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ScienceDirect

Solar Energy 115 (2015) 369–378

SOLAR ENERGY

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Solar energy on building envelopes – 3D modelling in a 2D environment

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Received 7 May 2014; received in revised form 20 February 2015; accepted 1 March 2015
Available online 25 March 2015

Communicated by: Associate Editor David Renne

Abstract

A new model, Solar Energy on Building Envelopes (SEBE) for estimating shortwave irradiance on ground, roofs and building walls is presented. SEBE adopts a 2D raster modelling approach to derive 3D irradiance information, which makes it possible to compute extensive areas up to city scale. High resolution digital surface models (DSMs) are used to describe the urban geometry and additional DSMs including 3D vegetation structures can also be incorporated. Inclusion of vegetation is shown to be essential when modelling irradiances for wall surfaces within the urban environment. To obtain a detailed description of input forcing conditions, the model utilizes observed hourly data of shortwave radiation as meteorological input information. The model is evaluated for a tilted roof as well as for a wall location in Göteborg, Sweden. The overall performance of the model is high, both for the roof and wall evaluation point. Application of the model is exemplified by 3D visualisation and city scale model output presentation.

Keywords: GIS; Raster modelling; Vegetation; Sweden

1. Introduction

Solar energy is projected to increase in importance as a global energy source. In such a scenario, electricity from photo voltaic (PV) systems will be important due to increasing performance, decreasing production costs, and increasing costs for electricity from other energy sources. Solar energy also holds a position as a democratic energy source, available for anyone to explore and utilise. Owners of buildings (residential, industrial, tenement) possess solar energy re-sources that usually are unexplored, namely their surfaces. These surfaces might be directed towards the sun in a favourable angle, while obstructed by neighbouring houses and vegetation. Altogether, it is likely that roofs in built-up areas are more or less suitable for PV installation (Wiginton et al., 2010).

Deriving solar energy potential for roof tops as well as solar radiation within urban areas in general, a number of GIS-based tools have been developed (e.g. Fu and Rich, 2002; Lindberg et al., 2008; Šúri et al., 2007). Such applications make use of high-resolution digital surface models (DSMs) derived from LiDAR data (Yu et al., 2009) or other geodata e.g. CAD-based information regarding roof structures within a city (Lindberg, 2007). The GIS-based approaches mentioned above have the ability to estimate solar radiation for extensive areas due to the efficiency using 2.5D raster-based calculation techniques. Recent 2.5D model developments by Redweik et al. (2013) also include estimations of wall irradiances. Their model (SOL) calculates, for each separate hour, diffuse and direct irradiances on ground, roofs and walls on a high

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http://dx.doi.org/10.1016/j.solener.2015.03.001
0038-092X/

resolution DSM. Other vector-based methods for estimating solar radiation also exist (Montero et al., 2009; Teller and Azar, 2001). The high accuracy that could be achieved using vector-based method makes them highly suitable for examining smaller areas, e.g. building to neighbourhood scale. However, including the level of detail necessary for deriving solar radiation fluxes in an extensive (e.g. city scale) and complex urban environment, the relatively high computation cost using vector-based methods makes raster-based approaches more suitable for large scale applications. Most of the models mentioned above, estimates sky irradiance based on clear-sky situations and clearness estimations. Other approaches would be to use observations of solar radiation in order to improve the accuracy when estimating the surface irradiance.

The performance of building integrated photovoltaics on roofs as well as walls is getting more enhanced (Norton et al., 2011). In high latitude cities, the potential use of wall integrated solar energy devises is high due to the relatively low Sun altitude throughout the year. Therefore, the need to develop accurate and simple methods for estimating solar irradiance on wall surfaces for extensive areas is needed.

In this paper, the development of a new 2D solar radiation model, SEBE (Solar Energy on Building Structures), which simulates solar radiation on building roofs and walls, is presented. SEBE makes use of observed solar radiation data with the purpose of deriving highly accurate irradiances for the surfaces modelled. The first part of the paper presents the features of SEBE (version 2014a) followed by an evaluation of the model using solar radiation measurements in Göteborg, Sweden. Finally, applicable examples are presented.

2. Model structure

SEBE is classified as a 2.5-dimensional model and make use of digital surface models (DSMs) to calculate solar radiation. The main DSM consists of building and ground heights. Two optional DSMs of the same resolution and extent as the ground and building DSM can be used to represent 3D vegetation of trees and bushes. The two vegetation DSMs account for the canopy height and for the trunk zone height, respectively. For the vegetation pixels, the canopy DSM (CDSM) represent the height of bushes and/or trees (meter over ground), whereas the trunk zone DEM represent the height of the base of the canopy (see Lindberg and Grimmond, 2011a, their Fig. 2). Thus, each tree has its own shape which is dependent on the spatial resolution of the DSMs. Where no 3D vegetation is present, pixels are set to zero. The model is currently executed in Mathworks®Matlab, (version 2012a).

2.1. Generation of shadow pattern

Essential for estimating solar radiation in urban areas is the ability to generate accurate shadow patterns from buildings and vegetation as well as ground topography within the model domain. To cast a shadow, the altitude and azimuth of a distant light source (the Sun) are specified. Following Ratti and Richens (1999), 'shadow volumes' are computed by sequentially moving the raster DSM at the azimuth angle of the Sun, reducing the height at each iteration based on sun elevation angle. For each iteration a part of the shadow volume is derived and by taking the maximum of this volume, the whole shadow volume is built up. This shadow volume is stored as a new digital terrain model (DTM). The 2D map of shadows is determined by subtracting the shadow volume DTM from the original DSM. A Boolean image is produced, with pixels that are $\leqslant 0$ are in sunlight (new value = 1), and positive values are in shade (new value = 0). For a detailed description of the shadow casting algorithm, see Ratti and Richens (2004) and Lindberg and Grimmond (2010).

When shadow patterns from full 3-D objects (e.g. vegetation units) are created, further developments of the original shadow casting algorithm has been made (Lindberg and Grimmond, 2011a). This new algorithm used to generate a separate 'shadow volume' DSM for vegetation units only. In SEBE, the shadow volumes of both the vegetation canopy and the trunk zone DSM (volume underneath the tree canopy) are moving simultaneously based on the position of the Sun. For each iteration, a part of the shadow volume is created only where the pixels in the moving canopy DSM is above the stationary ground and building DSM or stationary canopy DSM at the same time as the moving trunk zone pixels are below. The shadow pattern developed, accounts for the area underneath the vegetation which does not cast a shadow. The importance of the trunk zone varies with the Sun's angle. At low Sun altitudes, ignoring the trunk zone would introduce a large bias. As the trunk zones areas are used in urban outdoor activities, it is important that these are explicitly included in the model. Low Sun altitudes are important at high latitudes in terms of solar access and energy applications.

To derive sunlit fractions on walls, a modified version of the shadow casting algorithm is used. The algorithm is relatively straightforward to obtain the height of the shadow when it hits a building wall using an ordinary edge detecting filter to identify wall pixels. Note that a wall section is considered to be shadowed if the sun beam falls oblique to that section. This is determined by computing an aspect grid from all wall pixels and comparing it with Sun azimuth. One important factor in deriving accurate sunlit factions on walls is the spatial resolution of the DSM used. A coarse resolution DSM introduces biased results as walls could be offset by the pixel resolution of the DSM. Therefore, the wall sunlit fraction should only be derived using a relatively high resolution DSM. In the current version, only vertical walls can be analysed. Walls with more complex geometries such as overhanging façades and balconies are not included.