunshine hours ranging from 100 to 175, suggesting a comparatively shorter sunlight exposure period. Green is used for areas with less than 100 hours of sunshine per month, highlighting extremely limited sunlight exposure. As a result, Tibet and Xinjiang are two provinces with extended sunlight exposure, which positively impacts their solar energy production.

4. Conclusion

After a thorough analysis of the data and scores from the preceding section and collecting data from various regions of China based on multiple factors, including environmental and socioeconomic, a novel evaluation metric was formulated. This metric assigns a score to each region's suitability for the construction of solar power plants, allowing for an easy ranking of regions according to their scores. The results reveal that the Qinghai-Tibet Plateau is the most optimal region for the construction of solar power plants. Among the provinces, Tibet tops the list as the most suitable for PV power plant construction, followed by Inner Mongolia, Xinjiang, Qinghai, Ningxia, and Gansu. Within Tibet, Gar is identified as the most favorable location for solar plant construction, followed by Shigatse, Lhasa, Nagchu, and Chamdo. On the other end of the spectrum, Chongqing is identified as the least suitable location for the construction of PV power plants, followed by Shanghai, Zhejiang, Guangdong, Sichuan, and Guizhou. Moreover, the future of PV production appears promising and holds certain advantages over the United States. Importantly, Northwest China possesses certain advantages in PV power production compared to Southeast China.

The findings of this study are significant as they provide a comprehensive and detailed analysis of the suitability of different regions in China for solar power plant construction. This evaluation framework not only helps in ranking the regions based on their suitability but also provides a roadmap for policymakers and investors to make informed decisions. Ultimately, this research will potentially contribute to the broader goal of transitioning to renewable energy sources, addressing environmental concerns, and promoting sustainable development in China.

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