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Evaluation of the electricity savings resulting from a control system for artificial lights based on the available daylight

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ABSTRACT
Natural lighting in building environments is an important aspect for the occupants' mental and physical health. Furthermore, the proper exploitation of this resource can bring energy benefits related to the reduced use of artificial lighting. This work provides some estimates of the energy that can be saved by using a lighting system that recognises indoor illuminance. In particular, it is able to manage the switching on of lights according to the daylight detected in the room. The savings from this solution depend on the size and orientation of the window. The analysis is conducted on an office by means of simulations using the INLUX-DBR code. The locations have an influence on the luminance characteristics of the sky. The analysis is conducted with reference to one city in the south and one in the north of Italy (Cosenza and Milan). The energy saving is almost independent of latitude and therefore representative of the Italian territory. it is highly variable according to exposure, being the highest for southern exposure (97 % with the window size equal to 36 % of the floor area) and between 26 % and 48 % (as a function of window size) for northern exposure.

Section: RESEARCH PAPER

Keywords: Daylight; artificial lights; energy savings

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1. INTRODUCTION

Buildings are the place where man spends most of his time. A large amount of energy is used inside buildings to meet human needs and to provide thermal-hygrometric and visual comfort. In the coming years, it is very important to adopt solutions to reduce consumption. The most widespread strategy to reduce consumption consists of improving the efficiency of the building envelope (reducing thermal losses through transmission by opaque surfaces [1]-[5]) and the efficiency of plant components [6]. It is especially important to also utilize solar gains in a smart way because they bring thermal and visual benefits. The solar source, in fact, has a considerable influence on the behavior of the building. Scientific research in this regard is dedicated to three main objectives: 1) production of electrical and thermal power through solar panels [7], [8], 2) control of solar inputs to reduce winter and summer heat load, 3) reach adequate daylight within the rooms. In addition to user awareness to reduce waste, intelligent solutions to better exploit solar radiation are divided into passive and active systems. Passive systems do not require a control system. Examples include bioclimatic solar greenhouses [9], green roofs [10], [11], Trombe walls [12]. Active systems, on the other hand, use sensors and actuators, which often communicate via IoT technology to make automatic adjustments [13], [14]. The visual comfort of the occupants, which is often neglected, is also a primary objective. This research is concerned with analyzing a dynamic system for controlling artificial lighting to avoid unnecessary switching on when natural illuminance is adequate. Daylight plays a key role in visual comfort inside buildings. Estimating daylight inside a room is not a simple problem. Over the years, different methodologies have been developed to consider the different variables involved.

Numerous computational codes are available to estimate the illuminance on the working plane [15]-[17]. These codes, however, are difficult to adapt to a real case since they use the sky luminance models present within their libraries. In particular, the models are predominantly related to the CIE clear sky model [18] or standard overcast sky distributions. The use of locally measured or estimated luminance is not allowed. In this regard, the authors developed the INLUX-DBR calculation code [19], [20]. The luminous contributions that the code considers are: light carried by direct rays, scattered light from the sky and reflected light from the outside ground. It allows realistic estimation of illuminance at various points in the room. The code is very flexible since it allows the use of measured distributions of sky luminance and also classical model calculations. The resolution method used is "radiosity model" by which luminance distributions in walls are evaluated by an implicit method. The validation of the code was performed with an example case conducted in Japan and allows the extension of case studies to perform parametric analysis. In the present study, we investigate the possibility of replacing the artificial lighting system using a system that can adapt to confer setpoint illuminance based on the already present daylight contribution. This is a control strategy that is often applied in smart buildings. This work provides numerical data to quantitatively assess the energy savings from this investment. It depends, in fact, on a number of factors: in particular, the geometry of the room and the size and orientation of the window. The objective of the work is to provide useful indications to take advantage of daylight and save electricity from artificial lights. In addition, this solution provides visual comfort and makes the environment healthier for the occupants. Two Italian locations will be simulated in the work, one in southern Italy and one in northern Italy: Cosenza and Milan.

1.1. Literature Review

Controlling artificial light according to natural illuminance is useful to provide an environment with constant illuminance over time, reducing unnecessary waste. The daylight recorded in rooms depends greatly on the geometry of the rooms and the ratio of window to wall areas. In addition, illuminance depends on the position of the sun. In the past, many authors have made important contributions on this topic.

The most important parameter used in building design is the daylight factor (DF), defined by Trotter [21]. The estimation of this was improved by Dresler [22] by formulating empirical relationships. Hopkinson et al [23] introduced the need to consider external obstacles and ground reflection. Later, Tregenza [24] defined an analytical method called Split-Flux, which is based on overcast conditions. Numerous models are formulated in order to estimate DF; these use scaled models, empirical formulas and corresponding diagrams [25], [26].

The DF, however, allows for valid considerations only under overcast conditions because on clear days it is highly dependent on the position of the sun in the sky. In these cases, in fact, it would result that the indoor illuminance distributions would not depend on the orientation of the window. It would be appropriate to define indices to evaluate illuminance on an annual scale. This greatly increases the complexity of the problem. For our purpose, therefore, classical DF-based methods are not useful. Nabil et al. [27] showed that alternating clear, intermediate and cloudy days makes indoor lighting highly dependent on window orientation.

The models mainly used to simulate the distribution of light inside a room are divided into "radiance models" and "ray tracing models". The two models provide equal results being based on valid assumptions. The code used in the present work belongs to the first category. The method consists of solving, at each instant of time, a system of equations obtained from the balance on each surface of the room. Each surface is treated as a body that reflects incident light isotropically. It is defined by the reflectivity and view factors toward all other surfaces. In ray tracing models, the path of the solar ray through its various reflections on the walls of the room is followed. Illuminance is calculated by setting the maximum number of reflections. No system of equations is solved.

Daylighting studies are very diversified. In fact, the problems are always significantly different depending on the building conformation and scale. Alhagla et al. [28] obtained in a study that the benefits of daylight depend on location. In particular, in hot locations, the exploitation of sunlight leads to an increase in the cooling heat demand in the summer period. On the other hand, in locations where the climate is colder, the use of daylight could favour the input of solar radiation and thus reduce the winter heat demand. Athienitis et al. [29], analysed control systems for artificial lights associated with daylight to manage electricity use and reduce energy consumption. The authors were also able to achieve excellent results in terms of visual well-being. The benefits achieved on electricity consumption are remarkable, although the authors claim that there is a risk of overheating during summer periods.

Krarti et al [30] studied different geometric room configurations in order to analyse the impact of daylight on energy consumption. The analysis was conducted with different window sizes and different types of glass. They analysed four locations in America. They also observed that geographical location has a low impact on daylight.

Hee et al [31] presented a review to analyse scientific paper where the impact of windows on room illuminance and the resulting energy savings are assessed. They also listed the different optimization techniques used to choose glass. Their advice is to perform a careful economic evaluation when choosing glass and defining the size of the opening in a room.

The largest number of scientific studies concerns the assessment of solar radiation introduced through windows, together with daylight. Of course, these effects are important because they have a considerable influence on the energy balance of a building. The present work, however, has a different objective. In fact, solar contributions are defined by the geometry of the building and the ratio of windows to opaque walls. This paper, unlike the others, does not aim to evaluate the best architectural design for the building. Instead, the aim is to evaluate, for a given building (thus for a given daylight and solar gains), whether the artificial lighting system can be more efficient, by making it intelligent, to exploit daylight. For example, when the room is long and narrow, the illuminance established in the areas away from the window is not sufficient. These rooms are generally not suitable for exploiting daylight properly. Moon et al. [32] performed an analysis on the control of the lighting system using photosensors in the room. They performed simulations using Lightscape software. The use of software to simulate daylight can be interesting as it allows comparison between different locations with reference to the same geometry.

It is therefore necessary to understand whether the presence of an artificial light control system can lead to savings by trying to quantify them [33]-[35]. Li et al. [36] carried out experimental studies on daylight and energy consumption for atrium corridors. Doulos et al. [37] showed that the power factor for LED lamps worsens when they are dimmed and this could make the use of fluorescent lamps more advantageous than LEDs under certain conditions. Bellia et al. [38] observed experimentally that there are no significant differences between using a proportional dimmable system and an on/off system. In particular, for southern exposures they observed that the difference is very low. The installation of a dimmable system is therefore not recommended in these cases due to the higher costs compared to an on/off system.

The number of variables on which lighting problems depend is high and it is not always clear how many benefits the presence of a dimmable system can bring. The present work aims to overcome this gap and to provide useful information for locations in the latitude range equal to those of Italy.

2. METHODOLOGY

2.1. The INLUX-DBR code and its experimental validation

The lighting analysis was carried out using the INLUX-DBR calculation code. This code allows to evaluate the luminance distribution within an environment. In particular, it divides opaque structures and transparent structures into “n” and “m” surface elements respectively. On each of these the illuminance value depends on:

a. A component of direct solar radiation which, passing through the transparent surfaces, hits the surface under examination;
b. A component of the diffuse solar radiation which, passing through the transparent surfaces, hits the surface under examination;
c. A component of solar radiation reflected from the external environment which, passing through the glass surfaces, hits the surface under examination;
d. A component due to the infinite internal reflections by the other surfaces that make up the environment in question.

These components influence both the illuminance of opaque surfaces and the illuminance of glazed surfaces. In the present analysis, it is considered that the glazed surfaces are made by means of ordinary clear glass, therefore the direction of the solar radiation incident on the surface remains unchanged. Having to consider the effects due to the radiation reflected from the ground outside the environment, the latter is divided into “p” surface elements.

Taking into account the various incident radiative components, it is possible to determine the illuminance E_i of the “i-th” surface by means of the Eq. (1).

$$\begin{aligned} E_i \cdot \Delta A_i = & \sum_{\mathrm{w}=1}^{m} \left[\tau(\alpha,\varphi) \cdot L_{\mathrm{p}}(\alpha,\varphi) \cdot \Delta A_{\mathrm{w}} \cdot \pi \times F_{\mathrm{w-i}}\right] + \\ & k \cdot \tau(\alpha_{\mathrm{s}},\varphi_{\mathrm{s}}) \cdot \Delta A_{\mathrm{i}} \cdot E_{\mathrm{vs}} \cdot \cos\vartheta_{\mathrm{si}} + \\ & \sum_{\mathrm{g}=1}^{p} \left[\tau(\alpha_{\mathrm{g}},\varphi_{\mathrm{g}}) \cdot L_{\mathrm{g}} \cdot \Delta A_{\mathrm{g}} \cdot \pi \cdot F_{\mathrm{g-i}}\right] + \\ & \sum_{j=1}^{n+m} \Delta A_j \cdot \rho_{\mathrm{j}} \cdot E_{\mathrm{j}} \cdot F_{j-\mathrm{i}}\,. \end{aligned} \quad (1)$$

In the first term, the illuminance of the “i-th” element (E_i) multiplied by the relative surface (ΔA_i) appears. In the second term, on the other hand, all the radiative components that influence the value of the illuminance on the surface under examination appear. In particular, with $\tau(\alpha,\varphi)$ indicates the transmissivity of the glazed surface, with $L_{\mathrm{p}}(\alpha,\varphi)$ indicates the luminance of the celestial vault (this varies according to the point of the celestial vault considered), with α indicates the angular height of the point of the celestial vault considered, with φ indicates the azimuth of the point considered in the celestial vault, with ΔA_w indicates the area of the glazed element under examination, with F_{w-i} indicates the view factor between the glazed element under examination "w" and the "i-th" element, k is a coefficient that has a unit value if the element in question is directly affected by solar radiation and a zero value otherwise, with $\tau(\alpha_s,\varphi_s)$ indicates the transmissivity of the glazed surface to direct solar illumination (E_{vs}), with α_s indicates the height of direct solar radiation, with φ_s indicates the azimuth of direct solar radiation, with ϑ_{si} indicates the angle between direct solar radiation and the normal to the surface of the "i-th" element, with $\tau(\alpha_g,\varphi_g)$ indicates the transmissivity of the glazed surface to reflected radiation from the ground, with L_g indicates the luminance of the ground, with ΔA_g indicates the surface of the "g-th" element of the ground, with F_{g-i} indicates the view factor between the "g-th" element and the "i-th "in question, ρ_j is the reflexivity of the elements internal to the environment in question is indicated and ΔA_j is the surface of the" j-th "element inside the environment that reflects part of the incident radiation (E_j) on the" i-th "element in exam, finally, F_{j-i} indicates the view factor between the" j-th "element and the" i-th "element. This balance equation is written for each “i-th” opaque element inside the environment. Figure 1 shows a graphic representation of the various radiative components exchanged by the different surfaces and considered in the INLUX - DBR code.

Considering the external ground as an isotropic surface and assuming that the reflectivity ρ_g does not vary between direct and diffuse radiation, it is possible to calculate the luminance of the ground L_g by means of Eq. 2.

$$L_g = \frac{\rho_g \cdot (E_{vs} \cdot \sin(\alpha_s) + E_0)}{\pi}\,, \quad (2)$$

where with E_0 indicates the diffused illuminance on the horizontal plane.

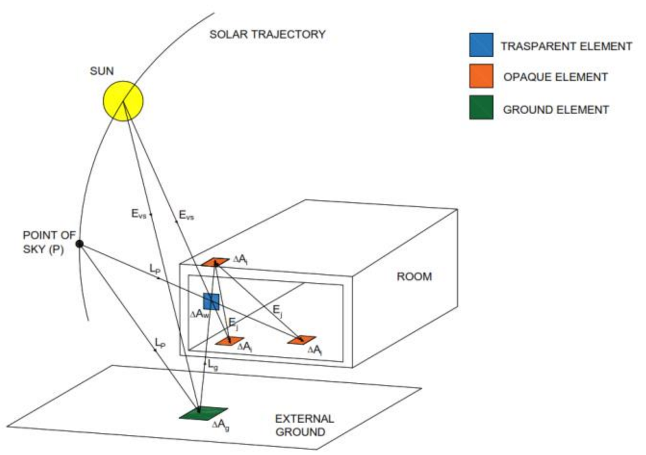

Figure 1. Representation of the various radiative components exchanged by the different surfaces inside the room.

In the case in question, the illuminance on the glass surface depends solely on the radiative components reflected by the surfaces inside the environment. In fact, it is considered by hypothesis a single glazed surface in the room. Consequently, it is possible to simplify the Eq. (1). Therefore, the illuminance on a glass element inside the room can be determined by means of the Eq. (3).

$$E_w \cdot \Delta A_w = \sum_{i=1}^{n} [\Delta A_i \cdot \rho_i \cdot E_i \cdot F_{i-w}] \,, \tag{3}$$

where with E_w indicates the internal illuminance of the "w-th" element of the glazed surface under examination, while F_{i-w} is the view factor between the "i-th" element and the "w-th" element of the glazed surface in exam.

Finally, a system of unknown $(n+m)$ equations with $(n+m)$ variables is obtained which is solved with an iterative method by means of a finite difference methodology starting from a uniform initial solution.

The calculation code has been implemented in the Matlab environment and other details are provided in [19]. One of the advantages of this computational code is that it can implement different methodologies to model the behavior of the celestial vault. For example, it is possible to use:

1) The distribution of clear and cloudy CIE [39];
2) Perez's model of clear skies [40];
3) Igawa's model [41];
4) The model of Kittler and Darula [18], [42]
5) The Tregenza model [43];
6) Experimental models created ad hoc for the location in question.

The developed code was validated by means of data measured in an experimental site in Osaka. In the experimental validation, clear, overcast and intermediate days were considered. The validation was carried out considering two error indices: the Normalized Mean Bias Error (NMBE) and the Normalized Root Mean Square Error (NRMSE) evaluated between the measured and calculated illuminance at various points in the environment. In particular, the NMBE is calculated by means of the following equation:

$$NMBE = \frac{\sum_{i=1}^{N} \frac{V_{\mathrm{calc},i} - V_{\mathrm{meas},i}}{V_{\mathrm{meas},i}}}{N} \,, \tag{4}$$

The NRMSE is calculated by means of the following relation:

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{N} \left(\frac{V_{\mathrm{calc},i} - V_{\mathrm{meas},i}}{V_{\mathrm{meas},i}}\right)^2}{N}} \tag{5}$$

The values of these error indices are summarized in Figure 2.

It is observed that there is a good correspondence between the measured values and the calculated values. Of course, the error increases as the solar radiation entering the environment increases.

2.2. Calculation methodology of the electrical energy saving

The analysis was conducted with reference to two different locations: Cosenza (Lat: 39° 18 'N) and Milan (Lat: 45° 28' N). The distribution of the point illuminance and the average illuminance in the environment were determined using the INLUX-DBR code.

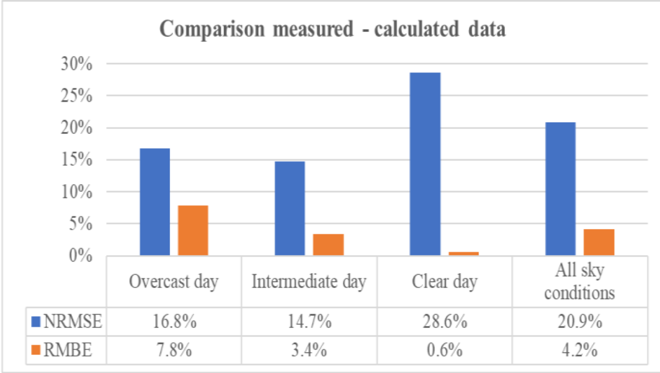

Figure 2. Analysis of the error indices during the experimental campaign done by means of an experimental site located in Osaka 7.

The code requires some input data such as direct solar radiation and diffuse hourly monthly average and illuminance on the horizontal plane. These parameters were obtained through the “European Database of Daylight and Solar Radiation” provided by Satel-light [44]. The luminance of the sky was determined by setting the Perez model. The latter was chosen on the basis of an accuracy analysis carried out in a previous study [20], which showed the goodness of the model. The Perez model [40] is a full-sky calculation methodology based on the clarity index. The latter is determined by means of the following relation:

$$\varepsilon = \frac{\frac{G_{d0} + \frac{G_{bo}}{\sin \alpha_s}}{G_{d0}} + 5.535 \cdot 10^{-6} \cdot z_s^3}{1 + 5.535 \cdot 10^{-6} \cdot z_s^3} \,, \tag{6}$$

where with G_{d0} indicates the diffused irradiation on the horizontal plane and with G_{bo} indicates the direct irradiation on the horizontal plane. This index can vary between $\varepsilon = 1$ (with completely cloudy skies) and $\varepsilon = 6.2$ (with completely clear skies). As a function of the clarity index, eight sky conditions have been identified, varying the parameters and formulas for calculating the luminance of the sky; this quantity varies point by point in the celestial vault and appears in Eq. (1).

In particular, the luminance of the sky can be calculated by means of the following relationship:

$$L_P = L_Z \cdot l_r \,, \tag{7}$$

where with l_r indicates the relative luminance and with L_Z indicates the zenith luminance.

Relative luminance can be determined by means of the following relationship:

$$l_r = \frac{\Phi(\alpha) \cdot f(\zeta)}{\Phi(\pi/2) \cdot f(\pi/2 - \alpha_s)} \,, \tag{8}$$

where α is the solar height of the considered point of the sky, ζ is the angular distance between the considered point of the sky and the position of the sun. The functions $\Phi(x)$ and $f(x)$ can be determined by means of the following equations:

$$\Phi(x) = 1 + \mathrm{a} \cdot \mathrm{e}^{\frac{b}{\sin x}} \tag{9}$$

$$f(x) = 1 + \mathrm{c} \cdot \mathrm{e}^{d\,x} + e \cdot \cos^2 x \,. \tag{10}$$

In Eqs. (9) and (10) the parameters a, b, c, d and e are functions of the solar height α_s, the brightness of the sky Δ and the clarity index ε. More information on the calculation of these parameters can be found in Ref. [25].

The luminance of zenith, which appears in Eq. (7), can be determined by means of the following correlation developed by Perez [45] as the sky condition varies.

$$L_Z = G_{d0}\left[a_{\mathrm{i}} + c_{\mathrm{i}} \sin \alpha_s + c_{\mathrm{i}}' \,\mathrm{e}^{-3(\pi/2-\alpha_s)} + d_{\mathrm{i}}\,\Delta\right], \qquad (11)$$

where the constants a_{i}, c_{i}, c'_{i} and d_{i} are function of the clarity index ε.

2.3. Case study

The analysis will be conducted with reference to a case study. The geometry of the room for which the smart lighting system is simulated is $6 \times 6 \times 3\ \mathrm{m}^3$ in which there is a window with double glazing and transmissivity equal to 0.75. The size of the window varies between $5.04\ \mathrm{m}^2$ and $12.96\ \mathrm{m}^2$. The minimum size is fixed on the basis of what is reported by the Italian legislation [46] which imposes a minimum size of the glass surfaces of a room of $1/8$ ($12.5\ \%$) of the total floor area. The reflectivity of the room's opaque vertical and horizontal structures is summarized in Table 1.

By means of the INLUX-DBR calculation code, an analysis was carried out for a whole year in order to evaluate the distribution of natural lighting inside the room. In particular, the natural illuminance was evaluated with reference to the 12 points shown in Figure 3.

In each of these points it will be assumed to place a luminescent lamp with power $36\ \mathrm{W}$ and brightness of $3200\ \mathrm{lumen}$. The set lamp control logic envisages activating a row of lamps only if the natural illuminance of two points out of three (for the same row) is less than $500\ \mathrm{lux}$.

As the orientation and size of the window vary, the distribution and intensity of natural lighting varies. Consequently, the number of switch-on of the lighting system and the electrical consumption will vary. The final goal is precisely to determine the energy savings that can be obtained by varying the configuration.

3. ANALYSIS OF RESULTS

In Figure 4 it is possible to observe the distribution of natural lighting on the 12 points selected for the town of Cosenza at 12:30 am on 15 January. The analysis is carried out with reference to a surface window equal to $5.04\ \mathrm{m}^2$ for different variation of the exposure.

With the window exposed to the north, only in the row closest to the window the illuminance intensity is greater than $500\ \mathrm{lux}$; with the exposure to the east the natural illuminance is higher than $500\ \mathrm{lux}$ in the first row and in two points out of three of the second line; with the southern exposure the natural illuminance in all points is higher than $500\ \mathrm{lux}$; finally, with the western exposure, only in the last two lines farthest from the window the natural illuminance is higher than a $500\ \mathrm{lux}$.

The same analysis was conducted at 12:30 am on July 15th. The results are reported in Figure 5.

Table 1. Characteristics of the walls of the reference room.

	Dimensions	Area (m²)	ρ
Floor	6 × 6 m²	36	0.2
Ceiling	6 × 6 m²	36	0.7
Rear wall	6 × 3 m²	18	0.5
Left wall	6 × 3 m²	18	0.5
Right wall	6 × 3 m²	18	0.5
Front wall	6 × 3 m²	12.96	0.5
Ref. window	4.2 × 1.2 m²	5.04	0.15
Work plane	6 × 6 m²	36	-

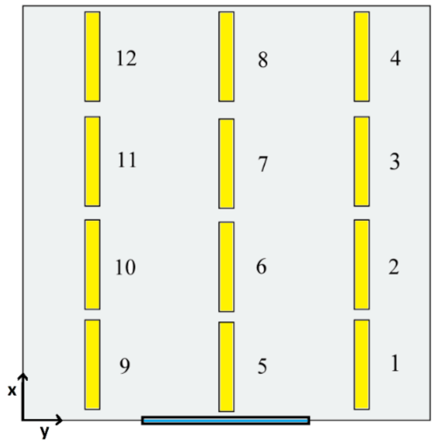

Figure 3. Position of reference points in which the analysis of the natural illuminance was conducted.

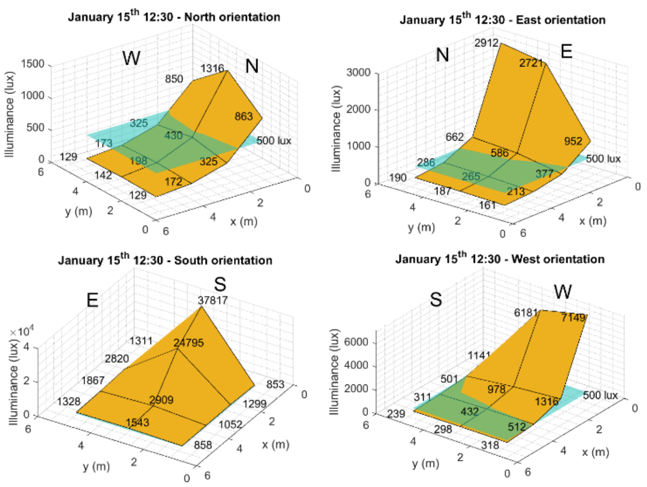

Figure 4. Natural illuminance on 12 points of the work plane. January 15th - time 12:30 am - Cosenza.

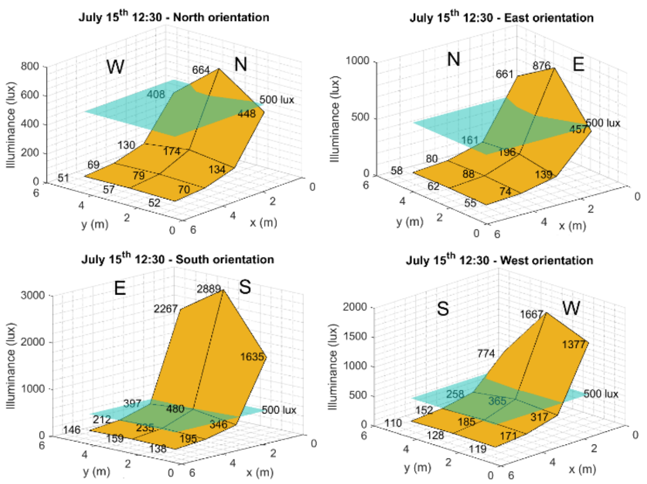

Figure 5. Natural illuminance on 12 points of the work plane. July 15th - time 12:30 am - Cosenza.

The results are similar but the values obtained for natural lighting are sharply lower. This is due to the higher solar trajectory in the sky in the summer months. This affects the solar height which varies from $\alpha_s = 29.37°$ January 15th at 12:30 am to $\alpha_s = 70.77°$ July 15th at 12:30 am. This lower solar trajectory causes less direct solar radiation to hit the surfaces inside the room in July. It goes from an average solar radiation of $200\ \mathrm{kluxhour/day}$ for January to $119\ \mathrm{kluxhour/day}$ for July. Furthermore, the lower illuminance in July is due to the lower brightness of the celestial vault due to the greater distance of the sun.

The distribution of the luminance of the sky varies a lot between the month of January and the month of July. This can be easily observed in Figure 6 which shows how the luminance of the sky varies as the angular height α and azimuth ϕ of the celestial point considered at 12:00 am on January 15 (a) and at noon on 15 July (b) in the city of Cosenza.

It is observed that in all cases for all points of the celestial vault there is a higher intensity of the luminance of the sky in the month of January than in the month of July. This is due to the above.

For the case in question, considering a $5.04\ \mathrm{m}^2$ south-facing window, the opaque elements arranged centrally in the room have a radiative exchange with the points of the celestial vault comprised between an angular height of $\alpha = 2°$ and an angular height of $\alpha = 23°$.

The difference in sky brightness can also be evaluated with reference to the distributions obtained by varying the azimuth for $\alpha = 5°$ and $\alpha = 25°$ with reference to noon on 15th January

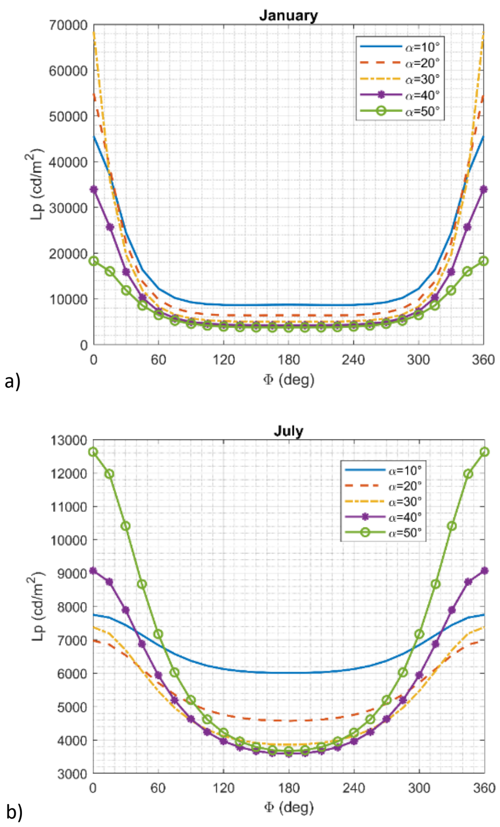

Figure 6 a) Sky luminance distribution (Perez) as a function of azimuth and elevation angles. Noon on January 15th, Cosenza,
b) Sky luminance distribution (Perez) as a function of azimuth and elevation angles. Noon on July 15th, Cosenza.

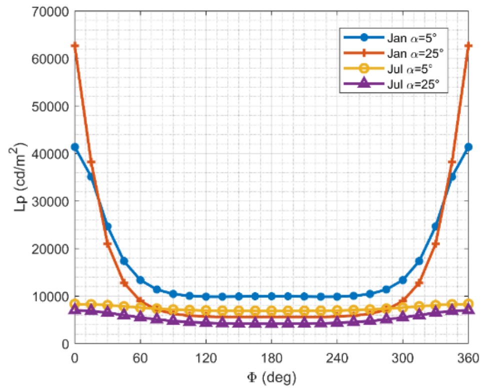

Figure 7. Comparison of sky luminance distributions for noon of January 15th and July 15th, Cosenza.

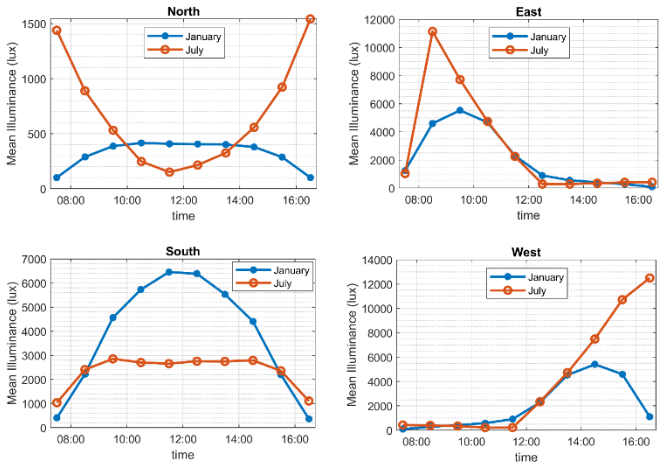

Figure 8. Mean Illuminance on the work plane as a function of time, Cosenza.

and to noon on 15th July. The distributions obtained were represented in Figure 7.

Once again, the brightness of the sky in January is much greater than that of July under the same conditions.

In Figure 8 it is observed how the average illuminance in the room varies as the orientation of the window varies at the hours of January 15th and July 15th.

In Figure 9 and Figure 10 it is possible to observe, respectively, how the illumination in point 7 and point 8 of the room (see Figure 3) varies as the orientation of the window varies on January 15th and July 15th. Therefore, the two central points furthest from the window were taken into consideration.

With reference to the case with the window exposed to north, in July in the first and last hours of the day, natural illuminance is the highest due to the longer and lower solar trajectory in the celestial vault. Therefore, in the first and last hours of the day, a certain amount of direct solar radiation will affect the internal opaque surfaces, consequently affecting the natural internal lighting. In the central hours of the day, the direct solar radiation incident on the glass surface is obviously zero and this affects the natural lighting inside the room. In January, however, the solar trajectory will be shorter but higher in the celestial vault and this generates a typical "bell-like trend" of the natural illuminance inside the room.

With the window exposed to south, the natural lighting has trends similar to those described in reference to the case with north orientation but with much higher intensity. In fact, in this case the sun passes in front of the window in its trajectory.

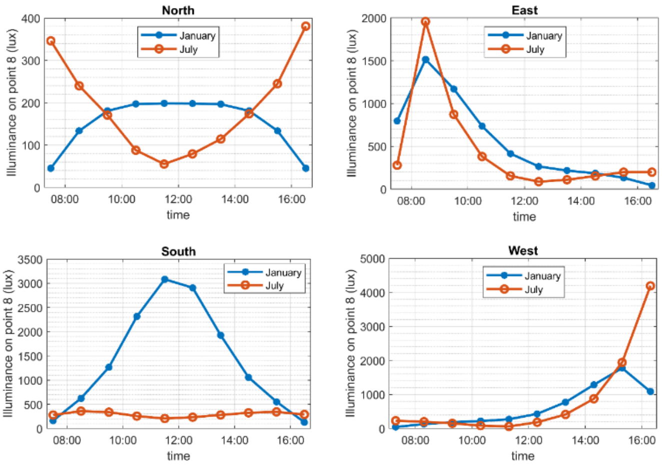

Figure 9. Local Illuminance on point 7 as a function of time, Cosenza.

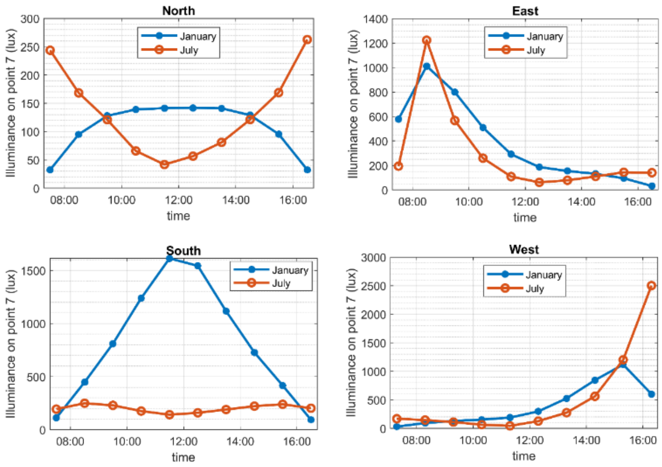

Figure 10. Local Illuminance on point 8 as a function of time, Cosenza.

Finally, with reference to the cases with the eastern and western exposure, in the first and last hours of the day, respectively, there is a peak of illuminance due to the solar path (sunrise and sunset). The higher intensity of natural lighting respectively in the first and last hours of the day in the month of July is once again due to the longer solar trajectory which affects the amount of direct solar radiation entering the room through the window. In the central hours, on the other hand, there is a greater intensity of natural lighting in the month of January due to the lower solar trajectory.

The electricity consumption in reference to the city of Cosenza was also analyzed as the area and the orientation of the window changed. By hypothesis it is considered that the environment is used as an office and has a working period of 8 hours ranging from 8:00 am to 4:00 pm. To evaluate the convenience of each individual configuration taken into consideration, two different energy saving indices have been introduced:

1) The percentage of energy savings compared to a case in the total absence of natural light (R_1). In particular, in the case in which it is assumed that in the room in question there is no contribution due to natural light, an annual electricity consumption is estimated $C_{\max}$ equal to 860 kW h. The energy saving index R_1 can be calculated using the following formula:

$$R_1 = \frac{C_{\max} - C}{C_{\max}} . \tag{12}$$

2) The percentage of energy savings compared to a reference case (R_2). In particular, the case with a north-facing window is taken as reference and the relative annual electricity consumption C_{ref} is indicated with $5.04\ \mathrm{m}^2$. This case has been imposed as a reference as it constitutes the configuration with the lowest natural illuminance. Therefore, the index R_2 can be determined by means of the following formula:

$$R_2 = \frac{C_{\mathrm{ref}} - C}{C_{\mathrm{ref}}} . \tag{13}$$

Table 2 summarizes the monthly and annual electricity consumption depending on the orientation and area of the window. Furthermore, the same table shows the values of the indices R_1 and for the various configurations R_2.

Table 2. Electrical Energy Consumptions in a room 6 × 6 × 3 m³ of a building located in Cosenza.

	MONTH		J	F	M	A	M	J	J	A	S	O	N	D	Year	R_1	R_2
	Exposure	Days	21	20	22	19	22	21	21	22	21	22	21	17	249	-	-
Reference window 1.2 × 4.2 m² = 5.04 m² (14 % floor area)	NORTH	kW h	54.4	51.8	57.0	45.1	52.3	54.4	54.4	54.4	52.3	57.0	54.4	44.0	633	26	0
	EAST		29.5	30.2	35.6	34.9	40.4	38.5	38.5	40.4	34.0	33.3	29.5	25.7	411	52	35
	SOUTH		4.5	0.0	0.0	20.5	38.0	43.1	43.1	0.0	0.0	0.0	0.0	0.0	183	78	71
	WEST		29.5	28.1	35.6	32.8	40.4	45.4	43.1	40.4	34	33.3	29.5	23.9	416	51	34
Window 1.8 × 4.2 m² = 7.56 m² (21 % floor area)	NORTH	kW h	45.4	38.9	47.5	41	47.5	45.4	47.6	47.5	45.3	38	38.5	36.7	520	39	18
	EAST		20.4	21.6	21.4	24.6	35.6	36.3	36.3	30.9	20.4	23.8	18.2	16.5	306	64	52
	SOUTH		0.0	0.0	0.0	0.0	23.8	29.5	24.9	4.7	0.0	0.0	0.0	0.0	83	90	86
	WEST		20.4	21.6	21.4	26.7	33.3	36.3	34	30.8	20.4	23.7	20.4	16.5	306	64	52
Window 1.8 × 5.4 m² = 9.72 m² (27 % floor area)	NORTH	kW h	40.8	34.5	38	32.8	42.7	40.8	40.8	45.1	36.3	38	36.3	33	459	46	27
	EAST		18.1	15.1	21.4	20.5	28.5	29.5	27.2	23.7	20.4	16.6	15.8	14.6	252	70	60
	SOUTH		0.0	0.0	0.0	0.0	9.5	24.9	13.6	00.0	0.0	0.0	0.0	0.0	48.1	94	92
	WEST		18.1	15.1	21.3	20.5	28.5	31.7	27.2	23.8	20.4	16.6	18.1	14.6	256	70	59
Window 2.4 × 5.4 m² = 12.96 m² (36 % floor area)	NORTH	kW h	40.8	34.6	38.0	32.8	38	40.8	40.8	38	34	38	36.2	33	445	48	30
	EAST		18.1	15.1	19.0	18.5	28.5	27.2	27.2	23.8	20.4	16.6	15.9	14.7	245	71	61
	SOUTH		0.0	0.0	0.0	0.0	4.7	9	6.8	0.0	0.0	0.0	0.0	0.0	20.6	98	97
	WEST		18.1	15.1	19.0	18.5	28.5	27.2	27.2	23.8	20.4	16.6	13.6	14.7	243	72	61

Table 3. Electrical Energy Consumptions in a room 6 × 6 × 3 m³ of a building located in Milan.

	MONTH		J	F	M	A	M	J	J	A	S	O	N	D	Year	R_1	R_2
	Exposure	Days	21	20	22	19	22	21	21	22	21	22	21	17	249	-	-
Reference window 1.2 × 4.2 m² = 5.04 m² (14 % floor area)	NORTH	kW h	56.7	51.8	57.0	49.2	52.3	49.9	49.9	54.6	54.4	57.0	54.4	44.0	631	27	-
	EAST		34.0	28.0	33.2	30.8	40.4	38.5	38.5	35.6	34.0	30.8	31.7	23.9	400	53	37
	SOUTH		0.0	0.0	0.0	8.2	35.6	36.3	36.3	19.0	0.0	0.0	0.0	0.0	135	84	79
	WEST		31.7	28.0	33.2	30.8	40.4	38.5	38.5	35.6	34.0	30.9	29.5	22.0	393	54	38
Window 1.8 × 4.2 m² = 7.56 m² (21 % floor area)	NORTH	kW h	52.0	38.8	42.7	41.0	47.5	45.3	45.3	47.5	43.1	38.0	52.2	38.5	532	38	16
	EAST		25.0	19.4	21.4	22.6	30.9	34	31.7	28.5	20.4	21.4	24.9	14.7	295	66	53
	SOUTH		0.0	0.0	0.0	0	4.7	18.1	9.1	0.0	0.0	0.0	0.0	0.0	32	96	95
	WEST		20.4	19.4	21.4	22.6	30.9	31.7	31.7	28.5	20.4	19.0	20.4	16.5	283	67	55
Window 1.8 × 5.4 m² = 9.72 m² (27 % floor area)	NORTH	kW h	40.8	34.6	38.0	36.9	38.0	38.5	38.5	40.4	36.3	38.0	38.5	33	452	47	28
	EAST		18.1	15.1	19.0	18.5	28.5	29.5	24.9	21.4	18.1	16.6	18.1	12.8	241	72	62
	SOUTH		0.0	0.0	0.0	0.0	0.0	6.8	0.0	0.0	0.0	0.0	0.0	0.0	6.8	99	99
	WEST		18.1	15.1	16.6	18.5	23.7	27.2	22.3	21.4	18.1	16.6	15.9	12.8	227	74	64
Window 2.4 × 5.4 m² = 12.96 m² (36 % floor area)	NORTH	kW h	40.8	34.6	38.0	32.8	38.0	38.5	36.3	35.6	36.3	38.0	38.5	33.0	441	49	30
	EAST		18.1	15.1	16.6	18.5	23.8	24.9	22.7	21.4	18.1	16.6	18.1	11.0	225	74	37
	SOUTH		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0	100	100
	WEST		18.1	15.1	16.6	18.5	23.8	24.9	22.7	21.4	15.9	14.3	15.9	12.8	220	74	38

In Table 2 it is observed that the index R_1 assumes values including:

a. between 26% and 48% for the northern exposure;
b. between 52% and 72% due to east and west exposure;
c. between 78% and 98% for the southern exposure.

The index R_2 assumes values including:

a. between 0% and 30% for the northern exposure;
b. between 35% and 61% due to east and west exposure;
c. between 71% and 97% for the southern exposure.

The same analysis was repeated with reference to the city of Milan in order to evaluate the effects of latitude and climate zone (Cosenza belongs to climate zone C and Milan belongs to climate zone E) on electricity consumption. The resalts was summarized in Table 3.

A comparison of electricity consumption between the city of Milan and the city of Cosenza shows that there is less electricity consumption in Milan.

By means of the Satel-light Database it can be observed that Cosenza is characterized by an annual cumulative diffuse illuminance on the horizontal plane greater than approximately 6.5% compared to that of Milan (37656 kluxhour versus 35345 kluxhour). Furthermore, Cosenza has an annual cumulative direct illuminance on the vertical plane greater than about 13% compared to that of Milan (44420 kluxhour versus 39235 kluxhour). However, the sky in Milan appears brighter due to the lower solar trajectory. This phenomenon causes greater internal natural lighting and therefore lower electricity consumption.

In Figure 11 a) and b) the trends of the energy saving indices R_1 and R_2 are shown respectively. In this trends the indices vary with the window area and orientation and with location.

The analysis carried out shows similar values of the indices with reference to the north, east and west exposures for the two locations in question. The values of the indices differ a lot for a southern exposure of the window. This highlights how the latitude has a greater effect on natural lighting and consequently on electricity consumption only with an exposure to the south of the window. In the other cases this effect is completely negligible.

These results are very useful in evaluating what could be the natural illuminance present inside an environment and how much this can vary with the variation of the surface and orientation of the window. This could also suggest control techniques for dimmable artificial lighting systems. Thus, adapting the artificial lighting to the natural lighting present in the environment.

4. CONCLUSIONS

The calculation code for illuminance used in this article was INLUX-DBR. This code is experimentally validated through measurements taken in a scaled room at a building located in

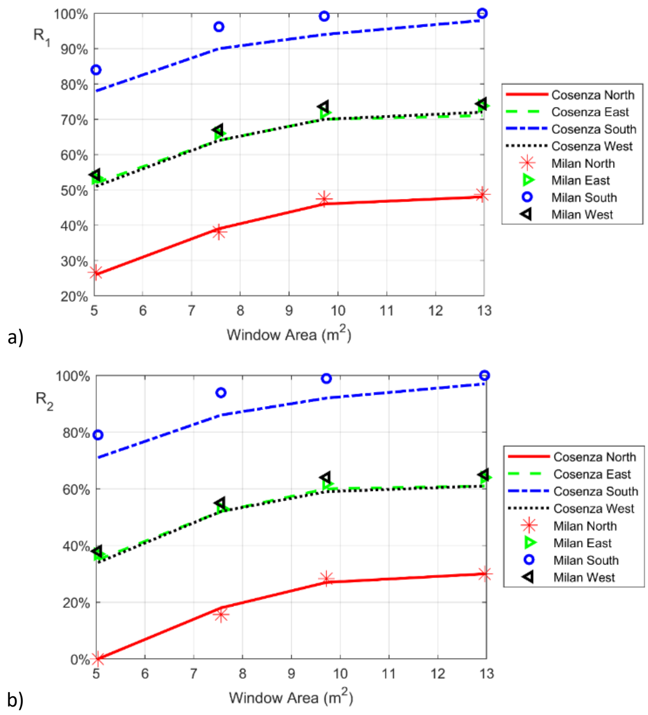

Figure 11. a) Saving index R_1 as a function of window area and orientation for Cosenza and Milan,
b) Saving index R_2 as a function of window area and orientation for Cosenza and Milan

Osaka (Japan). Estimates of the electricity consumption of artificial lights were performed assuming switching on at critical times. The luminance of the sky is given by the Perez model. The evaluation of the luminance distribution in the interior walls of the room is obtained using the radiosity model. The building in question is an office which has been placed alternatively in two Italian locations: Cosenza and Milan. Estimates were made by changing the window size and orientation of the building, analysing the behaviour by placing the window on the four orientations coinciding with the cardinal points.

In the case of the city of Cosenza, the electrical savings obtained varied between 26% and 48% for glazed surfaces exposed to the north, between 52% and 72% to the east and west, and between 78% and 97% to the south. The variations refer to different window sizes ranging from 14% to 36% of the room's floor area.

With reference to the city of Milan, electricity savings vary between 27% and 49% per window surface exposed to the north, between 53% and 74% to the east and west, and between 84% and 100% to the south.

Of course, if the building envelope has a very large window area, using an intelligent management system for artificial light is very convenient. The results show, however, that even when the windows are typically large (14% of the floor area), electricity savings are considerable. In particular, it is up to 84% for the city of Milan. The results obtained for Milan are better than those obtained for the city of Cosenza, which is at a lower latitude. Although, the results are very similar.

The results are therefore considered similar for all areas within this latitude range. The numerical results obtained can serve as a reference for making proper use of daylight and reducing the unnecessary use of electricity.

NOMENCLATURE

(a, b, c, d, e); (a_i, b_i, c_i', d_i)	Coefficients used in the Perez sky model
Φ, f	Functions used in the Perez sky model
k	Coefficient used in the illuminance balance
G_{bo}	Direct irradiance on horizontal plane, W/m²
G_{do}	Diffuse irradiance on horizontal plane, W/m²
L_p	luminance of a point of the sky, cd/m²
L_g	Luminance of a point of the ground, cd/m²
l_r	Relative luminance
L_Z	Zenith luminance, cd/m²
z_s	Sun zenith angle, rad
E	Illuminance of the surface element, lx/m²
E_{vs}	Solar direct illuminance, lx/m²
ΔA	Area of the surface element, m²
n	Number of opaque surface element inside the room
m	Number of glazed surface element inside the room
p	Number of ground surface element
i	Index opaque surface element
w	Index glazed surface element
g	Index ground surface element
C	Yearly energy consumption in the case in exam, W/year
$C_{\max}$	Yearly energy consumption in the case in absence of natural illuminance, W/year
C_{ref}	Yearly energy consumption in the reference case, W/year
R_1	Percentage of energy savings compared to the case in absence of natural illuminance
R_2	Percentage of energy savings compared to a reference case
NMBE	Normalized Mean Bias Error
RMSEP	Root Mean Square Error Percentage
V_{calc}	Calculated data
V_{meas}	Measured data
N	Total number of data

GREEK SYMBOLS

α	Elevation angle of a point of the sky, rad
α_s	Sun elevation angle, rad
α_g	Elevation angle of a point of the ground, rad
Δ	Sky brightness
ε	Clearness index
ζ	Angular distance between the sun and a point of the sky, rad
ρ	Reflectivity
φ	Azimuth of a point of the sky, rad
φ_s	Solar azimuth, rad
φ_g	Azimuth of a point of the ground, rad
τ	Transmissivity
ϑ_s	Angle between the direction of solar radiation and the normal direction of the surface, rad

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