Application of Geographic Information System in Assessing Rooftop Photovoltaic Potential

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Abstract. Achieving net-zero carbon emissions is a fundamental way to slow global warming, and dealing with massive carbon emissions from the construction industry is a priority. These days, with the growth of the clean energy industry, the market for photovoltaic (PV) power generation using solar energy is booming. In order to estimate PV power potential on a large scale, geographic information systems (GIS) have been applied in case studies in selected areas; however, there is a lack of overview of the comprehensive application of GIS technology in this subject. In this paper, the application of GIS in estimating PV potential is thoroughly analyzed from three perspectives: data source, application, and limitation. In terms of data source, this paper classifies the data into low, medium, and high precision, and the merits and demerits of each class are analyzed. The paper divides the application into two parts: calculating the received solar energy and the available roof area. The former analyses two available plug-ins in GIS software and a calculation formula that combines with GIS. The latter includes a variety of methods for calculating the total roof area, shading effects, vegetation coverage, and tilt & Azimuth. Although using GIS to estimate PV potential is well-developed, there are still limitations regarding accuracy, speed, and data accessibility. This paper hopes to contribute to the estimation of PV power potential to reach a higher level of accuracy and maturity in order to promote more projects and constructions with large-scale PV power generation systems. Indeed, the future of PV power generation is promising and will be a significant step towards net-zero carbon dioxide emissions for all humankind.

Keywords: GIS; Solar PV Potential; building rooftop; net zero carbon emission.

1. Introduction

Global warming is now a common challenge for all humankind in the present day. Ever since the term was first introduced, countless approaches to tackle the problem have been proposed, among which, the most important is to reach net-zero carbon emissions. In response to the Paris Agreement, nations agreed to limit further temperature rise to 2 degrees, and more than 100 countries have been working to develop or have already begun implementing net-zero carbon emissions policies [1]. Construction carbon emissions are a large part of total carbon emissions. Take China as an example; construction carbon emissions reached 4.93 billion tones in 2018, which accounted for 51.3% of the country's total emissions [2]. Therefore, the construction industry has an obligation and a lot of room to reduce carbon emissions in order to meet national and global net-zero carbon emission targets. Photovoltaic power generation is regarded as an essential way to achieve carbon neutrality as it does not produce large amounts of greenhouse gases such as carbon oxides. According to the International Energy Agency, solar photovoltaic power will reach 50 percent of total renewable energy by 2024 [3]. Indeed, PV power generation is a booming industry. Since 1997, the industry has been growing at a rate of 33 percent per year, and it is estimated to reach 100 billion euros in the 20th century [4].

While many countries have developed PV-related policies and are actively promoting the installation of PV panels on the roofs of buildings, the question of how to efficiently and accurately estimate the PV power potential on a large scale for policymaking or projects implemented is a challenge that needs to be faced by both the government and the installing companies. One of the most complicated steps is to determine the suitable roof area for the construction of a PV system. In the past, the usable roof area was measured by manual field survey, but with the development of geographic information technology, the usable space can be calculated more efficiently.

GIS has always been used to calculate PV power potential, from the early days when it was only used to calculate the total roof area to the later days when more and more variables have been taken into account to get more accurate results. The applications of GIS in the estimation of PV power potential are various. Although this method is often mentioned in research as one of the steps in calculating potential, there is no comprehensive analysis of the application of GIS under this topic. What's more, the commonly used methods that include GIS usually involve the selective use of influencing factors by people, and the use of all feasible variables in the calculation of the roof area has not yet been included in any case studies. A well-rounded application of GIS to this problem could provide more options and accuracy for future estimating of PV potential and offer a broad view as a guideline for beginners towards this problem.

This paper provides a thorough overview of the application of GIS tools in estimating PV power potential for measuring available roof area, including data sources of different accuracy and diversified practical approaches. At the same time, the limitations of GIS tools are analyzed.

2. Data Source

For single houses, the most accurate and simplest estimation method is to calculate based on data from field measurements. For example, Mehadi et al. in 2021 used field-measured meteorological data and architectural data for the PV system for the roof of the North Hall of Residence of the Islamic University of Technology, Gazipur [5]. Accurate data tends to have higher resolution and is obtained or processed by more advanced techniques. The accuracy is more pronounced when estimating the PV power potential for a large area such as the whole city or even across the entire country.

For the estimation of rooftop PV potential, the data source is very significant as it determines the accuracy and reliability of the final results. These data can be classified into three classes according to their accuracy, which are low, medium, and high levels [6].

2.1. Low Level Data

Low-accuracy data often rely on definitive statistics, including substituting known data into formulas containing coefficients to get the intended result. This can be seen in the calculation of usable roof area, vegetated area, shaded area, average annual insolation per square meter, etc. As an example, Dehwah and Asif used coefficients such as maintenance and accessibility coefficient (Cacc) and shading coefficient (Csh) to derive the available roof area in the city of Al-Khobar in Saudi Arabia [7]. Chaudhari et al. used solar energy data from several weather stations in a typical meteorological year to estimate the solar energy data received throughout the United States [8]. Vardimon estimated the national total roof area in the country using the information provided by the Israeli Central Bureau of Statistics regarding building types and the corresponding data [9]. In addition, the IEA Energy Technology Perspectives report suggested a method based on the parameterization of rooftop PV potential by population density and solar insolation [10]. This level of data does not require a significant amount of time or money to obtain and is not subject to highly complex processing, making it a handy option. However, the use of this data causes accuracy to be abandoned on a selective basis. This type of data is usually generalized and very much influenced by external environmental factors. Therefore, some scholars have turned to data of medium precision.

2.2. Medium Level Data

The mid-level accuracy data are based on statistical data with the addition of Light Detection and Ranging (LiDAR) methods and GIS methods. With Airborne LiDAR, a 3D Digital Elevation Model (DEM) can be generated, and GIS software can thus calculate the roof area [11]. For instance, Palmer et al. performed lidar scans of all house roofs in Plymouth, UK, and used the data obtained to estimate total roof areas across the UK [12]. Without the need for extra people to be on-site to measure the data, the medium level of data has a higher accuracy level than the low level because it is more targeted and high-tech is used. However, the medium level of data requires more time and a certain amount of technology and money to obtain. Indeed, for accuracy-seeking scholars, medium-level data is still not good enough as not all roof areas are suitable for the installation of solar panels.

2.3. High Level Data

To overcome the shortcomings of medium level data, high level data uses more advanced techniques such as deep learning models, AI, 3D models for shading calculations, rooftop digitization, etc. These methods allow the environmental factors to be excluded as much as possible, making the calculations more accurate. For example, Google carried out an estimation of rooftop solar power potential for hundreds of US cities in 2017 based on 3D models generated by aerial vehicles, GIS and rooftop shading estimation, which resulted in Project Sunroof [13]. The accuracy of the high level data is unlimited and is constantly being updated till date. This thesis will primarily focus on high level data that using remote sensing.

3. Application of GIS

The advantage of using GIS by remote sensing is that the suitability of the roof does not need to be manually selected or determined by a constant value, and the GIS software can automatically filter the target area according to the set parameters. Currently, the mainstream GIS tools include ArcGIS, QGIS, Google Earth, etc., and even Photovoltaic Geographical Information System (PVGIS), PVWatts, and RETScreen, which are specially designed for PV power assessment. The reliability and maturity of these tools have been recognized by others, such as Psomopoulos et al., who tested them in Athens, Greece [14].

There are various uses of remote sensing in rooftop Photovoltaic power generation, which can be divided into two parts: the estimation of insolation and the assessment of the suitable rooftop area for PV panels, which will be introduced in this part of the paper.

3.1. Estimation of Insolation

Incoming solar radiation (insulation) refers to the solar radiation received by the Earth's surface, which varies with the seasons, time of the day, atmospheric conditions, cloud cover, obliquity, etc.

Taking ArcGIS as an example, a method for calculating insolation is first to obtain the exterior shape of the building in ArcGIS, and then based on the shape of the roof of the building, combine the meteorological epw data obtained from the Grasshopper plug-in Ladybug. The final data in units of GWh per year is obtained. This method was applied by Ni et al. in evaluating the PV power potential of the Hongkou district in Shanghai, and the insolation of the Hongkou district was obtained to be 991.6 GWh/year [15]. Another tool in ArcGIS can also be used to estimate solar radiation. The area solar radiation tool handles digital surface maps (DSM) generated by LiDAR data. One can independently calculate the solar radiation for each month of the year and then average it for the year, as Santos et al. did in Lisbon, Portugal, and the results will be more accurate [16].

In addition, another approach employs coefficient formulas combined with the means of GIS. The daylight hours, the available roof area, and the solar energy resources are considered in this method. The solar energy resource can be derived from the formula (1).

$$G_{tot}=\left(a_s+b_s\frac{n}{N}\right)G_0+f_{diffuse}G_b \tag{1}$$

This formula expresses that total radiation equals direct radiation plus dispersion radiation in fine weather conditions. While G_0representing the astronomical radiation, a_s is a parameter that varies with atmospheric conditions and b_s is a parameter that changes with the sun's declination. $f_{diffuse}$ represents the proportion of diffuse radiation. This formula was applied by Zhang et al. in evaluating rooftop solar technologies [17].

3.2. Estimation of Suitable Area for PV Panels Installation

One of the most significant uses of GIS in estimating the PV potential of a roof is to determine the usable area of the roof. The total area of a roof can be easily and quickly calculated by a GIS tool using data from satellites or air drones. While not all roof areas can be used for installing PV panels because roofs are often cluttered with objects, covered by shadows from other buildings, or have non-horizontal ground surfaces. If the total roof area is used directly to calculate the PV power potential, the results will be subject to significant errors. In order to estimate the available area more precisely, a number of methods have been proposed, which are described below (Fig. 1).

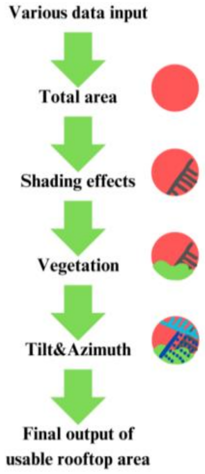

Figure 1. Process to calculate available rooftop area for PV installation (Picture credit: Original)

3.2.1 Total area

The total area can be calculated by random forest, a classification machine learning algorithm consisting of many decision trees. Each tree depends on the value of an independently sampled random vector sampled separately and has the same distribution for all the trees in the forest [18].

The random forest tool is provided with commonly used GIS software for semi-automatic classification. The processing of the data by the software involves manual training. After the target objects are manually screened in a small area, the tool automatically recognizes the area of interest on a large scale. Using QGIS as an example, the final result can be obtained through three steps (i) Input Data, (ii) Create the ROIs, and (iii) Random Forest Classification. Assouline et al. used a detailed mathematical approach for random forest combined with GIS and solar models and machine learning (ML) algorithms to calculate rooftop PV installations across Switzerland [19].

3.2.2 Shading effects

Shading can have a very strong impact on PV generation as it will minimize the amount of solar energy received by the PV panel. Even if a PV system is installed in a certain area of this roof space, frequent shading will result in low power generation, which is very uneconomical and unproductive. Although this is not apparent in single houses with scattered settlements, it is very pronounced in metropolitan areas with high population density. These cities tend to have a vast number of skyscrapers, which block the sunlight for nearby shorter buildings. Therefore, it is vital to assess the shading factor in these cases.

Due to the difficulty of directly calculating the shading effect because the shading to different locations on the roof of the building varies from day to day depending on the weather, season, etc., one method of calculating the shading effect is to calculate the monthly irradiation loss using the day of the year on which the irradiation loss is closest to the average value. This method uses the Area Solar Radiation (ASR) tool in GIS software, e.g., ArcGIS. Based on the DSM data, input parameters such as latitude and longitude are inputted into the ASR tool, and data such as direct irradiation, diffuse irradiation, sun hours, etc. are generated. Boz et al. applied this method in estimating the PV power generation in Philadelphia, PA, USA [20].

Besides this, another tool in GIS software that can also be used to estimate shading is Hillshade analysis, which, unlike ASR, calculates the area of shading directly and averages it over several calculations based on data from representative times of the year. Hillshade analysis generates a grayscale 3D image of the intended area after inputting the altitude and azimuth to determine the sun's position. As a result, areas of strong grey are identified as unsuitable for the PV power system and are excluded from the total area. Hong et al. conducted a case study of estimation, proving this method's practicability in the Gangnam district in Seoul, South Korea [21]. The underlying arithmetic algorithm of the Hillshade analysis tool can be represented by the equation (2).

$$\text{Hillshade} = 255 \times \{[\cos(\text{Zenith}_{\text{rad}}) \times \cos(\text{Slope}_{\text{rad}})] + [\sin(\text{Zenith}_{\text{rad}}) \times \sin(\text{Slope}_{\text{rad}}) \times \cos(\text{Azimuth}_{\text{rad}}) \times \cos(\text{Aspect}_{\text{rad}})]\} \quad (2)$$

whereas, $\text{Zenith}_{\text{rad}}$ is the radian of the zenith angle of the sun; $\text{Slope}_{\text{rad}}$ is the radian of slope at a point; $\text{Azimuth}_{\text{rad}}$ is the radian of the angle of direction of the incident sun rays; and $\text{Aspect}_{\text{rad}}$ is the radian of slope at a point.

3.2.3 Vegetation

Vegetation cover is one factor that influences the suitable rooftop area for PV panels in two main ways. Firstly, for low-rise buildings, particularly in urban areas, incident sunlight can be very susceptible to being blocked by trees, especially for houses at the sides of avenues next to roadside trees. In the second case, some roofs are fully or partially used for growing vegetables or gardening, making it difficult for low plants to be screened out by topographic analyses. Today, rooftop farming is becoming increasingly popular, and it is necessary to consider the influence of plants when evaluating the available roof area.

Therefore, to exclude the area affected by vegetation, GIS is applied to solve this task by calculating the Normalised Difference Vegetation Index (NVDI), a commonly used and widely accepted indicator of vegetation assessment in GIS. This index is usually calculated from remote sensing data from satellites, as shown in formula (3).

$$\text{NDVI} = \frac{(\text{NIR-RED})}{(\text{NIR+RED})} \quad (3)$$

NIR is the near-infrared light reflection in the formula, and RED is the red light reflection. Typically, the NDVI value is set between -1 and 1. When the resulting index is positive, there is vegetation cover; when the index is negative, there is no vegetation cover. The higher the NDVI value, the more vegetation cover. To give an example of this in an application, Chen et al. became one of the few who take vegetation shading into account by including the vegetation index in calculating the PV power potential of Guangzhou, China. For some specific cities, vegetation is indeed an important factor [22].

3.2.4 Tilt and Azimuth

Generally, building roofs can be categorized into flat regular roofs and irregularly shaped roofs. For flat roofs, there is more flexibility in installing solar panels as the tilt and orientation of the panels can be adjusted to get the maximum power output. In contrast, shaped roofs are more limited as the orientation and tilt are fixed. In some regions, roofs with a specific inclination hardly receive sufficient sunlight and therefore need to be distinguished from flat roofs and be analyzed more thoroughly. The two factors that primarily affect shaped roofs are tilt and azimuth, which combines to give various power output and can both be measured using GIS [23].

Both tilt and azimuth can be measured from a 3D image generated by GIS software using data set obtained from LiDAR. GIS software such as ArcGIS has a Zonal Mean tool that can be used on the tilt data to calculate the average tilt of a roof.

Beyond LiDAR, a number of satellites can provide data used to calculate inclination and azimuth, such as the geostationary MTSAT satellite. Solar zenith angle (SZA), viewing zenith angle (VZA), and the relative azimuth, which is the difference between the solar azimuth angle and the satellite azimuth angle, makes up a major part of solar geometry [24].

4. Limitations and Challenges

Certainly, some limitations are revealed when using GIS methods. Firstly, assessing rooftop PV potential is a task where accuracy is very crucial. However, with the current state of technology, it is impossible to take into account all the cases, even if many factors affecting the situation are excluded. Additionally, much of the data utilized in GIS is averaged, which makes yearly, monthly, and daily values subject to large deviations due to the rapidly changing environment.

Secondly, the existing GIS in rooftop photovoltaic potential must be supported by more modern technology to achieve incredible speed and higher accuracy. For example, deep learning-based methods such as using the DeepLab v3 can be applied to extract suitable rooftop areas [25].

GIS relies on high-precision data, yet these data have a relatively high barrier to access. High-precision satellites and LiDAR will be used to obtain tailored data for those who can afford to pay or who can control it. In this case, GIS tools may not be optimal for those who cannot fit into the group with easy access. Publicly available data such as project sunroof can provide information on some regions of interest, and there is even a method that involves image recognition and machine learning for aerial imagery that is being used in Freiburg, Switzerland [26].

5. Conclusion

GIS tools are indispensable for accurate and efficient calculation of roof PV potential. The data sources for this calculation are diverse, ranging from low, medium, and high precision. While calculations using known coefficients are the most convenient, they lack precision because they do not consider the environmental and human factors specific to a site. On the other hand, although medium and high precision data have economic barriers to collect, they are more reliable. The use of GIS tools in calculating the PV potential is mainly in two ways: calculating the insolation and the available roof area. Two tools in GIS software and a method using GIS combined with a formula are discussed for estimating the insolation. For obtaining the available roof area, in addition to calculating the total roof area utilizing the random forest tool, three influencing factors are considered. Shading effects are the most commonly considered factor, which can be calculated using the ASR tool and Hillshade analysis. Vegetation factors are generally seldom mentioned, which can be calculated using the NVDI. Finally, Tilt and Azimuth can be calculated or directly obtained from 3D models built from LiDAR data and satellites, such as geostationary MTSAT satellites. While the application of GIS in this area is quite mature, there are still limitations and challenges regarding higher accuracy, better access to high-quality data, and faster analysis using more advanced technologies such as DeepLab v3. In the future, GIS tools will be more sophisticated, and the use of PV power systems will increase exponentially, which may result in reductions in carbon emissions in the construction industry, contributing to net-zero carbon emissions. This paper provides a comprehensive analysis of the use of GIS in calculating PV power potential.

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