Research on Photovoltaic Development in Northwestern China using Remote Sensing Images

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Abstract

Photovoltaics, a clean energy source, have received widespread attention worldwide recently. Many countries are carrying out photovoltaic construction, while also compiling and analyzing their photovoltaic development status. The same goes for China. In northwestern China, a considerable number of cities lack electricity. Meanwhile, its vast plains and abundant sunlight are conducive to the construction of photovoltaics. Therefore, the northwestern China has vigorously carried out photovoltaic construction nowadays. With the support of high-resolution and multi-temporal remote sensing images, we are able to analyze the development status of photovoltaics in these regions. We chose six provinces in northwestern China as our research areas and took three steps to complete our studies. Firstly, we extracted patterns of photovoltaics using deep learning methods. Secondly, based on the patterns and national land use survey data, we calculated the distribution and development status of photovoltaics in each province. Thirdly, we present the statistical results in figures and charts, showing the photovoltaic construction status and its development trend. We finally made conclusions and discussions about our insufficiency in work and future plans for further study.

1. Introduction

Photovoltaics, a clean, safe, and renewable energy, is now catching more and more attention. Photovoltaics (Piano and Mayumi, 2017) is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect, a phenomenon studied in physics, photochemistry, and electrochemistry. A photovoltaic system employs solar modules, each comprising a number of solar cells, which generate electrical power. Photovoltaic technology helps to mitigate climate change because it emits much less carbon dioxide than fossil fuels. Its production and installation does cause some pollution and greenhouse gas emissions, only a fraction of the emissions caused by fossil fuels. While once installed, its operation does not generate any pollution or any greenhouse gas emissions. Besides, since its first mass-production in 2000 (Palz, 2014), it has grown from special applications (Bazilian et al., 2013) to a normal source energy. Decreasing costs led by improvements in manufacturing technology and efficiency (Roser, 2023, Shubbak, 2019) have also added to its growth. Therefore, photovoltaic construction has spread quickly worldwide and people around the world nowadays have used various methods through different data resources to study photovoltaics, aiming to find its power and potential (Dada and Popoola, 2023, Benalcazar et al., 2024, Cai et al., 2024).

Researchers have already conducted a lot studies about photovoltaics in China. For instance, Wang et al have studied the energy transition towards photovoltaics (Wang et al., 2023). Yu et al have studied the potential of photovoltaics (Yu et al., 2023). Wang et al have studied the policies about photovoltaics in China, and have paid attention to its economic performance (Zhao et al., 2015). Xue has come up with a new kind of application of photovoltaics, using photovoltaics to produce green and sustainable electricity for agriculture (Xue, 2017). Huo et al have studied the photovoltaic policies in China to discover the reason for success, and to make plans for future development (Huo and Zhang, 2012). Chong et al have studied three photovoltaic projects in Tianjin, in order to find the benefits of photovoltaic applications (Chong et al., 2023). Ji et al have even learned from their studies that China could fulfill a net-zero electricity system by 2050 even facing climate change risks (Ji et al., 2022). However, most of these studies are carrying out only using policies and text data, lacking more specific data as their support.

Since remote sensing images nowadays have advantages of wide range, high resolution, and multiple temporal phases. Therefore, studies of photovoltaics using remote sensing images are carrying out more often. From the images, researchers can learn what was happening in an exact time, thus can serve as more efficient data for their studies. For instance, Xia et al have discovered from remote sensing images that photovoltaic programs have helped deserts turn green (Xia et al., 2022b). Xia et al have studied the rapid development of photovoltaic power stations using remote sensing images (Xia et al., 2022a). Chen et al have studied how to apply remote sensing images in photovoltaic scenarios, mainly techniques, applications and future directions (Chen et al., 2023). Chen et al have studied the rapid expansion of photovoltaic plants from 2010 to 2022 using satellite images (Chen et al., 2024). Nevertheless, these studies still have some defects. For instance, some studies lack advanced methods to fully extract information from images. Others lack land information data which can help to study photovoltaic distribution in research area.

Therefore, we decided to use deep learning methods and land use survey data to fully extract information from remote sensing images. Deep learning methods have been proved to perform well in information extraction, which can help us obtain more features from satellite images. Then, based on the extracted information and land type data, we can conduct a statistical analysis of the increase and distribution of photovoltaics. Considering the national status and the data characteristics, we chose six provinces in northwestern China as our research area. These provinces are of high research value for their lack of electricity and powerful conditions for constructing photovoltaics. After

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finishing our studies, the statistical results can partly serve as a basis for evaluating the photovoltaic development status and making future plans in northwestern region.

2. Study Area

We selected six provinces (Inner Mongolia Autonomous Region (Inner Mongolia), Shaanxi Province (Shaanxi), Gansu Province (Gansu), Qinghai Province (Qinghai), Ningxia Hui Autonomous Region (Ningxia) and Xinjiang Uygur Autonomous Region (Xinjiang)) in northwestern China as our research area (figure 1). The six provinces cover an area of 422 square kilometers, accounting for approximately 44% of China's total. Since the region is inland and far from the sea, coupled with plateaus and mountains, precipitation is scarce and the climate is arid (Chen et al., 2020). These conditions are conducive to the development of photovoltaics. Firstly, the severe environment leads to vast land and sparse population, coupled with sufficient sunlight, making it suitable for photovoltaic power generation. Secondly, nearly affected by land use, the desert in northwestern region is suitable for the development and construction of large-scale photovoltaic bases. Besides, the Chinese government has provided strong support for the development of renewable energy in northwestern region, where policy support for photovoltaic projects is quite remarkable (Luo et al., 2023, Li, 2022, Wu et al., 2022, Liao et al., 2022, Qiu et al., 2022). Therefore, the geographical advantages as well as China's policy have driven the development of photovoltaics in northwestern region these years, which is of high research significance and value. Based on remote sensing images of 2m-resolution in 2019 and 2021, we conducted our study mainly by extracting photovoltaic information from the data and doing analysis according to land use survey data. Our aim is to study its current development status and its distribution on land types. Then we can form systematic conclusions and make plans for the future.

3. Data and Methods

We mainly used two kinds of data.

One is remote sensing images, we used the data of 2m-resolution in year 2019 and year 2021. The raw images were produced by GF-1, GF-2 and GF-6 satellite. Through fusing panchromatic images of 2m-resolution and multispectral images of 8m-resolution, we obtained 2m-resolution image products. Then after cloud recognition, we mosaic the multi-temporal images to national scale while minimized the impact of cloud as much as possible. The final image datasets were used for our study.

The other is national land use survey data, updated in 2020, which divided China's land into 51 types. The 51 types of land is also classified into 12 major categories: Agriculture Land (AL), Plantation Land (PL), Woodland (WL), Grassland (GL), Commercial Services Land (CSL), Industrial and Mining Land (IML), Residential Land (RL), Public Management and Service Land (PMSL), Special-used Land (SL), Transportation Land (TL), Water and Water Conservancy Facility Land (WWCFL), Other-used Land (OL). The data is in vector format, and its distribution is shown in figure 2.

Our study methods can also be divided into three steps. Firstly, we extracted feature maps of photovoltaics using deep learning methods. We chose Swin-UNet (figure 3) as our network to conduct semantic segmentation. Swin-UNet (Cao et al., 2022) uses self-attention module (figure 4) instead of traditional convolutional Layer to encode and decode information from images, thus extracting more specific features on the pixel level.

We used the following formula to calculate self-attention:

$$Attention(Q, K, V) = softmax(\frac{QK^T}{\sqrt{d_k}})V \tag{1}$$

where
Q = Query
K = Key
V = Value
d = dimension

After we have extracted the information from satellite images, we can make further analysis by doing intersect process with land use survey data. Since land type data is in vector format, we converted the raster data we obtained from Swin-UNet to vector data. Then, with the help of Arcpy, we can make batch intersection analysis of these two datasets. The results were also in vector format, combining information of land type and photovoltaics.

Finally, we calculated and made various analysis for different targets. For instance, we calculated the total area of each province to find its photovoltaic growth rate. Also, we counted the numbers of photovoltaics patterns to find its additions in sites. Most importantly, we calculated the area of photovoltaics on each land type, which can serve as specific and significant information for our analysis.

4. Results and Analysis

Except for some areas in Keshiketeng Banner, Chifeng City, Inner Mongolia that cannot be processed due to topology issues, we dealt with other satellite images using methods mentioned above. The results contained rich information, which was presented in figure 5. The specific content and its analysis is as follows.

Firstly, we conducted an overall photovoltaic area analysis of the research area (figure 6), which can intuitively reflect its development status. The area of photovoltaics in six northwestern provinces in 2021 increased by 27.15% compared to 2019. Among these provinces, Ningxia has the greatest growth rate, 41.77%, followed by Qinghai, Inner Mongolia, Shaanxi, Xinjiang, which reached 36.75%, 29.34%, 29.10%, 23.07%, respectively. Gansu has the least growth, increased by only 4.25%. We can easily learned from the results that Gansu has the least developed photovoltaic industry among the six northwestern provinces.

Then, we studied the dispersion of photovoltaic distribution (figure 7), using the photovoltaic patterns extracted from satellite images. Our aim was to find the addition of photovoltaic industry sites. The number of photovoltaic spots in 2021 increased by 1765 compared to 2019, with an increase of 40.05%. The average photovoltaic spot area decreased by 9.21% compared to 2019. We can learn from the statistic number that the photovoltaic industry has opened up quite a few new construction sites. However, among these provinces, we found that Inner Mongolia has the largest growth rate, increased by

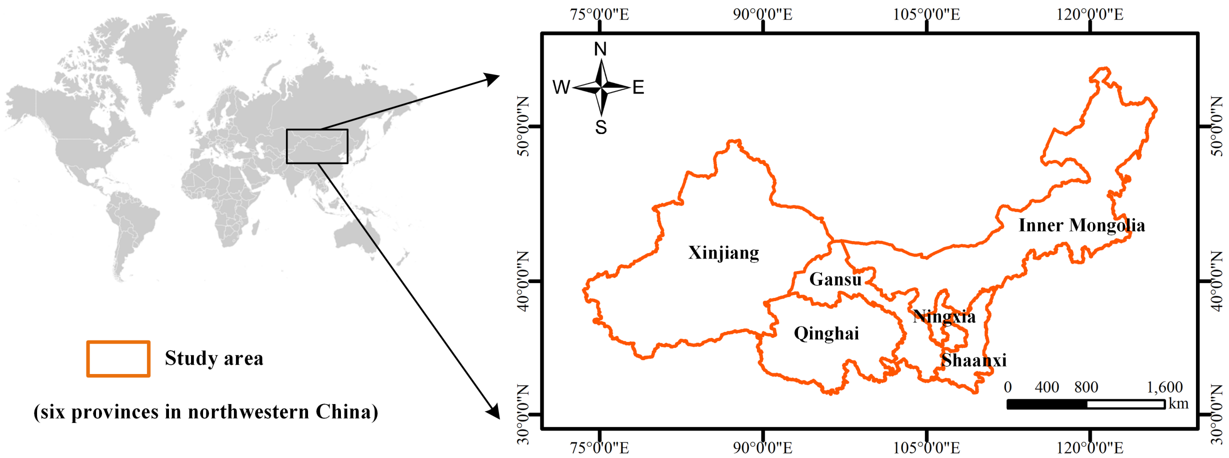

Figure 1. Research Area.

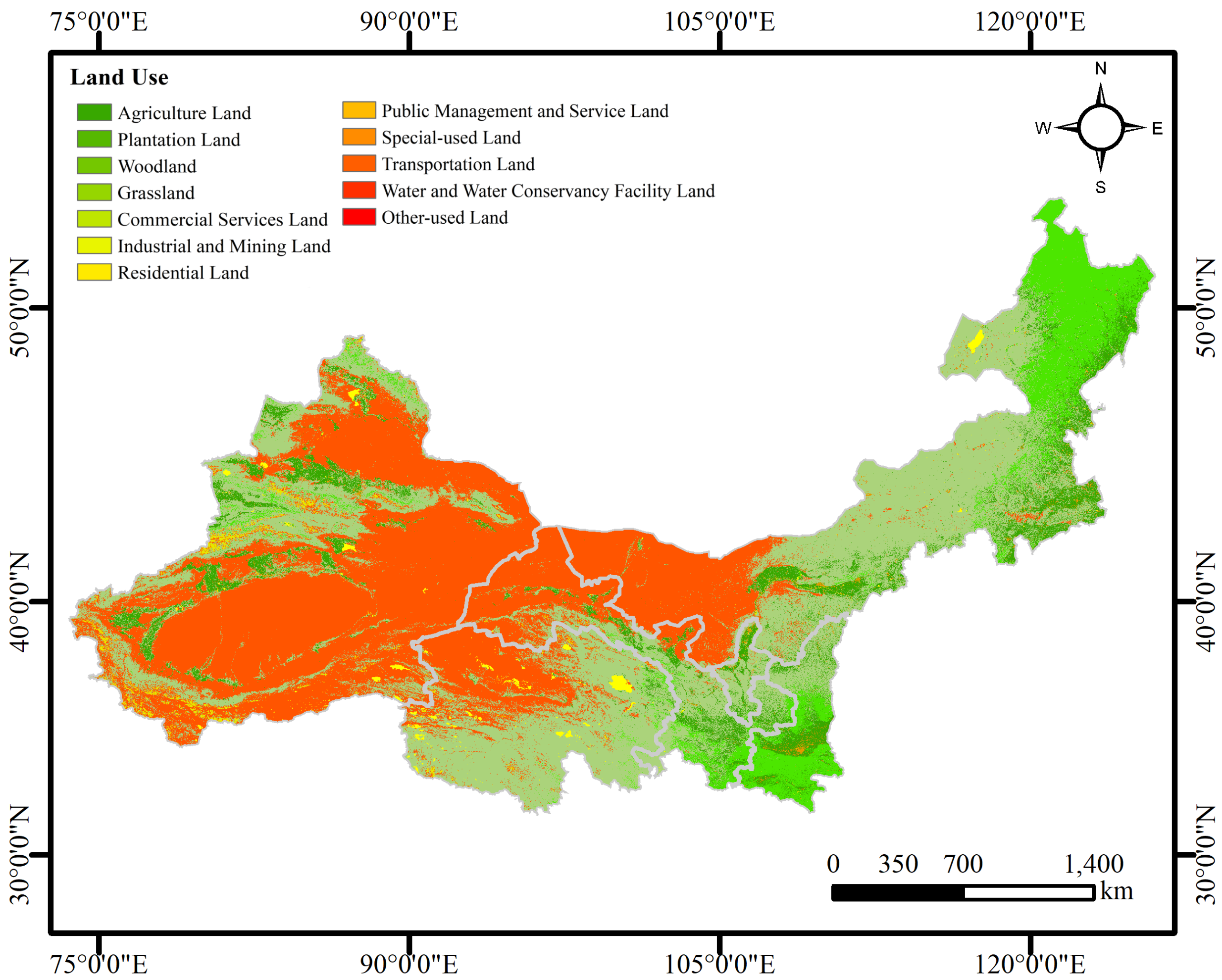

Figure 2. Diagram of Land Use Types in Research Area.

122.48%. While the growth rate of Ningxia, Shaanxi, Xinjiang, Gansu, Qinghai is 43.84%, 30.05%, 5.48%, 0.53%, -12.22%, respectively. Xinjiang and Gansu have nearly increased, and Qinghai has even decreased. This phenomenon may be caused by photovoltaic industries' combination in the process of development.

By comparing the two figures (figure 6, figure 7) above, we can learn that each province has a unique development mode. For instance, Inner Mongolia develops its photovoltaics by add more construction points, trying to spread the whole industry all over its region. However, Qinghai Province may take the strategy to expand on its original construction. By combin-

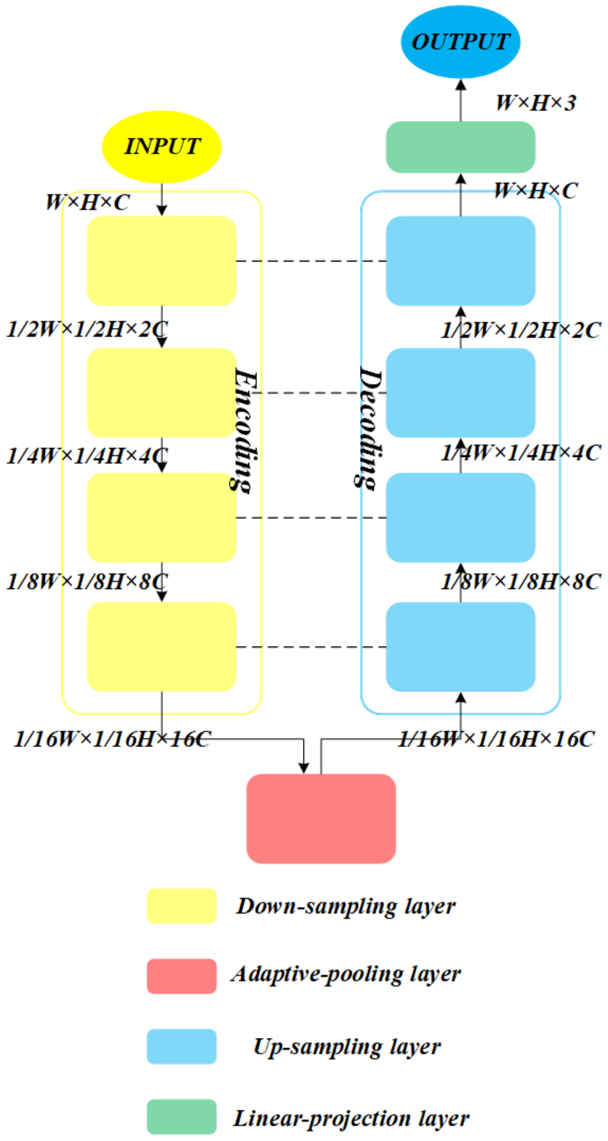

Figure 3. Diagram of Swin-UNet.

ing several industries, Qinghai can make the development of its photovoltaic industry more concentrated and systematic. The results above showed that the photovoltaic industry in the six provinces not only increases in area, but in concentration as well. In general, the development status and trend of photovoltaics in northwestern China is full of vitality and potential.

Next, we calculated and counted the area of photovoltaics on different land types in each province, aiming to study its distribution on land types. After detailed statistics, we can see that except for Shaanxi Province, the photovoltaic systems in the other five provinces are mainly distributed on three types of land use: grassland (GL), industrial and mining land (IML), and other land use types (OL), with a total proportion of over 90%. To be specific, the number of total proportion is: (1) Inner Mongolia: 90.17%, (2) Shaanxi: 60.96%, (3) Gansu: 96.35%, (4) Qinghai: 98.47%, (5) Ningxia: 90.56%, (6) Xinjiang: 99.24%, respectively (Table 1).

The photovoltaic system in Shaanxi Province is mainly distributed on GL and agriculture land (AL), accounting for 89.64% of the province's overall photovoltaic area. While photovoltaic

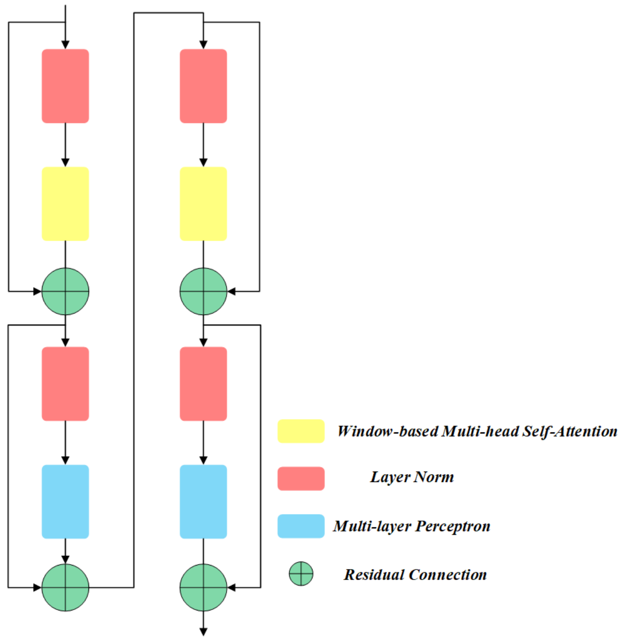

Figure 4. Diagram of Sampling Module.

Province	Land Types			
	GL	IML	OL	SUM
Inner Mongolia	74.60%	1.22%	14.35%	90.17%
Shaanxi	57.61%	0.41%	2.94%	60.96%
Gansu	48.45%	24.22%	23.68%	96.35%
Qinghai	39.04%	45.94%	13.49%	98.47%
Ningxia	74.40%	2.12%	14.04%	90.56%
Xinjiang	19.94%	58.04%	21.26%	99.24%

Table 1. Photovoltaic distribution by 3 land types (GL, IML, OL).

in other provinces nearly distributes on AL, the proportion of which is: (1) Inner Mongolia: 5.28%, (2) Gansu: 2.97%, (3) Qinghai: 0.60%, (4) Ningxia: 2.31%, (5) Xinjiang: 0.38%, respectively (Table 2).

Province	Land Types		
	GL	AL	SUM
Inner Mongolia	74.60%	5.28%	79.88%
Shaanxi	57.61%	32.03%	89.64%
Gansu	48.45%	2.97%	51.42%
Qinghai	39.04%	0.60%	39.64%
Ningxia	74.40%	2.31%	76.71%
Xinjiang	19.94%	0.38%	20.32%

Table 2. Photovoltaic distribution by 2 land types (GL, AL).

We can learn from the above charts (Table 1,Table 2) that photovoltaic industries in northwestern china mainly distribute on 4 land use types: GL, IML, OL, and AL. The advantages of constructing photovoltaics on these places and whether it has an impact on people's lives can serve as our future research targets.

5. Conclusions and Discussions

With the study results and analysis above, we can fully draw the following conclusions and discussions.

1. The photovoltaic industries in northwestern China are now in a great state of development. On the one hand, the

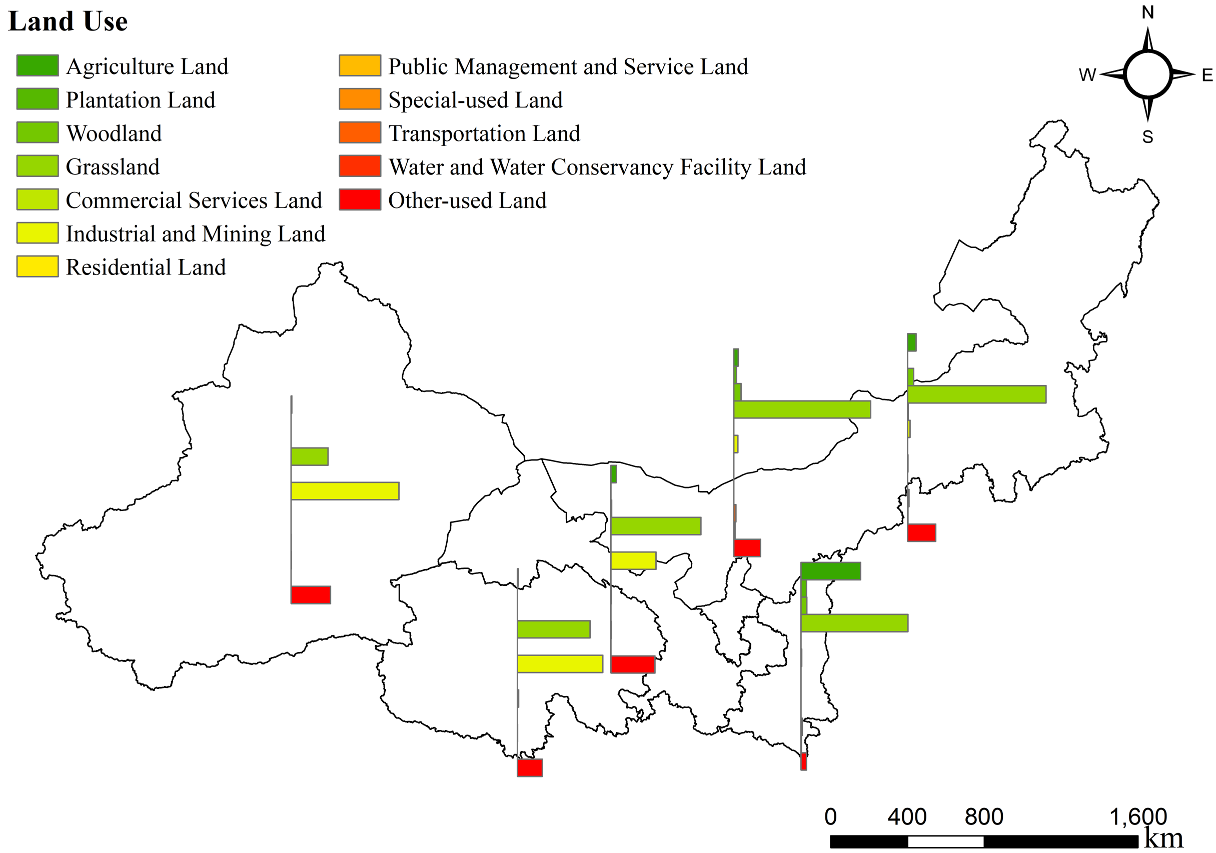

Figure 5. Diagram of Photovoltaic Statistic Results.

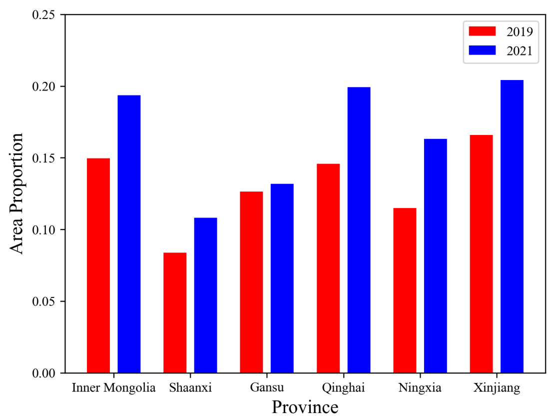

Figure 6. Area proportion of six provinces in 2019 and 2021.

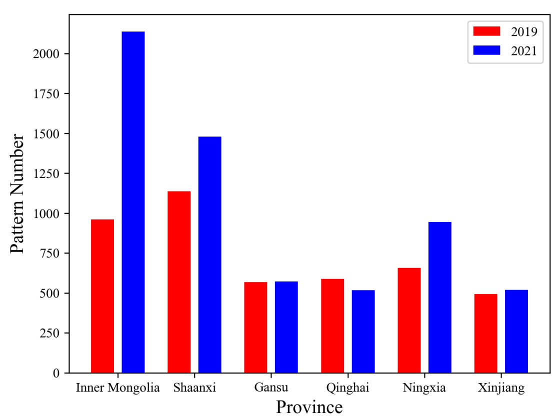

Figure 7. Pattern number of six provinces in 2019 and 2021.

photovoltaic area have increased 27.15% in two years. One the other hand, more places suitable have been discovered and put into construction, which can be seen from the number of patterns extracted from satellite images.

2. Apart from the overall thriving development, each province has generated a unique photovoltaic development model that suits itself. For instance, Inner Mongolia mainly develops its photovoltaic industries through investigating and discovering more suitable places for construction. This method has largely utilized its advantage of vast territory as well as explored its potential in terms of abundant sunlight. However, Qinghai has adopted an almost opposite strategy. Qinghai mainly develops its photovoltaic industries by expanding and merging on its original basis. They may find their place better at developing large-scale photovoltaic industries. Although methods are quite different, the results are satisfying. Diversified development can also be conducive to mutual learning and progress among provinces.

3. While the development status of photovoltaics is attracted, the environmental and social problems it brings also needs attention. For instance, we have learned that many photo-

voltaic industries are located in agriculture land and grass land. The former may influence the living quality of farmers. Also, its noise may disturb people living around. The latter may cause damages to natural environment for it cannot avoid pollution during its construction. However, the land use survey data cannot truly show the current status of land. The land can be divided into agriculture land even it has not been put into use yet. So the land cover data is essential for our next step to fully extract photovoltaic distribution on current land types. Then we can make more convincing results.

4. Finally, we thought we can carry out our work by collecting data about economic value of photovoltaics in these provinces. We did make specific studies about its area, distribution and so on, but we lacked information to prove whether it was meaningful. We still needed more diverse data to find the meanings and benefits of photovoltaic industries, thus making our studies more comprehensive and plentiful.

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