Journal of Cleaner Production 182 (2018) 177–186

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Revenue assessment and visualisation of photovoltaic projects on building envelopes

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ARTICLE INFO

Article history:
Available online 3 February 2018

Keywords:
Net present value
Building simulation
Solar energy assessment
3D visualisation
Photovoltaic projects

ABSTRACT

Increased environmental and economic awareness, coupled with local government incentives, means that solar energy applications in buildings are crucial to sustainable urban development and commercial energy investment. Considering the large available areas on building rooftops and walls, and the application of building-integrated photovoltaic products, previous research has paid extensive attention to solar radiation estimation for roofs and vertical walls. This paper proposes a developed pixel method integrated with Net Present Value (NPV) analysis and applies the measurement to 3D visualisation of the revenue distribution of potential PV projects on building surfaces, including vertical and non-vertical facades. A building model derived from a real student accommodation building is then chosen as a case study in this paper. The developed algorithm extracts data built in SketchUp, exports instantaneous shadow images and estimates solar energy potential over building surfaces for each pixel unit. Coloured 3D radiation maps illustrate the distribution of solar energy potential on roofs and facades. 3D contour lines with NPVs are introduced to visually conduct PV installation strategies with desirable revenues over project lifetimes. The results reveal that facade installation is also worthwhile, as the corresponding project revenues are competitive with rooftop installation during specific periods. This study will benefit designers and construction managers in determining the optimal solution for implementing solar rooftop and facade systems in the design and construction phases.

1. Introduction

Solar energy is considered the most significant renewable-based replacement for fossil fuels, since it is environmentally and economically friendly, being clean, free and unlimited (Perea-Moreno et al., 2017). It can be directly applied to energy consumption through solar photovoltaic (PV) technologies, which aim to absorb solar radiation and generate electricity directly using PV cells. Therefore, construction of solar PV projects has the potential to deliver economic and environmental benefits to householders, businesses and sustainable urban development. In 2016, the global installed solar PV capacity reached nearly 300 GW with over US$113 billion invested in solar energy technologies. PV capacity is projected to reach around 2000 GW by 2030 (International Renewable Energy Agency, 2017).

In urban areas, building roofs are traditionally considered suitable places to install solar collectors (Lukač et al., 2014; Szabó et al., 2016). However, a common issue is that building roofs do not always have the available free space appropriate for constructing PV projects. Furthermore, facade installation is also worthwhile owing to the large available areas on walls, increases in heat insulation and the application of building-integrated PV products (Redweik et al., 2013; Ghazali et al., 2017). Thus, seeking optimum construction sites on building envelopes, including facades, and identifying optimum design strategies are crucial to achieving desirable economic returns from potential PV projects their lifetimes. Moreover, researchers and engineers have been devoting extensive effort to measuring solar energy potential on building roofs (Lukač et al., 2014; Horváth et al., 2016). However, assessing and visualising the potential revenue of PV projects are more beneficial for designers and construction managers in order to determine the optimal solution for implementing rooftop and facade PV systems in the design and construction phases. It is, therefore, worthwhile to explore a method for evaluating the project revenue of installing PV systems and visualising their revenue distribution over building envelopes, including roofs and facades, to promote efficient use of capital and satisfy as much urban energy demand as possible.

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https://doi.org/10.1016/j.jclepro.2018.01.128
0959-6526/

2. Solar radiation estimation for building envelopes

An important step in assessing and visualising the revenue distribution for constructing PV projects on building envelopes is to evaluate the solar energy potential on building roofs and facades, as the operational income of a PV system is derived mainly from the amount of electricity generated by converting solar radiation. So far, various models and technologies have been explored and developed by researchers for radiation estimation over given building surfaces (Ascione et al., 2010), especially Light Detection and Ranging (LiDAR) based approaches and 3D model methods.

Relatively more research has paid attention to LiDAR mapping for measuring solar energy potential. In 2005, Voegtle et al. (2005) analysed the solar energy potential on extracted roof planes in an urban environment. In 2013, a solar radiation method proposed by Redweik et al. (2013) adopted the *r.sun* radiation model constructed by Šúri et al. (2007) and incorporated this in the open-source GRASS GIS (Neteler and Mitasova, 2008). The study demonstrated that the solar potential of building facades is often lower than that of roofs. However, facade installation can be regarded as a good way to supplement existing rooftop arrays, achieve sustainable construction and improve the energy performances of buildings in practice, as shown in Fig. 1.

Recently, to estimate solar energy potential, many methods developed have also used LiDAR data. For example, the urban topography extracted from LiDAR data was integrated to a pyranometer measurement (Lukač et al., 2013). ESRI's Solar Analyst Toolbox was linked with LiDAR data (Kodysh et al., 2013). Building models were created through a drone-based LiDAR survey (Szabó et al., 2016). Martínez-Rubio et al. (2016) presented LiDAR-related technology for evaluating solar irradiance over vertical facades in building cities. The area of projected shadow on building facades was considered a significant factor influencing solar energy conversion (Rocha et al., 2016). Overall, this widely used data acquisition technology adopts airborne LiDAR surveys to make height data accessible and allows for the rapid reconstruction of terrain surfaces (Agugiaro et al., 2011).

However, a LiDAR-based procedure starts with data collection through aerial detection, usually constructing a continuous Digital Surface Model (DSM) with a raster size ranging from 0.3 m to 1 m (Redweik et al., 2013; Catita et al., 2014; Lukač et al., 2014). Thus, LiDAR-based procedures are more suited to existing buildings, limited to relatively simple structures and restricted to data availability for many energy investors. In addition, the technology measures the reflected pulses with a sensor. Pulses are not always reflected properly from wet, non-reflective or complex building surfaces, but the complexity of roofs and facades is the dominant determinant of solar energy potential (Li et al., 2015).

Many researchers consider that 3D building models facilitate the assessment and visualisation of PV potential on building surfaces. They suit more building types (Hofierka and Zlocha, 2012).

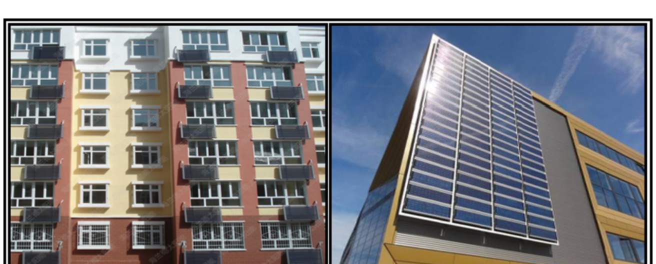

Fig. 1. Solar hot water collectors and photovoltaic panels on building facades.

Inspired by a combined vector–voxel solar radiation model, Liang et al. (2014) computed solar potential building models through a method in which 3D vector objects were all segmented into polygonal elements using a voxel-intersecting rule and 3D meshes were discretised into a set of 2D raster cells. Yet the authors considered that the voxel-based shadow-casting technologies were not sufficiently sensitive to geometric complexity. Void spaces inside building models greatly affect geometric property identification and calculation results during some voxel-based procedures. Thus, previously constructed models usually oversimplify the complex topographic features of building roofs. Recently, a pixel-based approach was applied to estimate the solar energy potential on building roofs (Li et al., 2016). This measurement has the capability to achieve higher resolution photography, as the complexity of buildings can be effectively preserved, features of building surfaces can be observed closely and image properties can be easily controlled by research programmers for outputting the required images. Moreover, the approach can be easily integrated with economic models.

Next, it is essential to combine the solar energy estimation with the economic analysis of PV systems to evaluate the project revenue from installing PV systems on building envelopes. In particular, the economic indicator Net Present Value (NPV) is capable of estimating the difference between the present value of future cash flows from an investment and the amount of the investment (Miller et al., 2011). NPV also includes the cost breakdown of a project. For example, costs for a solar PV system can be categorised as capital costs and future costs in order to quantify the projected costs incurred during its lifetime. Capital costs include the installation cost and the purchasing cost of system components that are incurred prior to the occupation of the facility. Future costs are the forthcoming expenditures projected from the operational and decommissioning phases (Jakhrani et al., 2012). However, deconstruction and disposal of PV systems are not often taken into account, since such systems are still running within their lifetimes in many countries (Kannan et al., 2006; Hou et al., 2016).

In 2014, Ioannou et al. (2014) presented a model that combined PV energy production and an NPV index. To identify the investment efficiencies of PV projects, the authors sketched several contour lines of annually produced solar energy for outlining a feasible installation area. Results demonstrated that optimal PV systems were potentially different from optimal strategies for maximising energy. From two economic perspectives, those of the NPV and Savings to Investment Ratio (SIR) over 25 years, Jeong et al. (2015) tested 12 PV installation scenarios to achieve optimal strategies for implementing a rooftop PV system on the gable roof of a military facility. In 2017, Ban et al. (2017) took advantage of the RETScreen software program to estimate energy production. In terms of NPV and SIR, the installation scenarios of PV systems were further summarised in seeking optimal construction strategies on a gable roof. However, visualising the revenue distribution of constructing PV projects on buildings further facilitates optimal design and construction.

This paper further develops the pixel-based method by integrating it with NPV analysis and applies the measurement to 3D visualisation of the revenue distribution of potential PV projects on building surfaces, including roofs and facades. In particular, contour lines with NPVs are introduced to visually conduct PV installation strategies with desirable project revenues over project lifetimes. Building models are firstly constructed on the SketchUp platform. The Ruby application programming interface is then used to output the Sun position data built in SketchUp and to export digital images regarding instantaneous shadow situations. The total solar radiation yields over building roofs and facades can be calculated through formulating the exported data in pixel units and