Prediction of vertical irradiance on building surfaces: an empirical comparison of two models

Ehsan Vazifeh – Vienna University of Technology, Austria – ehsan.mahmoudzadehvazifeh@tuwien.ac.at
Matthias Schuss – Vienna University of Technology, Austria – matthias.schuss@tuwien.ac.at
Ardeshir Mahdavi – Vienna University of Technology, Austria – bpi@tuwien.ac.at

Abstract

Computational assessment of buildings' thermal and visual performance as well as the estimation of building-integrated solar-thermal and photovoltaic collectors require detailed boundary condition information regarding sky conditions. Advanced building performance simulation tools for energy and daylight modelling typically rely on high-resolution sky models that provide radiance and luminance values of discrete sky patches. Perez et al. (1993) and CIE (1996) represent instances of such models, incorporated, for instance, in the RADIANCE lighting simulation application. The performance of such models needs to be examined against measured data in various locations. In this paper, we used the RADIANCE application to compute irradiance values on vertical surfaces facing four cardinal for a location in Vienna, Austria. Thereby, both Perez et al. and CIE models were deployed. The simulated vertical irradiance values were compared with corresponding measurement results. The statistical appraisal of the comparison points to limits in the predictive accuracy of both models. The results are discussed to address potential contributing factors and future research needs.

1. Introduction

Deployment of performance simulation in building design and control phase is believed to have the potential to enhance the buildings' performance in their life cycle. This requires reliable input data for simulation models. Specifically, obtaining high-resolution solar radiation data can represent a challenge. Consequently, a number of models have been developed to compute radiance/luminance data for arbitrary patches of the sky dome (Nakamura et al. 1985, Perez et al. 1991, Brunger and Hooper 1993, Igawa et al. 1997, Kittler et al. 1997, Kittler et al 1998, Darula and Kittler 2002, Mahdavi and Dervishi 2013). Among these models, two (CIE 1996 and Perez et al. 1993) are well-known and applied in RADIANCE application (Ward 1994). This paper reports on the comparison of simulated vertical irradiance values (obtained using the above mentioned sky models incorporated in the RADIANCE application) with corresponding measurements (April to November 2014) for the location Vienna, Austria (48N11’54”, 16E22’10”).

2. Methods

2.1 Models

Combining physical principles and a large set of experimental data, Perez et al. 1993 introduced a model to predict the sky luminance for discrete sky patches. Basically, the model contains two variables and five coefficients (See equation 1). The variables are zenith angle of the considered sky point and angular distance between the sky point and the sun disk. The coefficients resulted from least square fitting of the data and can be obtained from a table.

$$L_r = \left[1 + ae^{\frac{b}{\cos z}}\right] \times \left[1 + ce^{d\xi} + e\cos^2\xi\right] \qquad (1)$$

Here, ξ is the angular distance between the sky element and the sun disk, z is the zenith angle of considered sky element and *a, b, c, d,* and *e* are the mentioned coefficients. In order to select from the table the values of the five coefficients, two variables, namely, sky brightness (Δ) and sky clearness (ϵ) must be calculated (See equation 2, 3).

$$\epsilon = \frac{\left[\frac{I_{h.dif} + I_{n.dir}}{I_{h.dif}} + 1.041 z_s^3\right]}{1 + 1.041 z_s^3} \quad (2)$$

$$\Delta = \frac{m_{air} \times I_{h.dif}}{I_{n.ext}} \quad (3)$$

Here, $I_{h.dif}$ is horizontal diffuse irradiance, $I_{n.dir}$ normal direct irradiance, z_s solar zenith angle, m_{air} optical air mass, and $I_{n.ext}$ is the extraterrestrial normal irradiance. $I_{n.dir}$ is generated based on the Perez et al. global to direct conversion model (1991).

To deploy the currently implemented version of the CIE model in RADIANCE, we made use of the option to assign specific values to the tool's pertinent parameter in accordance with the relevant sky category. Toward this end, we considered the following four categories: clear, intermediate without sun, intermediate with sun, and overcast. In order to map our weather station data into these four categories, we used a simple assignment rule based on the magnitude of the direct normal and diffuse horizontal irradiance components (see table 1).

Table 1 – Categorization of CIE skies in the model

$I_{n.dir}$	$I_{h.dif}$	Column 3
>=120	<130	Clear sky
>=120	>=130	Intermediate sky without sun
<120	<100	Overcast sky
<120	>=100	Intermediate sky with sun

2.2 Data

Department of Building Physics and Building Ecology at Vienna University of Technology is equipped with high-resolution microclimatic monitoring station. This station is located at the roof top of the main building of the university, which is situated in the Vienna city centre. To assess the performance of the models in capturing the sky radiance distribution, we used measured irradiance data incident on the aforementioned four vertical surfaces. Moreover, measured horizontal global (or direct normal) and diffuse irradiance data was used as input for CIE and Perez et al. models to generate the sky radiance distributions. In the present contribution, we focus on the 15-minute interval data collected in the period between April and November 2014.

2.3 Comparison

The RADIANCE lighting simulation program (Ward 1994) was used. Perez et al. 1993 and CIE 1996 sky models are embedded in the RADIANCE program in terms of Gendaylit (Ward 2014a) and Gensky (Ward 2014b) routines. Simulation results (vertical irradiance values) using these two models were compared with corresponding measurement results. Toward this end, a number of statistical measures were used, namely, root mean square error (RMSE), r-square (R^2), relative error (RE), coefficient of variation of RMSE (CV_{RMSE}), and cumulative distribution function.

3. Results

Figure 1 entails the fisheye false colour images of the sky hemisphere based on both sky models and HDR camera for partly cloudy and clear sky instances. The images are taken in 5-minute intervals using a LMK 98-3 luminance camera equipped with neutral density filter. In the presence of the clear sky instance, Perez et al. model (Gendaylit) appears to be more realistic than CIE (Gensky). However, in the presence of the cloudy sky instance, none of the models appear to generate a faithful representation of reality. This circumstance could be attributed to the complexity of the radiance distribution under cloudy conditions.

To compare the calculated vertical irradiance values with the measured one, the aforementioned statistics were derived (Table 2). Figure 2 shows the cumulative distribution function and histogram based on relative errors (RE) in percentages for the four cardinal directions plus the horizontal plane. The Perez et al. model displays a slightly better performance. Model errors are largest for the north orientation (almost half of results based on the Perez et al. model display a relative error larger than 20%) and smallest for the south orientation (some 80% of the results based on the Perez et al. model show errors less than 20%). With regard to the horizontal irradiance, both models perform quite satisfactorily. However, this was expected, given the fact that measured irradiance data is already fed to the RADIANCE as input information. The respective small errors may be due to the adopted approach to categorization of skies (Table 1).

Table 2 – Statistical measures of models based on measurements for different directions

	Direction	RMSE	CV_{RMSE}	R^2
Perez	North	30.6	31.7	0.567
CIE		34.3	35	0.495
Perez	East	97.23	33.3	0.924
CIE		99.1	32.4	0.926
Perez	South	32.9	12.9	0.981
CIE		35.1	13.8	0.981
Perez	West	60.1	22.4	0.965
CIE		61.4	21.8	0.963
Perez	Horizontal	16.1	3.6	0.999
CIE		15.8	3.6	0.999

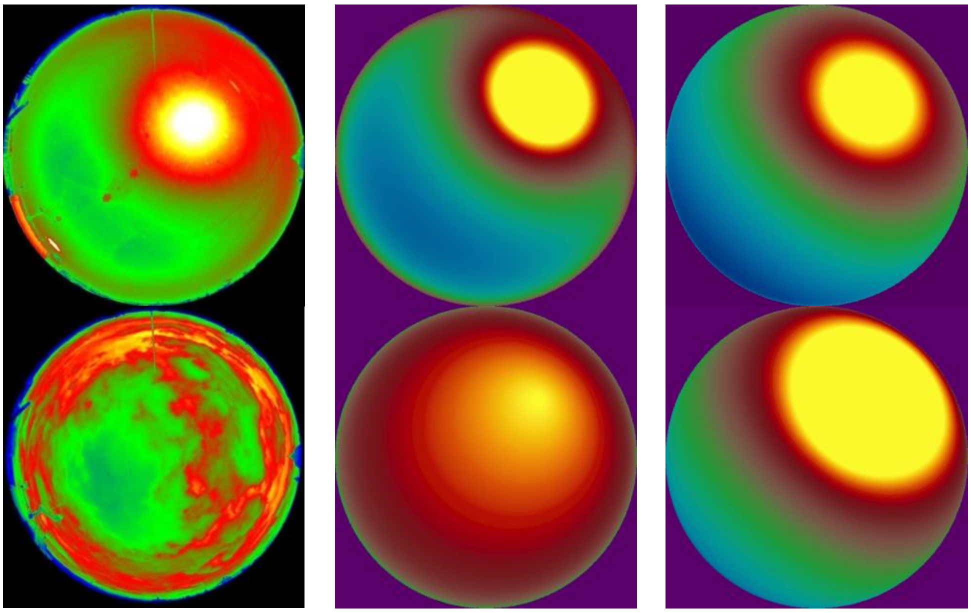

Fig. 1 – From left to right (HDR fisheye image, Gendaylit false color, Gensky false color), upper row: clear sky (4 July 2014 10:45 am local time), lower row: cloudy sky (10 July 2014 10:45 am local time)

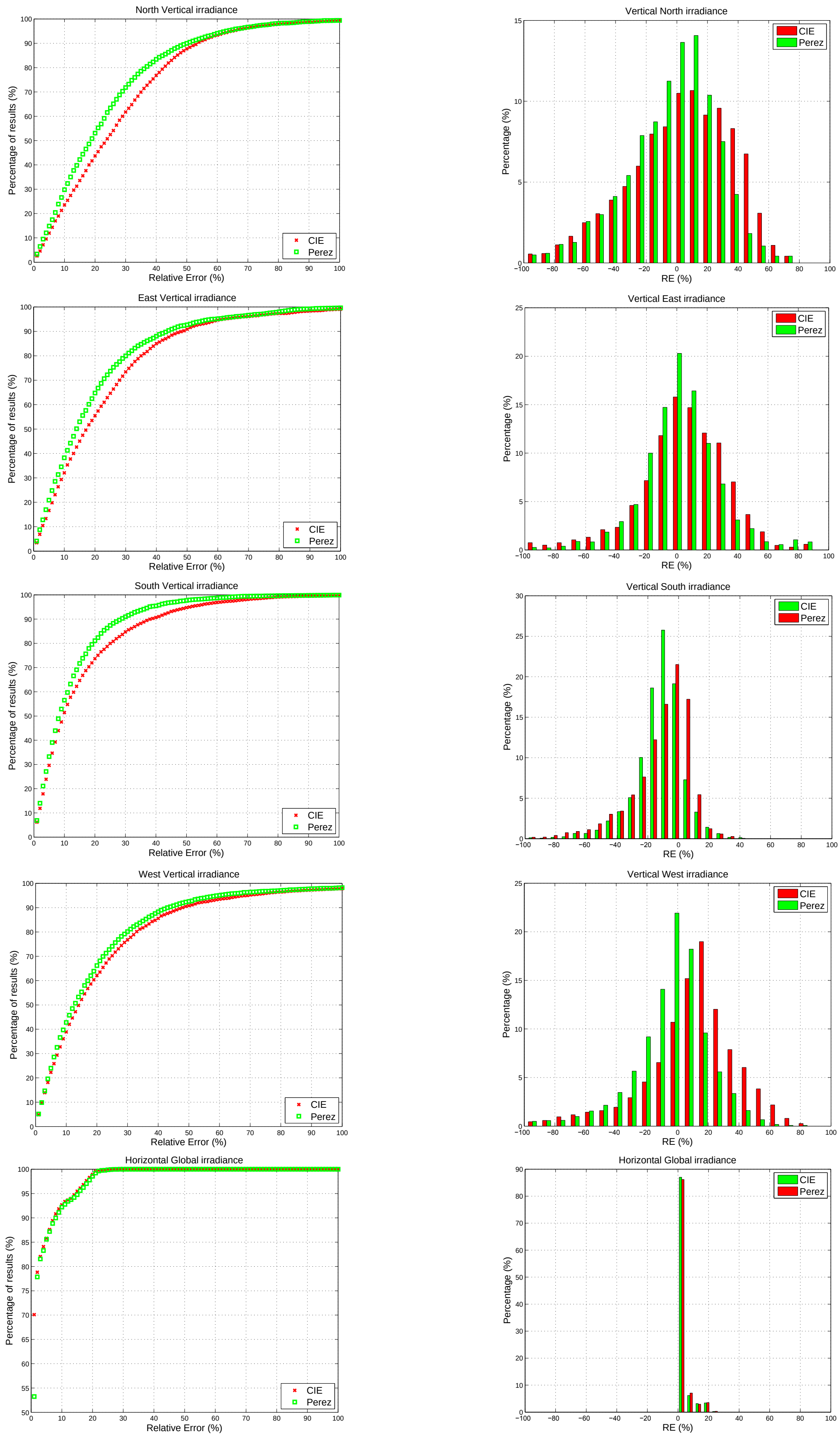

Fig. 2 – Comparison of CIE (Gensky) and Perez et al. (Gendaylit) sky models for vertical surfaces facing the four cardinal directions in terms of cumulative distribution functions (left) and distributions (right) of relative errors (location: Vienna, Austria)

4. Conclusion

Irradiance on four vertical surfaces was estimated using the RADIANCE application. Thereby, two embedded sky models (Perez et al., CIE) were deployed. The comparison of the computational results with corresponding measurements conducted in Vienna, suggests these sky models would have to be improved – or calibrated – to reproduce the measured data with sufficient accuracy. Future research will address a multi-location model comparison. Moreover, a more recent CIE sky model (Darula and Kittler 2002) involving the categorisation of sky conditions into 15 types will be considered for evaluation.

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6. Nomenclature

Symbols

Δ	sky brightness defined by Perez et al.(-)
ϵ	sky clearness defined by Perez et al.(-)
$I_{h.dif}$	horizontal diffuse irradiance (W/m²)
$I_{n.dir}$	normal direct irradiance (W/m²)
$I_{n.ext}$	normal extraterrestrial irradiance (W/m²)
L_r	Relative luminance (Perez et al.)
m_{air}	Optical air mass (-)
ξ	angular distance between the sky element and the sun disk (degrees)
z	zenith angle of considered sky element (degrees)
z_s	zenith angle of the Sun (degrees)

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