CHARACTERIZATION OF INDOOR PHOTOVOLTAIC DEVICES AND LIGHT

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ABSTRACT

Indoor photovoltaic (ipv) is a growing market area due to increasing numbers of wireless sensor node networks in green and intelligent buildings. The sensor nodes should be powered without batteries or wiring in order to reduce cost. One of the most promising sources of energy is light. Results of radiometric measurements depend on the test environment. However, the expected irradiance is essential for the dimensioning of the required module area and a reliable operation. Ipv designers therefore need a tool to determine irradiance values for their applications. This paper presents a simulation method for indoor irradiance combining different models of user presence, and the ray tracing programs Radiance and DAYSIM. The authors analyze a best case and a worst case scenario. Typical values of irradiance for these scenarios, the influence of the latitude and of the orientation, of the contribution of electric light in dependence of user presence, and the required complexity of a simulation model are discussed. Based on these studies, the authors provide expectable power densities for ipv devices.

Keywords - Indoor photovoltaic, ray tracing, characterization, low intensity, radiometric

I. INTRODUCTION

For the planning of an ipv system, the knowledge of the required module area based on the expected irradiance is essential for its feasibility [1]. Design failures due to wrong assumptions of the environment lead to lacking user acceptance and unsatisfying market introductions of ipv products.

While solar modules for outdoor conditions are a mature technology, there has been less research in the quality and quantity of light in indoor environments as well as in the behavior of solar modules under indoor conditions.
Indoor light conditions are typically based on an artificial light source with a spectral distribution optimized for the human visibility and intensities below 10 W/m². The characterization of solar modules under indoor conditions is far from standards concerning even the used light source with its spectral distribution and intensity.

Standard Test Conditions (STC) and IEC 60904-3, Ed. 2, respectively, are not practicable to characterize the performance of photovoltaic devices under low intensities [1], [2]. For ipv systems, studies on available indoor light have been presented by Randall [3], Roundy [4] and Roth et al. [5]. Randall and Roth provided measurements; Roundy performed first order estimations using standard values of office lighting and measurements made with a light bulb.
All these studies do not provide a solution to the variety of factors like user presence and behaviour or different places of installation. Investigated rooms have been simple, which for a room will not always be true in reality.
The available data are based on single measurements of specific places and mainly kept in photometric units. As a result, at the current state of available data and methods, users are forced to perform their own measurements for each application. Furthermore, measurements of low intensity light are complex, expensive, and are not transferable to other settings.

In this work, we present a method for a dynamic calculation of annual indoor light densities including both artificial and solar light and measurements for its detailed validation. The method is based on the ray tracing programs *DAYSIM [6]* and *Radiance [7].*
We investigated typical values of expectable indoor irradiance, the influence of the latitude and of the orientation, of the contribution of electric light in dependence of user presence, the required complexity of a simulation model and compared results to radiometric measurements. Methods and results are discussed in the following sections.

II. MATERIALS AND METHODS

The study investigated light in office buildings based on the ray tracing programs *Radiance* and *DAYSIM,* measurements and user models. First weather data for solar irradiation were obtained by the climate simulation program METEONORM based on real weather stations. Figure 1 gives a schematic overview of used simulation pathways, models, and measurement data.
The room models refer to two office rooms at the IMTEK in Freiburg, Germany. One office has a window orientated to the North, is permanently used by eight office workers and contains many objects (Figure 2). The second office is used by one person, has a south window and basic furniture containing two work desks and a cupboard.

Direct and diffuse solar irradiance and irradiance by artificial light were measured for five months for both rooms. The data obtained were used for validation and as input data for simulation models. The frequency of use of electric light was approximated by user presence models based on measurement data. Simulations have also been performed for Helsinki, Rom, Toronto, and Boston. The study refers to the northern hemisphere.

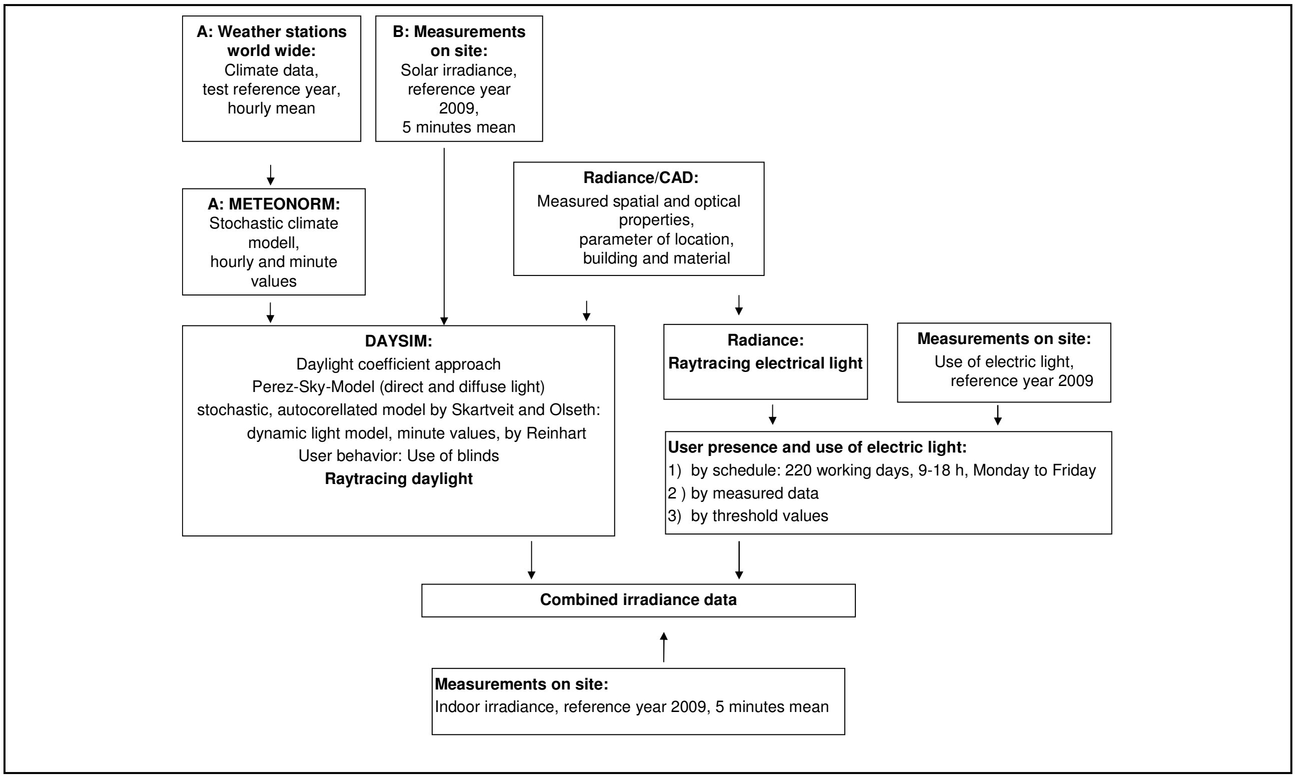

Figure 1. Simulation pathways, used models, and measurement data

A. *Simulations*

The electric light distribution was simulated with *Radiance*. *Radiance* is a validated backwards ray tracer which enables the calculating of both electric and natural light, and to model complex material properties.

The reflection parameters of the main room surfaces have been measured as described in [7] and implemented in the simulation. Table I compares the measured reflection coefficients with values recommended for lighting design calculations in the European standard EN 12464-1 [8].

TABLE I. COMPARISON OF USED REFLECTION COEFFICENTS TO RECOMMENDED VALUES FOR LIGHTING DESING CALCULATIONS IN EUROPEAN STANDARD EN 12464

Element	North office*	South office*	EN12464
Floor	0.24	0.23	0.1-0.5
Ceiling	0.7	0.7	0.6-0.9
Wall	0.85	0.84	0.3-0.8
Work desk	0.47	0.47	0.2-0.6

* Arithmetic mean values, measured as described in [7], n = 25.The coefficient for the ceiling has been assumed based on experience values.

The installed and simulated lighting in both offices is a fluorescent light tube with a daylight spectrum (OSRAM LUMILUX 58W/840, Cool White, 5200 Lumen). The lamp ballast factor of the luminaire is 0.64.

Also the index of transmittance *Tn* of each window has been measured. As a measured *Tn* already includes reflected rays within in the material, the index of transmissivity *tn* is required. The resulting index of transmissivity *tn* was calculated using an index of refraction *n* of 1.52 for glass and the reduced formula suggested in [7].

Due to a special gold coating, in comparison to common windows the north window has a very low index of transmissivity of 0.58 without respect to additional losses due to contamination or window-frames. Therefore, the real coefficient was only used for validating simulations being compared to measurements. For general considerations, a simple coefficient approach was used. The transmittance was assumed to be 75 per cent. Adding a loss of ten per cent due to contamination and 15 per cent due to window-frame shadings, gave an index of transmissivity of 0.63. This index was also mainly used for the south window with a real transmissivity coefficient of 0.67.

The daylight contribution was simulated with *DAYSIM,* using the same room models as in *Radiance*. *DAYSIM* is based on *Radiance,* and calculates daylight on a time step basis using the daylight coefficient method.

Data for the incoming solar light were based on measurement data from weather stations located at the simulated places, provided by a climate simulation program called *METEONORM*. A one-year on-site measurement of direct normal and diffuse horizontal solar irradiance has been installed for validation.

Three models were investigated to implement the use of electric light in the simulations:

1. User presence by schedule: Monday until Friday from 9 am to 6 pm, 220 working days, roughly fitting habitudes in our laboratory, where models and measurements are conducted. Presence was identical with use of electric light.
2. User presence by measurements: Indoor irradiance is measured permanently, so the use of light is measured. Simulated electric light has been added for measured presence of a user.
3. User presence by schedule, use of electric light using a threshold value being determined by measured radiometric data. A complicated issue for this approach is the visibility function of the human eye.

For all models, the simple dynamic shading model within DAYSIM was used, i.e. a simple model of user defined use of venetian blinds.

B. *Measurements*

Measurements were performed both long-term for a validation of the simulations and in detail to investigate the best methods to measure weak light in radiometric units at acceptable costs.

In order to minimize the spectral evaluation of the measurements, CMP3 pyranometers by Kipp and Zonen have been chosen, instead of the commonly used luxmeters. Based on thermoelectric arrays, the instruments have a spectral response wave band from 310 to 2800 nm and are standard instruments in outside measurements of solar radiation. The output signal per W/m² is typically about 20 µV.

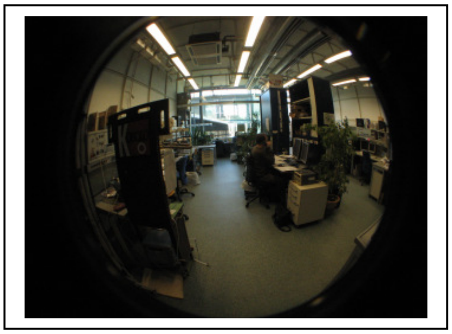

Figure 2. Simulated, complex office with north window, hemispherical view

C. *Investigated points-localisation and orientation*

Typical places of installation for an autonomous sensor node can be found on work desks, next to light switches, fixed on the wall or next to a window.

Six points of installation were both measured and simulated (Table II). For both offices, virtual control sensors controlled the data for the outside radiation by the weather file. In addition, virtual sensor arrays with increasing distance to the window and varied sensor orientations were simulated.

TABLE II. MEASURED AND SIMULATED INSTALLATION POINTS

Position (m) / Sensor	x	y	z	Description
N1	2.55	0.05	1.08	Next to lightswitch, facing window
N2	2.80	5.20	0.63	Next to work desk, facing ceiling
N3	0.28	7.20	1.83	facing wall, parallel to window
S1	1.00	5.29	1.10	Next to lightswitch, facing window
S2	3.41	0.30	1.60	Facing window
S3	3.69	0.40	1.60	Facing wall, parallel to window

III. RESULTS

A. *Required complexity of a simulation model*

The required complexity and resulting working effort of a simulation model has been analyzed for the three reference points of the sophisticated north office. Figure 4 shows the *Radiance* model for the North-office: A typical room with many complex shapes and reflecting elements. Table 3 presents simulation results of this room with no furniture (figure 4), only tables and cupboards (figure 5), and with room details such as plants included (figure 6). The ray tracing was performed with *Radiance*. In order to have a constant light source for the validation measurements, only the electrical light was simulated. The sensor N2 is facing the electric light and placed on a trolley. N1 is facing the window at a distance of 10 m, and N3 is orientated to the wall.

For N2, irradiance was measured with CMP3 pyranometers. First, the glas dome of each pyranometer was shielded from thermal and optical radiation to determine the signal offset in dependence of the room temperature and thermal flow. The pyranometer was at thermal equilibrium with the environment at the beginning of the measurements. The output voltage was measured with an AGILENT 6134. The measured irradiance of 2.2 W/m² differed 10 % from the simulated value.

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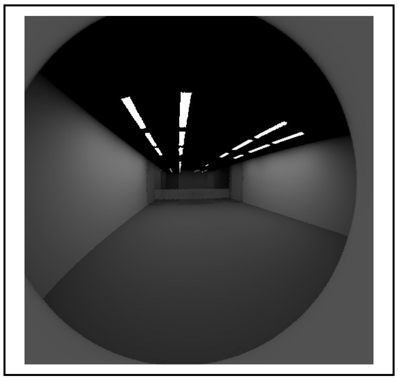

Figure 3. Simple room model of the North office: only geometry, lighting and windows. Hemisperical view.

As expected, the simulation results differed significantly between an empty and a furnished room. The difference between the results of the simple model of Figure 5 and the complex model of Figure 6 varies between 2 % for N2 and 14 % for N3. In case of the approximations used with DAYSIM, the results would even be the same for both models. Respecting most parts of the room equipment enhances the quality of simulation results. However, the difference compared to the simplified model omitting details is below 5 % for a sensor illuminated mainly by direct light and below 15 % for sensors illuminated by indirect light. Hence, in this example designing ipv modules does not necessarily require the effort of detailed models.

TABLE III. IRRADIANCE BY ELECTRIC LIGHT IN W/M^2 DEPENDING ON COMPLEXITY OF SIMULATION MODEL

Irradiance (W/m^2) / **Sensor**	**Model: only geometry**	**Model: main objects**	**Model: details included**
N1	1.44	1.29	1.19
N2	2.55	2.04	2.00
N3	0.69	0.49	0.43

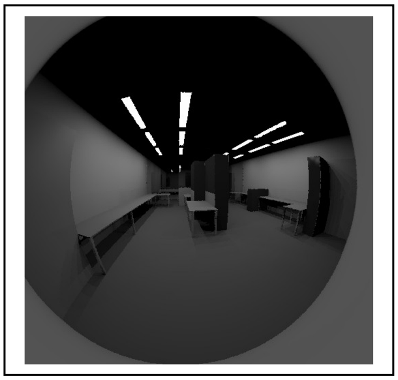

Figure 4. More detailed model of the same room. Main office equipment is included.

B. Typical irradiation values by orientation and latitude: Daylight

In practice, an ipv product should be reliable world-wide, i.e. under different latitudes. This section investigates the influence of the orientation to the window, of the latitude, and of the window orientation on the annual mean irradiance. Therefore, the simple model of the north office, i.e. without any furniture, has been simulated in DAYSIM investigating three lines of virtual sensors on a height of 1 m. Each orientation vector was simulated independently. The x-line is facing the wall, the y-line the window and the z-line the ceiling. The distance to the window started with 0.5 m and increased in 1 m steps.

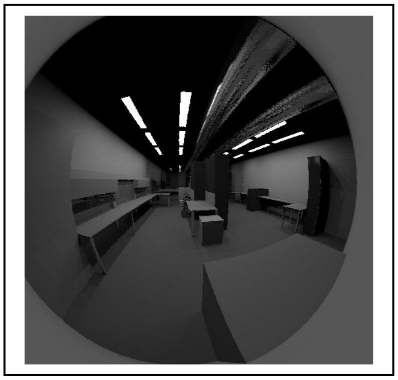

Figure 5. Sophisticated model, including smaller items of furniture, ducts and big plants

In the model, the window was either placed on the north side (figure 6) or on the south side of the room (figure 7). To define the influence of the latitude, the ones of Helsinki and Rom have been chosen. The difference in latitude between these locations is 19 degrees. Following these simulations, the influence of the window orientation, i.e. its cardinal point noun, exceeds the influence of the latitude. Simulation results for Helsinki fell below the results for Rom with an approximated factor of 0.75. For both locations, the intensity for a window orientation to the north was 25 % of the intensity obtained with a south window. The irradiance for sensors orientated to the wall remained on a basic level for all simulations.

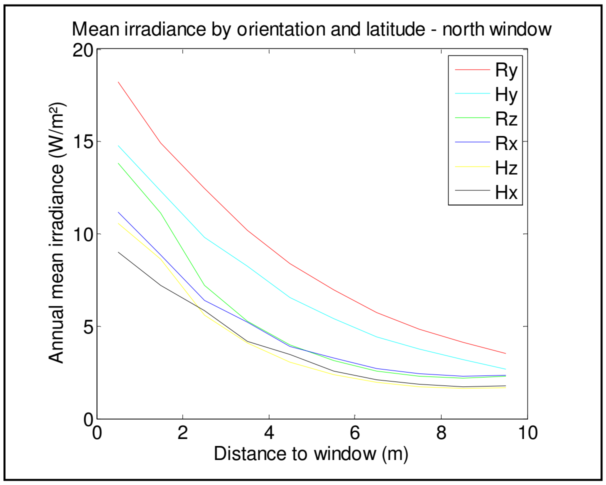

Figure 6. DAYSIM simulation of the annual mean solar irradiance in W/m² for an unfurnished room with a north window. ‘R’ indicates Rom, ‘H’ Helsinki. ‘x’,’y’,’z’ are the direction vectors.

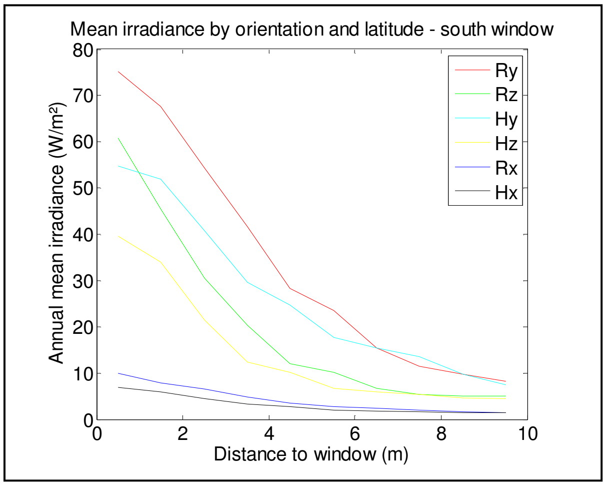

Figure 7. DAYSIM simulation of the annual mean solar irradiance in W/m² for an unfurnished room with a south window. ‘R’ indicates Rom, ‘H’ Helsinki. ‘x’,’y’,’z’ are the direction vectors

Figure 8 and 9 represent DAYSIM simulation results for the investigated installation points. The location is Freiburg. The maximum values obtained by solar irradiance range between 64.64 W/m² (S1) and 124.29 W/m² (S2) for the south office and between 1.71 W/m² (N2) and 10.90 W/m² (N3). The annual mean for sensors in the north office is below 5 W/m². For the south office, the annual mean ranges between 20 W/m² and 50 W/m².

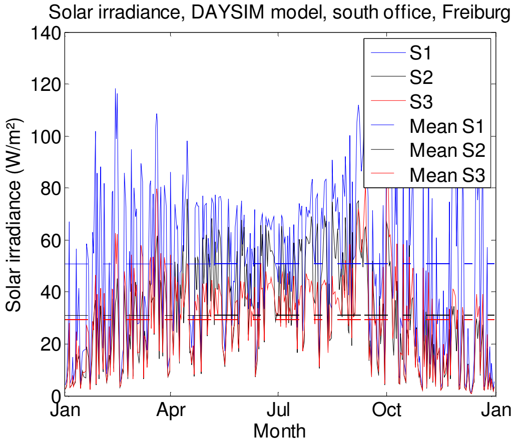

Figure 8. Solar irradiance for sensors in the south office. DAYSIM model, location Freiburg.

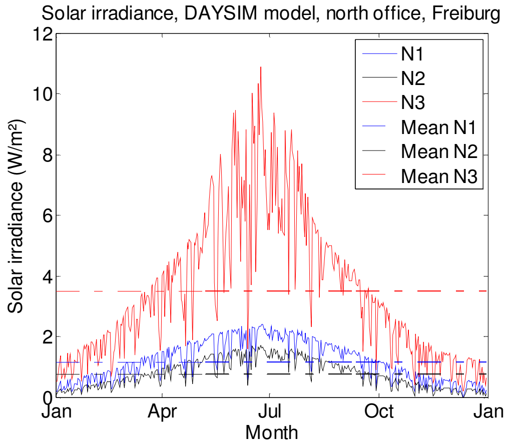

Figure 9. Solar irradiance for sensors in the north office. DAYSIM model, location Freiburg.

C. Electrical light: Influence and user models

An evaluation of the first five months of indoor measurements showed, that user presence in the north office was identical with the permanent use of electric light. Similar results have been found by Hunt [9]. Real working times exceeded the simple schedule model of working times from 9 o’clock until 18 o’clock from Monday until Friday. The south office is used by one working person. Following our measurements, the use of electric light was about 50 % below the estimations used in the simple schedule model. Measurement data from January to May showed no correlation between measured irradiance and the use of electric light. For both offices, also intermediate breaks could be neglected. Hence, the simple user presence model by working schedule of the simple user model by working schedule fit measurements to a certain grade. For offices with very irregular times of use, the schedule should be adjusted.

D. *Reliable systems- required self-suffiency*

While irradiance for a south-orientation and close to a window can exceed 500 W/m² only by solar irradiance, the critical issue for a reliable system is the longest period without light. This period defines the required area of the ipv-module to charge the required storage capacity. Therefore, the combined irradiance for the month December in the north office has been simulated. We assumed a worst-case scenario for the user-presence, with four non-labour days resulting from a week-end followed by two holidays. For this scenario, Figure 10 shows the frequency of occurrence of different classes of irradiance which are of relevance for ipv applications. The irradiance of Figure 10 was obtained by daylight. For Figure 11, electrical light was added. For sensors orientated to the ceiling, the electric light contributed 50 % of the irradiance.

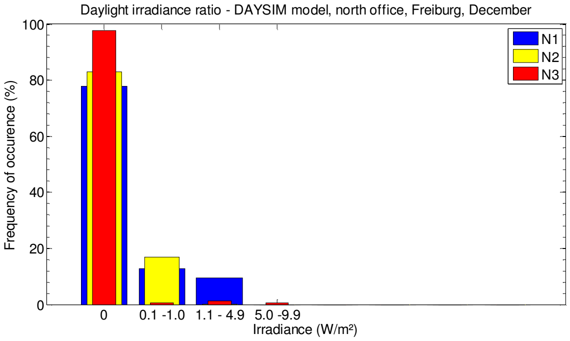

Figure 10. Irradiance ratio for December, daylight contribution. DAYSIM simulation model for Freiburg, north office.

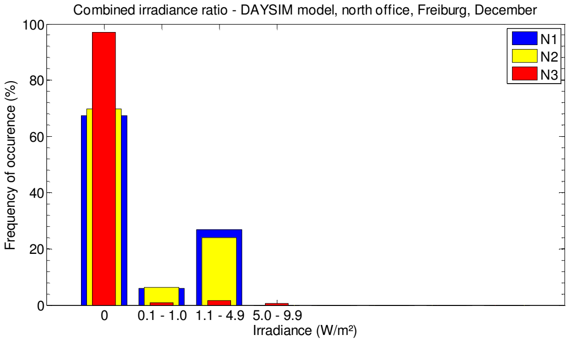

Figure 11. Irradiance ratio for December, daylight and electrical contribution. DAYSIM simulation and user model for Freiburg, north office.

E. *Measurements*

Due to their sensitivity in the range of µV, the signal of the pyranometers is also influenced by thermal flow and electromagnetic radiation of the environment. However, it was possible to measure the use of electric light during five month and to perform first validations for the simulation of the electric light with an enhanced measurement.

IV. CONCLUSIONS

Simulations and first measurements showed an accordance of 10 %. As theoretical models and measurements lack accuracy for lower intensities, their reliability is uncertain. This is part of current work. Simulation models only require the main objects of the room, especially for investigated areas orientated to a source of direct light. The measurements of indoor irradiance in the period of January to May showed that office workers tend to use the electric light in every season and during the whole working day. Hence, the simple user model by schedule is sufficient, if the investigated room will be used regularly. Typical irradiance values for the environment of ipv products as well as estimating methods have been investigated successfully. Based on these results, ipv designers are encouraged to use the presented approach for determining indoor irradiance.

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