Remote Sensing-Based Assessment of Urban Solar Distributed Photovoltaic Potential

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Abstract. As the main battlefield of energy transformation, how to evaluate the potential of solar photovoltaic (PV) in cities has become an important practical problem. This paper systematically summarizes the evaluation methods of urban solar photovoltaic potential based on remote sensing and GIS technology. The current methods for obtaining surface solar radiation data are classified into three categories, and their applicability in urban photovoltaic evaluation is analyzed by comparison. Among them, the satellite remote sensing physical inversion method has become the best means to obtain urban solar radiation data with the advantages of a rigorous mechanism. This paper mainly introduces the potential evaluation method of photovoltaic systems based on distributed technology. The automatic extraction method based on high-resolution remote sensing images and deep learning algorithms, which takes into account large-scale and high-precision, has become the mainstream trend of development. Finally, it is pointed out that in the future, the deep integration of technologies will promote the development of urban photovoltaic potential assessment in the direction of dynamic simulation and three-dimensional quantification, and provide methodological guidance for solar energy scientific planning.

Keywords: Remote sensing; GIS; Solar radiation; Solar photovoltaic potential; Distributed photovoltaic.

1. Introduction

With the intensification of global climate change, the concerted advancement of greenhouse gas emission reduction and energy structure transformation has become a consensus within the international community. High-energy-consuming urban areas have naturally become the main battlefield of green and low-carbon transformation. Among all kinds of renewable energy, solar energy has become a member that cannot be ignored in the transformation and development of urban energy due to its significant advantages such as wide distribution. The city itself has vast roof and wall space, and the photovoltaic development potential is huge. However, the urban internal building structure is relatively complex, so how to scientifically evaluate the potential of urban solar photovoltaics is an important prerequisite for the realization of urban energy transformation. The development of spatial information technology, especially the deep integration of remote sensing and GIS technology, provides a systematic method for this problem [1]. Although there have been many such studies at present, there is little work to compare and sort out: in the face of high-density urban areas with dense buildings and complex forms, what are the advantages and disadvantages of different multi-source data fusion methods?

In view of this, the present paper, grounded in the practical demands of urban energy transition, undertakes a systematic review of research on urban solar PV potential assessment based on remote sensing and GIS technologies, to provide methodological references and framework-level guidance for precision PV potential assessment oriented toward high-density cities.

2. Acquisition of Solar Radiation Data

The acquisition of surface solar radiation data constitutes the logical starting point for urban solar PV potential assessment. The global solar radiation reaching the Earth's surface is primarily composed of direct radiation and diffuse radiation. Based on differences in data sources and computational mechanisms, international research has principally developed along three lines:

traditional estimation methods based on ground observation data, statistical inversion methods based on satellite remote sensing observations, and radiative-transfer physical inversion methods [2].

2.1. Solar Radiation Estimation Methods Based on Ground Observation Data

When satellite remote sensing has not been widely used, the data obtained by ground weather stations are the main source of solar radiation data. The traditional methods of analyzing surface data can be roughly classified into two categories: direct measurement or conventional meteorological quantity conversion.

Direct observation relies on the radiation measurement instruments of meteorological stations, which can provide relatively real radiation. However, due to the small number of stations with corresponding instrument conditions, this method does not have the conditions for wide promotion.

To make up for the deficiency of the direct observation method, scholars have proposed a climatological statistical method to calculate solar radiation using conventional meteorological elements. The basic idea is to establish an empirical formula between surface solar radiation and conventional meteorological factors. For example, Li and other scholars linked precipitation and cloud cover with ground solar shortwave radiation and estimated daily radiation considering seasonal changes. From the perspective of fitting effect, autumn is the most ideal, with a goodness of 0.483 [3].

The method of climatology has obvious practical value. The basic meteorological elements used are physically determined quantities, which can directly explain the solar radiation received on the ground. From the point of view of the model, it is not difficult to deal with the calculation that only the primary or secondary function is used to express the correlation. However, its ability to deal with complex space is limited, and it cannot give the exact value of the shading condition in a small area, nor consider the building slope and orientation in the radiation distribution, so the error involved in photovoltaic potential analysis based on the block is often obvious.

2.2. Inversion Methods Based on Satellite Remote Sensing Observations

The rise of modern satellite remote sensing technology has realized the transformation of solar energy resource assessment to "top-down" earth observation. The utilization mechanism of satellite remote sensing data is divided into direct and indirect utilization, and the statistical inversion method and physical inversion method are distinguished.

2.2.1. Satellite remote sensing statistical inversion method

The statistical inversion method is the direct use of satellite remote sensing data. The basic idea is to establish the regression relationship between the satellite observation physical quantity, and the ground solar radiation measured value and then determine the regression coefficient according to the ground radiation observed value. In the specific application, the statistical inversion method can be further subdivided into the cloud cover inversion method and the narrow statistical inversion method.

The cloud amount inversion method uses an indirect path; that is, it uses satellite remote sensing data to invert the climatological parameters such as cloud amount and then calculates the surface solar radiation through these parameters based on the traditional Climatological Calculation formula. The estimation deviation of cloud cover parameters is the main error source of these methods. When the cloud cover is underestimated by more than 30%, the root mean square error of monthly radiation estimation can rise to more than 40 W/m^2 [4].

The narrow statistical inversion method is to skip the inversion steps of intermediate parameters such as cloud cover and directly construct the statistical regression equation between the satellite observation physical quantity and the total solar radiation on the surface, to realize the direct mapping of radiation data.

In essence, this kind of statistical method directly using remote sensing data is similar to the traditional climatology method. The core difference is that the meteorological observation value is replaced by the satellite remote sensing observation value. The actual performance of the two methods

is similar in calculation accuracy, but the satellite remote sensing data has higher spatial resolution. Therefore, in the area with sparse ground meteorological stations, this method has the practical significance of in-depth research in the spatial assessment of regional solar energy resources.

2.2.2. Satellite remote sensing physical inversion method

The indirect application of satellite data is a form of physical inversion. When solar radiation passes through the atmosphere and reaches the ground, it will be subject to complex extinction. The statistical inversion method cannot well express the details of the above transmission mechanism, so it may have large deviations. Modern radiative transfer theory provides a complete analytical framework for understanding such physical processes. Satellite remote sensing observation has natural advantages in three-dimensional detection. Therefore, the combination of radiative transfer theory and satellite remote sensing data for quantitative calculation of ground radiation has become an important means to improve the spatio-temporal accuracy of radiation assessment. As far as practical application is concerned, physical inversion methods can be classified by parameterization or by radiative transfer mode.

The parameterization method quantifies the weakening effect of different atmospheric factors on solar radiation through an empirical formula and combined with the atmospheric parameters retrieved from satellite remote sensing, the total radiation is approximately calculated. This method is flexible in calculation, but there are many kinds of parametric schemes, and the specific choices are different, so the results are often inconsistent.

The radiative transfer model method is to convert the mature radiative transfer physical theory into a standardized computational engineering tool, called the International General Model, input the initial boundary conditions of atmospheric information, and then calculate the ground radiation value.

These two categories of physical inversion methods fully exploit the outstanding advantages of satellite remote sensing in spatiotemporally continuous observation while preserving the authoritative physical basis of radiative transfer theory, and they are of high practical value for PV potential assessment. In the direction of large-scale satellite remote sensing inversion, Shi et al., building upon radiative transfer models and intelligent cloud detection algorithms, constructed the GSNO near-global surface solar radiation monitoring system, ultimately generating radiation products at a spatial resolution of 5 km with hourly observation frequency [5].

To more clearly delineate the methodological characteristics of each assessment technique described above, Table 1 presents a systematic comparison in terms of data sources, core computational mechanisms, advantages and disadvantages, and applicability to urban PV assessment:

Table 1. Comparison of Core Mechanisms, Advantages, and Disadvantages of Different Surface Solar Radiation Assessment Methods.

Assessment Method Category	Ground-Based Observation Methods	Satellite Remote Sensing Statistical Inversion Method	Satellite Remote Sensing Physical Inversion Method
Primary Data Sources	Ground meteorological station measurements	Geostationary/polar-orbiting satellite channel albedo	Atmospheric optical parameters indirectly inverted from satellite data
Core Computational Mechanism	Empirical formula estimation and GIS spatial interpolation	Regression mapping between satellite-observed physical quantities (e.g., albedo) and surface radiation	Based on classical atmospheric optics and radiative transfer theory
Main Advantages	Highest accuracy of single-point ground measurements; long historical records	Simple algorithmic structure; high local fitting accuracy	Rigorous physical mechanisms; high spatiotemporal universality
Main Disadvantages	Sparse station distribution; large errors in ungauged regions	Lacks physical mechanisms; poor spatiotemporal generalization capability	Complex formulations; substantial computational burden
Urban PV Applicability	Poor. Unable to reflect radiation heterogeneity within high-density urban environments.	Moderate. Suitable for high-frequency prediction in localized urban areas with dense observational coverage.	Excellent. Represents the core paradigm for constructing urban-wide baseline radiation datasets.

3. PV System Potential Assessment

Once the spatial distribution characteristics of regional solar radiation have been established, the delineation of the usable area for urban PV deployment constitutes the core step in realizing the assessment of urban PV development potential. The methodology for determining urban PV usable area adopts distributed PV potential assessment as the primary technical pathway.

Distributed PV systems generally refer to solar power generation systems that are closely integrated with existing infrastructure such as urban building surfaces [6]. Such systems possess core advantages including highly flexible deployment configurations and have been widely applied in urban low-carbon transitions in recent years. From the perspective of the overall technical workflow, the potential estimation of distributed PV systems first requires the accurate acquisition of solar radiation data and the identification of the effective area and orientation/spatial information of the infrastructure available for PV equipment deployment. On this basis, it is also necessary to quantitatively simulate and compute the shadow occlusion effects exerted by surrounding objects on PV equipment during operation. The photovoltaic potential is concluded after analyzing all factors [7]. Chen and other scholars systematically summarized the methodology of determining its available area into three mainstream practice paths [8].

The first is to directly extract the required information based on field measurements or lidar data [9]. Using LIDAR point cloud data, a three-dimensional city model, or official engineering design drawings, this method can obtain more accurate building details, but data acquisition is difficult and expensive, which is only suitable for dealing with the situation in a small area.

The second is the empirical model method, which uses the high-precision building data obtained from the local sampling area as the basis to determine the empirical coefficients such as the photovoltaic deployable area of different building types, and then substitutes it into the macro urban building statistics for regional extrapolation. For the large-scale census, the calculation efficiency is high, but the accuracy is restricted by the representativeness of the sample and the accuracy of the empirical coefficient. Wang et al. Used the typical building samples in Shanghai to obtain the empirical parameters such as photovoltaic power generation per unit area and then combined with the building statistical yearbook and GIS spatial base data to extrapolate the photovoltaic potential of 10 administrative regions in Shanghai, and the calculation efficiency was significantly higher than that of the building-by-building three-dimensional extraction method [10].

The third method is to use high-resolution satellite images together with various geographic information data and automatically identify and extract objects such as building facades with the help of machine learning ideas. Chen and other scholars use sub meter satellite remote sensing images, through deep learning algorithm processing, to divide semantic information from massive images, which can not only efficiently extract the roof contour of large-scale urban buildings, but also design an algorithm to judge the height with shadow or introduce three-dimensional mapping data to assist in measuring the elevation area, to achieve better automation results in the wide area survey, and the average recognition accuracy of buildings can reach 87% [11]. It should be regarded as the mainstream methodology to promote the intelligent engineering of urban distributed photovoltaic resource census.

The three are not mutually exclusive competitive relations, but the common elements of coordinating hierarchical technology. At present, in the practice of urban photovoltaic evaluation, the automatic extraction method is generally used to process the basic statistics of buildings in the whole urban area, and the empirical model is used to convert the potential of different building types. For areas with high accuracy requirements such as the core urban area, LIDAR 3D data or field measurements are used to make necessary detail corrections. From a multi-scale perspective, the combination of various methods can achieve the optimal balance between the evaluation efficiency and the accuracy of the results, which can not only guide the overall urban energy planning, but also not hinder the development of the specific scheme design of photovoltaic projects.

4. Conclusion

Cities have transitioned from being merely passive energy consumption endpoints to becoming important spaces for the large-scale deployment of PV equipment. The deep integration of remote sensing and GIS has elevated urban PV potential estimation from a coarse approach reliant on scattered station data to a new stage characterized by full-area coverage, fine-scale computation, and intelligent decision support.

In this paper, two kinds of problems, the acquisition of surface solar radiation and the evaluation of photovoltaic potential, have been summarized and analyzed. Among them, the physical inversion method is very advantageous for the calculation of spatial continuity, and the method of combining high-resolution remote sensing and deep learning to intelligently identify the usable area of buildings has become the main technical route in the current urban solar energy resource survey. According to the existing ideas, the evaluation method can basically meet the requirements of the production of an urban solar energy resource map, but the light scattering phenomenon between buildings and the acquisition of high-precision spatio-temporal atmospheric data are still some difficulties affecting the accuracy of the results. In the future, technologies such as RS, GIS, and artificial intelligence will accelerate the integration, so that the assessment of urban photovoltaic potential will change from static spatial distribution description to dynamic real-time simulation, and from two-dimensional plane estimation to accurate quantification of three-dimensional space, which will become the basis of feasible methods for high-density urban photovoltaic planning.

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