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A pixel-based approach to estimation of solar energy potential on building roofs

Yan Li [a], Ding Ding [b], Chunlu Liu [a,*], Chongjie Wang [b]

[a] School of Architecture and Built Environment, Deakin University, Geelong, Australia
[b] School of Architecture and Urban Planning, Shandong Jianzhu University, Jinan, China

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ABSTRACT

Precise estimation of solar energy on building roofs plays a critical role in sustainable development and renewable energy consumption of high-density human habitats. Conventional solar radiation models based on costly Light Detection and Ranging (LiDAR) data are only adequate for existing buildings, not for future construction areas. In this paper, a pixel-based methodology is constructed for estimating solar energy potential over roofs. Buildings with flat roofs in a newly planned construction area are chosen as a case study. The solar radiation at a certain cell is mathematically formulated in the pixel unit, and its yields over a certain time period are calculated by considering multiple instantaneous solar irradiances and are visually presented by image processing. Significant spatial and temporal variations in solar radiation are measured. Within the study area, the maximum and minimum annual radiation yields are estimated at 4717.72 MJ/m^2/year and 342.58 MJ/m^2/year respectively. Radiation contour lines are then mapped for outlining installation ranges of various solar devices. For each apartment building, around 20% of roof areas can obtain 4500 MJ/m^2/year or more solar radiation yields. This study will benefit energy investors and urban planners in accurately predicting solar radiation potential and identifying regions with high radiation over building roofs. The results can be utilised in government policies and urban planning to raise awareness of the use of renewable energy sources.

1. Introduction

As fossil fuels are projected to decline and the global demand for energy is increasing rapidly, many countries have to seek sustainable development by generating and acquiring energy in a sustainable way [1]. Renewable energy is sustainable energy derived from the natural environment. Since it significantly contributes to low emissions and national energy security, renewable energy is of great importance for future environmental protection and economic development [2]. In addition, the comfort of modern living conditions has been achieved at the cost of vast energy resources. Thus, governments and engineers often devote extensive effort to exploiting renewable energy sources in order to minimise conventional energy expenditure and improve living standards [3].

Among renewable energy resources, solar energy is considered a free, clean, unlimited, and environmentally and economically friendly energy source [4]. In urban areas, a building rooftop is often recognised as a suitable location for installing solar energy devices. These devices are also easy to install with little need to dig, and can achieve energy conversion without noise and greenhouse gases. Furthermore, the direct utilisation of solar energy in buildings is mainly through solar photovoltaic technology and thermal technologies [5]. The former technology aims to absorb solar radiation and generate electricity directly using photovoltaic cells. In addition, solar energy sources are also very cost effective. Compared to conventional energies, an investment in solar equipment provides long lasting energy for future generations [6]. Therefore, utilisation of solar energy in buildings can be used to support sustainable buildings, such as rating systems, namely Leadership in Energy and Environmental Design and Green Star [3,7].

However, great efforts are usually made in search of low manufacturing costs by technology research [8]. To promote the utilisation efficiency of solar energy and satisfy as much urban energy demand as possible, it is necessary to evaluate solar energy potential and analyse its distribution over urban areas. Yet evaluation of the solar energy potential for urban use is a significant challenge as there are significant spatial and temporal variations in solar radiation that are greatly impacted by many factors such as surface orientation, shadowing effects and terrain features [9]. To address these issues, researchers explored and developed various

* Corresponding author.
E-mail address: chunlu@deakin.edu.au (C. Liu).

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methods and technologies that are used for radiation estimation over given building surfaces [10]. Hachem, Athienitis and Fazio [11] chose two-story single housing units as case studies to investigate the effects of roof shapes on solar energy potential. Yet these initial studies are often limited to self-shadowing in the built environment. To address the spatial factors, geographic information system (GIS) techniques are also frequently incorporated in the estimation. Based on digital maps produced by Google Earth, Ordóñez, Jadraque, Alegre and Martínez [12] successfully determined the solar energy potential for installation of grid-connected photovoltaic systems on rooftops in Andalusia. In addition, some GIS-based tools have been widely used for the solar radiation estimation. For example, PVGIS, a web-based database, that integrates many relevant data sources, such as USGS GTOPO30 digital elevation models (DEM), is capable of calculating photovoltaic potential for many countries and regions [13]. Nevertheless, these solar radiation tools have not yet taken complex shadowing effects into account in GIS environment [14].

Since height grids in urban environments became easily accessible data through airborne Light Detection and Ranging (LiDAR) surveys, building detection based on remote sensing data has been popular in the solar energy estimation on the extracted building footprints. This is because the LiDAR-based data acquisition technology allows the rapid reconstruction of terrain surfaces, which is suitable for existing 2D models to assess building insolation [15]. In 2009, Tereci, Schneider, Kesten, Strzalka and Eicker [16] applied LiDAR data to build a Digital Surface Model (DSM), determining the annual solar potential for identified building roofs in combination with ALK map data and GIS software. Lee and Zlatanova [17] constructed a 2.5-D DSM on the basis of the use of LiDAR and 2D/3D vector data to compute the morphological properties of buildings. The implemented tool for solar radiation calculation is not only suitable to roof areas but also useful to analyse building facades. In 2013, in order to estimate solar potential over building surfaces, Redweik, Catita and Brito [18] also proposed a solar radiation method based on the *r.sun* radiation model developed by Šúri, Huld, Dunlop and Ossenbrink [19] and incorporated this in the open source GRASS GIS [20]. The results revealed that the potential of building facades is lower than that of roofs although they normally have large areas. By taking advantage of ESRI's Solar Analyst Toolbox and LiDAR data, Kodysh, Omitaomu, Bhaduri and Neish [21] introduced a method for estimating solar potential on multiple building rooftops through combining a DEM with an upward-looking hemispherical viewshed algorithm. Lukač and Žalik [22] presented a methodology through using graphics processing units with compute unified device architecture technology and LiDAR data for solar potential estimation. In addition, some evolutionary approaches have also been applied in the optimal design of solar building models based on LiDAR data [10,23].

Although previous research has paid extensive attention to evaluation of the solar energy potential over building surfaces, LiDAR-based procedures are more suited to existing buildings. However, for investors, potential energy investments may benefit from assessment measures of solar potential according to future urban planning. Moreover, rapid development and wide use of solar energies in urban areas more necessitate accurate measurements of solar resources, which means that higher resolution photography (or image) is an essential prerequisite in order to demonstrate the distribution of solar potential over building surfaces and provide accurate statistical analysis. Therefore, this paper establishes a pixel-based methodology for estimating solar energy potential. Based on digital image processing using MATLAB, the method allows for estimation of solar potential yields on rooftops (not only limited to building roofs) over a specific period by formulating solar irradiances in pixel unit. The method is here applied to flat roofs of buildings from future urban planning, in which GIS and SketchUp are used for terrain description and shadowing effects respectively. Statistical analysis and potential distribution with centimetre-level accuracy aim to promote assessment measures and indicate suitable regions for installing solar devices over roofs. The proposed method is detailed in the next section.

2. A pixel-based method for solar radiation estimation

2.1. Solar radiation estimation algorithm

In this paper, the basic algorithm of solar radiation estimation is implemented in terms of the approach presented by Kumar, Skidmore and Knowles [24]. Corresponding solar declination δ, hour angle h and altitude angle α can be then obtained and used to describe the Sun's position in the sky. The solar flux I_o (W/m^2) can be expressed as:

$$I_o = S_o\left[1 + 0.0344\cos\left(360^\circ N/365\right)\right] \tag{1}$$

in which N is the number of days of the actual date since 01 January and the solar constant S_o is set as 1367 W/m^2. The optical air mass M, the atmospheric transmittance for direct radiation τ_b and diffuse radiation τ_d can be written in Eqs. (2), (3) and (4), respectively.

$$M = \left[1229 + (614\sin\alpha)^2\right]^{0.5} - 614\sin\ \alpha \tag{2}$$

$$\tau_b = 0.56\left(e^{-0.65M} + e^{-0.095M}\right) \tag{3}$$

$$\tau_d = 0.271 - 0.294 \times \tau_b \tag{4}$$

Direct solar radiation I_b can be formulated as Eq. (5) when the Sun's rays are striking the surface whose normal makes an angle θ with the direction to the Sun. θ relies mainly on spatial factors, such as the slope and aspect of the surface, and temporal factors, such as the solar azimuth and altitude. η denotes the location-based sunshine percentage that aims to consider the probability of a cloudy sky. Diffuse solar radiation I_d can be expressed as Eq. (6) for the surface with the tilt angle β.

$$I_b = \eta \times I_o \times \tau_b \times \cos\ \theta \tag{5}$$

$$I_d = I_o \times \tau_d \times \cos^2\beta/2\sin\ \alpha \tag{6}$$

When solar radiation strikes a particular site, the total radiation is equal to the sum of the direct and diffuse solar irradiances for an unshaded spot. On the contrary, the total radiation excludes direct solar radiation if the spot is in shadow. This is because, unlike the diffuse radiation, the direct radiation cannot reach a shaded spot.

Shadowing effects at any moment can be illustrated by an image, in which all regions are equally discretised by pixels. As shown in Fig. 1, the left picture demonstrates a 3D shading model for an apartment building. The right picture depicts a shadow map of the building from a top view, in which dark pixels mean shaded spots. For a shadow map at a time point, the pixel value of the greyscale image V_{pixel} is a single number that represents the brightness of the pixel. The most common pixel format is the byte image, in which this number is stored as an 8-bit integer that ranges from 0 to 255.

In this research, the pixel value between 0 and 250 is taken to be a shaded cell in a shadow map, if 250 is selected as a threshold value. From 250 to 255 is considered an unshaded cell. The area for each cell A_{cell} is used to indicate the actual area in a map that a pixel represents in an image. The actual area represented by a pixel will be increased by $1/\cos\beta$ times once a surface is inclined with the tilt angle β. Therefore, the Nth day daily solar radiation yield for the pixel cell located in the ith row and jth column $E^N_{cell_{i,j}}$ can be