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Computational derivation of irradiance on building surfaces: An empirically-based model comparison

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ABSTRACT

Performance simulation applications require reliable information regarding the intensity of solar irradiance on arbitrarily oriented building surfaces in order to properly predict buildings' energy use or to configure building-integrated solar energy systems. Since measured irradiance databases typically include only horizontal irradiance values, solar radiation intensity on inclined surfaces must be computationally derived. In this context, the present paper compares six options to derive, from horizontal irradiance data, solar radiation intensity levels on inclined surfaces. To evaluate these options, simulated downward vertical irradiance on four orientations were compared with measurements obtained in Austria. Two options that use both global and diffuse horizontal irradiance values for sky radiance generation delivered slightly better results than the others, which require only global horizontal irradiance. However, the range of errors was rather high for all options. Even for the best-ranked option, no more than 64% of the results had a relative error of less than ±20%.

1. Introduction

Incident solar radiation on building surfaces is a crucial input information required in the simulation of buildings' energy use. Moreover, configuration and sizing of solar energy systems (e.g. photovoltaic cells, solar-thermal collectors) necessitates reliable data on incident solar radiation. However, only for relatively few locations detailed measured data concerning incident solar radiation on vertical or inclined surfaces are available. Concurrent measurements of horizontal global and horizontal diffuse (or direct normal) irradiance data are likewise available only for a limited number of locations. In contrast, the measurement of global horizontal irradiance is rather simple and cost-effective. It can be, conceivably, an integral part of the sensory equipment of every building. Thus, given appropriate computational procedures, incident irradiance values on vertical or inclined building surfaces could be computationally derived from measured global irradiance levels in a manner both reliable and convenient. Given this context, the present paper compares a number of options to compute incident irradiance values on building surfaces based on measured global (and – for certain options – diffuse) horizontal irradiance. The performance of the models is compared using a database of measured irradiance levels on vertical surfaces.

In the past, a number of studies have addressed the derivation of solar irradiance on inclined surfaces from corresponding horizontal irradiance data. This requires, in general, the availability of detailed information on the magnitude of diffuse and direct horizontal irradiance. A number of diffuse fraction models are available as documented in Refs. [1–6]. These models are usually expressed in terms of polynomial functions relating the diffuse fraction k_d (ratio of the diffuse-to-global solar radiation) to the clearness index k_t (ratio of the global-to-extraterrestrial solar radiation) as well as to other variables such as solar altitude, air temperature and relative humidity. Diffuse fraction models have been explored by various authors [7–11], some of them suggesting that the Refs. [4,6] provide somewhat better results.

Different models are used for the calculation of incident solar radiation on an inclined surface. The simplest model may be the isotropic model [1], which assumes that all diffuse radiation is distributed uniformly over the sky dome. In case of anisotropic models (e.g. [12–17]), the diffuse radiation is composed of a circumsolar region, an isotropic part uniformly emitted from the rest of the sky, and a diffuse component coming from the horizon

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brightness (mostly pronounced on clear days). Refs. [18,8,19] evaluated various mathematical models to predict global solar radiation on vertical surfaces. These studies have indicated that the Perez model delivers better predictions for all orientations. Notton et al. [20] tested 15 models to predict the global solar radiation for south-facing planes tilted at 45° and 60°. Gueymard [21] compared measurements of the global solar radiation on south facing planes (40° tilted and vertical) with corresponding calculations using 10 different models. Loutzenhiser et al. [22] investigated seven solar radiation models for the computation of solar radiation on tilted surfaces (on a facade oriented 29° West of South) implemented in building energy simulation codes. Padovan and Del Col [11] compared different models for the prediction of the irradiance on south-oriented planes tilted at 20° and 30° and on east-oriented planes inclined of 45° and 65°. However, it has to be stated that some of these studies were based on a limited set of data and surface orientations ([22,11]). Moreover, the mentioned studies mostly did not involve the direct use of measured diffuse irradiance (in addition to global irradiance measurements) as input for computation. This is, however, important, if the role of corresponding errors (estimation of the diffuse fraction) in the reliability of the end results (global irradiance on non-horizontal surfaces) is to be investigated.

As a further contribution to this research area, the present work focuses on the comparison of alternative methods to derive from horizontal irradiance data, solar radiation intensity levels on vertical surfaces based on an extensive database of measured global and diffuse horizontal irradiance data obtained in Vienna, Austria.

2. Method

First, different options were considered for the generation of sky radiance distribution maps. Such maps can be used to predict incident irradiance on arbitrarily surfaces. However, for the purpose of the present contribution, these maps were applied to predict irradiance on vertical surfaces. The predicted vertical irradiance values were then compared with corresponding measurements.

2.1. Options to derive vertical solar irradiance

To computationally derive vertical irradiance values, six options were considered (see Table 1).

The first option (ME-EP) involves the use of the measured horizontal diffuse and global irradiance values. Using this information, the horizontal direct irradiance can be derived. With the values of horizontal direct and diffuse irradiance as input, the EnergyPlus application Version 6 [23] was applied to generate detailed sky radiance distribution maps. For this purpose, EnergyPlus uses the Perez sky model [17]. This model requires, as input, the direct normal and the horizontal diffuse irradiance. The former was calculated based on measured values of the direct horizontal irradiance using standard trigonometric functions and the sun position. The sky radiance maps were then further processed in EnergyPlus to derive vertical irradiance values. The simulation tool EnergyPlus was tested with a number of industry standard methods such as ANSI/ASHRAE Standard 140-2011, and ASHRAE 1052-RP Toolkit. Toward this end, also results of incident solar radiation on south and east facing facades were taking into consideration, which compared very well to the analytical results [24].

Table 1
Overview of the six options: MEasured-EnergyPlus (ME-EP), MEasured-RAdiance (ME-RA), PErez-EnergyPlus (PE-EP), REindl-EnergyPlus (RE-EP), PErez-RAdiance (PE-RA), REindl-RAdiance (RE-RA).

Option	Utilized measured (horizontal irradiance) values	Derivation of direct and diffuse components	Simulation application
ME-EP	Global and diffuse	–	EnergyPlus
ME-RA	Global and diffuse	–	RADIANCE
PE-EP	Global	Perez et al., 1991	EnergyPlus
RE-EP	Global	Reindl et al., 1990a	EnergyPlus
PE-RA	Global	Perez et al., 1991	RADIANCE
RE-RA	Global	Reindl et al., 1990a	RADIANCE

The second option (ME-RA) is similar to the first option. However, in this case, the Radiance simulation program Version 4.1 [25] was used to generate the sky radiance distribution maps. It is a highly accurate ray-tracing software system, which includes over 50 tools. Radiance program is a suite of programs for the analysis and visualization of lighting in design. Input files specify the scene geometry, materials, luminaires, time, date and sky conditions (for daylight calculations). Calculated values include spectral radiance (ie. luminance + color), irradiance (illuminance + color) and glare indices [25]. Vertical irradiance values were also computed via RADIANCE. Radiance has been rigorously validated and proven to be highly accurate [26,27].

The third option (PE-EP) is also similar to the first option. However, in this case, only measured horizontal global irradiance values are used as the starting point. From this information, the corresponding diffuse radiation components were derived using Perez et al. [6] global to direct irradiance conversion algorithm (see Equation (1)). This algorithm, which is a modified version of the Maxwell model [28], was developed using a dataset composed of hourly measurements from stations located in the US and Europe. The direct irradiance I_b is obtained from:

$$I_b = I_{bDisc} * X\left(K_t', Z, W, \Delta K_t'\right) \tag{1}$$

Here, I_{bDisc} is the estimated direct horizontal irradiance (a function of global irradiance and solar zenith angle) and $X(K_t', Z, W, \Delta K_t')$ is a coefficient whose value depends on four factors, namely solar zenith angle Z, normalized clearness index K_t' [29], stability index $\Delta K_t'$, and precipitable water content W estimated from surface dew point temperature [30]. These dimensions are obtained from a look-up matrix.

The fourth option (RE-EP) is similar to the third option. However, in this case, the Reindl et al. [4] algorithm was used to derive the corresponding diffuse radiation components. This algorithm estimates diffuse fraction k_d based on measured global and diffuse horizontal irradiance data from 5 locations in the USA and Europe. The algorithm considers the following parameters: clearness index k_t, sun altitude α, outdoor air temperature T_a, and the relative humidity ϕ. Reindl et al. [4] identified three characteristic intervals for clearness index, defined as the ratio of global horizontal to extraterrestrial radiation. Depending on clearness index value, the diffuse fractions (I_d/I) are calculated as per Equations (2)–(4).

Interval: $0 \le k_t \le 0.3$

$$k_d = 1.0 - 0.232k_t + 0.0239 \sin\alpha - 0.000682T_a + 0.019\phi \tag{2}$$

Interval: $0.3 < k_t \le 0.78$

$$k_d = 1.329 - 1.716k_t + 0.267 \sin\alpha - 0.00357T_a + 0.106\phi \tag{3}$$

Interval: $k_t \ge 0.78$

$$k_d = 0.426k_t + 0.256 \sin\alpha - 0.00349T_a + 0.0734\phi \tag{4}$$

where