ESTIMATION OF TOTAL SOLAR RADIATION INCIDENT ON AN INCLINED SURFACE OF A SOUTH-FACING GREENHOUSE ROOF

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Abstract - Solar radiation is the driving force for the surface energy balance in buildings such as greenhouses. Greenhouses are generally tilted towards the sun in order to maximize the solar irradiance on the surfaces. Precise computation of the solar radiation received on these surfaces assumes an important role in the energy simulation. It is practical to calculate the total solar irradiance on inclined surfaces based on the solar global and diffuse radiation intensities on horizontal surfaces. This study focused on estimating the total solar radiation incident on inclined greenhouse roof surfaces. In this work, a south-facing thermal box inclined at 26.5° from the horizontal was used for solar radiation measurements. Additionally, recorded solar radiation data were retrieved for the study location and used to develop an empirical correlation. The conversion factors for the beam, the diffuse and the reflected solar radiation components were essential in the prediction of the total solar radiation incident on the tilted surface. The measured solar radiation data were then compared with the simulated data. The model performance was assessed using both graphical and statistical methods. Overall, locally calibrated data led to a satisfactory improvement in estimation of the total solar radiation on an inclined surface.

Keywords: modelling, reliability protection system, electrical network.

Nomenclature

a_i	coefficient, with $i = 0, 1, 2, 3$ and 4 [-]
F_d	diffuse fraction [-]
H_t	hour time [h]
I_b	beam radiation [W/m^2]
$I_{b,h}$	beam radiation on a horizontal surface [W/m^2]
$I_{b,t}$	beam radiation on a tilted surface [W/m^2]
I_c	hourly clearness index [-]
I_d	diffuse radiation [W/m^2]
$I_{d,h}$	diffuse radiation on a horizontal surface [W/m^2]
$I_{d,t}$	diffuse radiation on a tilted surface [W/m^2]
$I_{e,h}$	extraterrestrial radiation on a horizontal surface [W/m^2]
$I_{g,h}$	global radiation on a horizontal surface [W/m^2]
$I_{gr,h}$	ground reflected radiation on a horizontal surface [W/m^2]
$I_{gr,t}$	ground reflected radiation to a tilted surface [W/m^2]
I_n	radiation measured on the plane normal to the radiation at any given time [W/m^2]
I_o	hourly extraterrestrial solar radiation on a horizontal surface [W/m^2]
$I_{ref,t}$	reflected radiation from a tilted surface [W/m^2]
I_{sc}	solar constant = 1367 [W/m^2]
$I_{t,t}$	total solar radiation on a tilted surface [W/m^2]
n_d	day of the year [-]
α_s	albedo of the earth surface [-]
β	angle of inclination from the horizontal [°]
δ	angle of declination [°]
ω	hour angle [°]
φ	latitude [°]
Ψ_b	beam radiation conversion factor [-]
Ψ_d	diffuse radiation conversion factor [-]
Ψ_r	ground reflected radiation conversion factor [-]
ρ_g	ground reflectivity [-]
θ	incidence angle [°]
θz	zenith angle [°]

1. INTRODUCTION

Solar radiation is the primary energy source of the earth-atmosphere system, which derives the formation and evolution of weather and climate processes [1, 2]. Solar energy is nowadays one of the most promising and economical renewable energy sources in the world [3]. The solar radiation reaching the earth's surface depends on the climatic condition of the specific site location, and this is essential for accurate prediction and design of a solar energy system [4]. In the recent past, solar radiation incident on both horizontal and inclined surfaces have been taken into consideration. Quantitative assessment of the solar radiation incident on tilted surfaces is of critical importance for energy-efficient control of the indoor climate of buildings such as greenhouses [5].

The solar radiation incident on greenhouse surfaces can be broken down into three main components: direct (beam) radiation emanating from the sky, diffuse sky radiation, and radiation scattered or reflected by the ground [6, 7]. The beam radiation incident on a horizontal surface can be converted to the beam radiation incident on a tilted surface using a simple geometrical relationship between the two surfaces [8]. However, this is not the case regarding the diffuse radiation component since the diffuse radiation rays have no defined source

[8]. Most solar energy systems (e.g. greenhouses) are designed with tilted collected surfaces [9]. In the Northern Hemisphere, the wide-span and the Venlo greenhouses are inclined to the south with an inclination angle of about 26.5° and 24° from the horizontal, respectively [10]. Therefore, it is necessary to have the knowledge about the availability of solar radiation and also to be able to estimate the total solar irradiance on tilted surfaces.

The techniques for estimating the hourly global solar radiation on a horizontal surface have been elaborated and proposed by many researchers [11, 12, 13]. These techniques are based either on the analysis of recorded data or on the analysis of meteorological data [11]. The solar radiation reaching the earth's surface is expressed in terms of the solar constant I_{sc}. It is defined as the total radiation energy received from the sun per unit area in a unit time on the earth's surface perpendicular to the sun's rays at a mean distance of the earth from the sun (1.496 · 108 km). The I_{sc} is valued at 1367 W/m^2 [14, 15] and this is accepted by many standard organizations including the American Society for Standards and Measurement (ASTM). Although the National Oceanographic and Atmospheric Administration (NOAA) uses a value of 1376 W/m^2, the fluctuations are normally small [16].

Global solar radiation data is mostly available from the weather stations worldwide. However, in some areas, the solar radiation is infrequently measured [17] and thus reliable radiation prediction models are essential. The diffuse-to-global solar radiation correlation, originally developed by [18], is one such indirect technique which is gaining importance in terms of prediction. This correlation has been extensively used with high accuracy in simulations [18, 19]. However, the correlation is location-dependent and the empirical coefficients need to be determined for every study location. Hence, based on the locally calibrated coefficients in the Northern Hemisphere, the objective of this study was to accurately predict the total solar radiation incident on a greenhouse roof surface tilted to the south.

2. THERMAL BOX DESIGN AND DESCRIPTION

An experimental thermal box (Fig. 1) was developed to simulate conditions similar to those of greenhouses in a realistic way. The box measured 2.4 m long, 1.9 m wide and 1.2 m high. The surface, covered with a 4 mm normal single greenhouse float glass, was inclined at 26.5° facing south and had a length of 2 m and a width of 1.5 m. The glass-covered was reinforced with steel glazing bars, such that 86% of the total surface area was glass while 14% of the area was all glazing bars. The box was placed outdoors at the Biosystems Engineering Section, Institute of Horticultural Production Systems, Leibniz Universität Hannover (52.39° N, 9.706° E and altitude 52.3 m above mean sea level). This measurement site is located in Lower Saxony, Germany, and lies in the north of Germany. The box had no transpiration systems inside, so it represented absolutely dry greenhouses. It is worth mentioning that the developed thermal box system was also useful for the longwave radiation exchange measurement [20].

Fig. 1 - Thermal box setup for solar radiation measurements

Upward and downward facing solar radiation components were independently measured with a CNR 4 net radiometer (Kipp & Zonen, Delft, The Netherlands). The CNR 4 measures the energy that is received from the whole hemisphere [21]. Data acquisition and control was done with a USB-Datalogger LabJack U12 (LabJack Corporation, Lakewood, USA), a signal amplifier LabJack EI-1040 (LabJack Corporation, Lakewood, USA) and a relay box ME-UBRE (Meilhaus Electronic GmbH, Alling, Germany). For the CNR 4 net radiometer, the original calibration coefficients from the company Kipp & Zonen (Delft, The Netherlands) were used. For the shortwave detector (pyranometer), sensitivity values of the upper and lower sensors are given in Table 1.

Table 1. Sensitivity of the pyranometer sensors

S/No.	Sensor	Sensitivity [μV/Wm^2]
1	Upper	13.58
2	Lower	10.83

The measured parameters were recorded in the range of 0 V to 10 V and the necessary calibration factors applied to obtain the actual data. The measurements were carried out every 30 s during the months of January to April 2014. The hourly means were then computed from the collected data. For model validation purposes, an extra dataset of solar radiation was obtained from the Institute of Meteorology and Climatology, Leibniz Universität Hannover, Germany.

3. THEORETICAL CALCULATIONS

Due to the elliptical orbiting of the earth around the sun, the distance between the earth and the sun fluctuates annually and this makes the amount of energy received on the earth's surface fluctuate in a manner given by [22]:

$$I_n = I_{sc} \cdot \left(1 + 0.033 \cdot \cos\left(\frac{360 \cdot n_d}{365} \right) \right) \quad (1)$$

where, I_n is the radiation measured on the plane normal to the radiation at any given time, I_{sc} is the solar constant (1367 W/m^2) and n_d is the day of the year (n_d is 1 on 1st January and n_d is 365 or 366 on 31st December).

The hourly extraterrestrial solar radiation on a horizontal surface I_o in W/m^2 for a period defined by hour angles ω_1 and ω_2 (where ω_2 is larger) can be calculated as[22, 23]:

$$I_o = \frac{12 \cdot I_n}{\pi} \cdot \left(\frac{\pi \cdot (\omega_2 - \omega_1)}{180} \cdot \sin\varphi \cdot \sin\delta + \cos\delta \cdot \cos\varphi \cdot (\sin\omega_2 - \sin\omega_1) \right) \quad (2)$$

where, φ is the latitude, δ is the angle of declination, ω is the hour angle, and β is the angle of inclination from the horizontal.

The angle δ can be evaluated from the following expression [14, 24]:

$$\delta = 23.45 \cdot \sin\left(360 \cdot \left(\frac{284 + n_d}{365} \right) \right) \quad (3)$$

The hour angle ω is computed as a function of the hour of the day in 24 hour time H_t as [14]:

$$\omega = \frac{H_t - 12}{24} \cdot 360° \quad (4)$$

This means that the hour angle has a negative value before local solar noon, a positive value after local solar noon and is zero at local solar time [11]. As described by [25], the local solar time (LST) can be found by using the time correction factor (which incorporates an equation of time) to adjust the local time (LT). The time correction factor (TC), in minutes, accounts for the variation of LST within a given time zone due to the longitude variations within the time zone [22, 25, 26].

Due to a limited availability of diffuse radiation data, decomposition models have been developed to predict the diffuse radiation using the measured global data [27]. These models are based on some key parameters which include the clearness index and the diffuse fraction. There is need to recalibrate these parameters for the study location in order to account for local climatic differences [19]. The relationship between the diffuse fraction F_d and the clearness index I_c was established by using daily diffuse and global radiation data of the study site for the 5-year period (2009 to 2013). The data was obtained from the Institute of Meteorology and Climatology, Leibniz Universität Hannover, Germany.

The hourly clearness index I_c is can be estimated as the ratio of global radiation on the horizontal surface $I_{g,h}$ to the extraterrestrial radiation on the horizontal surface I_o [11, 23] and is expressed as:

$$I_c = \frac{I_{g,h}}{I_o} \quad (5)$$

The diffuse fraction F_d expresses the ratio of diffuse-to-global solar radiation [19]. The diffuse radiation I_d is that portion of solar radiation that is scattered downwards by the molecules in the atmosphere. The diffuse radiation was therefore calculated as:

$$I_d = I_{g,h} \cdot F_d \quad (6)$$

The beam radiation I_b reaching a unit area of a horizontal surface on the earth in the absence of the atmosphere can be expressed by [28]:

$$I_b = I_{g,h} - I_d \quad (7)$$

According to [19] and [29], the relationship between F_d and I_c can be expressed by a polynomial correlation. The following 4th order polynomial correlation was fitted to the data.

$$F_d = a_0 + a_1 \cdot I_c + a_2 \cdot I_c^2 + a_3 \cdot I_c^3 + a_4 \cdot I_c^4 \quad (8)$$

For the study location, and using the recorded data, the coefficients a_0, a_1, a_2, a_3 and a_4 were experimentally obtained as 0.985, 0.467, -3.156, 0.248 and 1.525, respectively [30]. The polynomial models, and thus the model coefficients, are dependent on latitude, precipitable water content, atmospheric turbidity, surface albedo, altitude and solar elevation angle [31].

According to [23], an estimation of total solar radiation incident on tilted surfaces can be expressed as:

$$I_{t,t} = I_{b,h} \cdot \psi_b + I_{d,h} \cdot \psi_d + I_{g,h} \cdot \rho_g \cdot \psi_r \quad (9)$$

where, $I_{t,t}$ is the total solar radiation incident on tilted surfaces, $I_{b,h}$ is the beam radiation on a horizontal surface, $I_{d,h}$ is the diffuse radiation on a horizontal surface, $I_{g,h}$ is the global radiation on a horizontal surface, ρ_g is the ground reflectivity, Ψ_b is the beam radiation conversion factor, Ψ_d is the diffuse radiation conversion factor and Ψ_r is the ground reflected radiation conversion factor.

For a surface with a given orientation β, the daily value of Ψ_b is related to the time variation of incident beam radiation, the intensity of which on the ground level is a function of the atmospheric transmittance [32]. These radiation conversion factors are given by [23]:

$$\psi_b = \frac{\cos\theta}{\cos\theta_z} \quad (10)$$

$$\psi_d = \frac{1 - \cos\beta}{2} \quad (11)$$

$$\psi_r = \frac{1 + \cos\beta}{2} \quad (12)$$

where, θ is the incidence angle, θz is the zenith angle and β is the surface inclination angle.

The upwelling shortwave radiation is the reflected global radiation and is given by:

$$I_{ref,t} = \alpha_s \cdot I_{t,t} \qquad (13)$$

where, $I_{ref,t}$ is the reflected radiation from a tilted surface, α_s is the albedo of the earth surface and $I_{t,t}$ is the total radiation incident on a tilted surface. An average albedo value of 0.2 was used in this study for sites which are not cultivated and have a low vegetation cover [33, 34]. This value is therefore applicable for fields where grass is present.

The steps involved in the model modification of the total solar irradiance on the tilted surface are shown in Fig. 2. Once the beam and the diffuse components of total solar radiation incident on a horizontal surface are determined, they can be transposed over any given tilted surface [23]. The data generated from the measurement system were beneficial in validation of the simulation models.

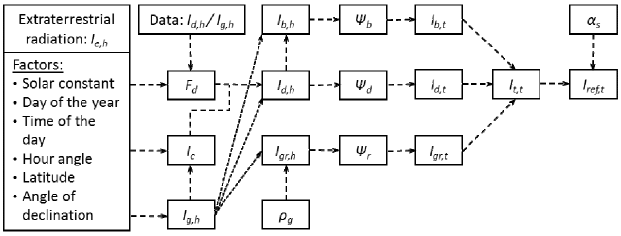

Fig. 2. Stepwise modelling of solar radiation components at the tilted surface

where, $I_{e,h}$ is the extraterrestrial radiation on a horizontal surface, F_d is the diffuse fraction, I_c is the clearness index, $I_{g,h}$ is global radiation on a horizontal surface, $I_{b,h}$ is the beam radiation on a horizontal surface, $I_{d,h}$ is the diffuse radiation on a horizontal surface, $I_{gr,h}$ is the ground reflected radiation on a horizontal surface, ρ_g is the ground reflectivity, Ψ_b is the beam radiation conversion factor, Ψ_d is the diffuse radiation conversion factor, Ψ_r is the ground reflected radiation conversion factor, $I_{b,t}$ is the beam radiation on a tilted surface, $I_{d,t}$ is the diffuse radiation on a tilted surface, $I_{gr,t}$ is the ground reflected radiation to a tilted surface, $I_{t,t}$ is the total solar radiation on a tilted surface, α_s is the albedo of the earth surface and $I_{ref,t}$ is the reflected radiation from a tilted surface.

4. RESULTS AND DISCUSSION

The measured solar radiation incident on an inclined glass-covered surface, the horizontal global radiation on the horizontal plane and the diffuse solar flux from the sky are compared in Fig. 3. The intensity of the measured solar radiation appears to increase with the change of season (from winter to early spring). This is revealed by relatively high solar radiation magnitudes as the hour number increased. The trend also shows that the total solar irradiance on the south-facing tilted surface $I_{t,t}$ was always higher than the horizontal global radiation $I_{g,h}$. The diffuse horizontal solar radiation $I_{d,h}$ was notably close to the $I_{g,h}$ values, especially after the 150th hour number. During the early stages of the study period (before the 150th hour number), the diffuse solar radiation data mostly registered very low values compared to the horizontal global solar radiation and the total solar flux incident on an inclined roof surface.

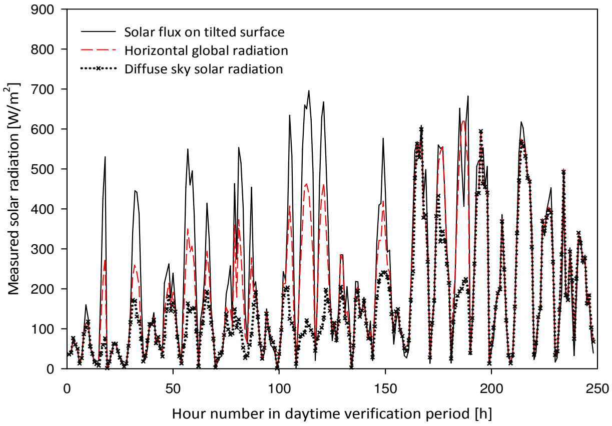

Fig. 3. Variation of measured solar radiation incident on horizontal and tilted surfaces

A comparison between the solar radiation measured by the two pyranometers of the CNR 4 net radiometer and the corresponding values calculated with the radiation models is presented in Fig. 4. The total solar irradiance on the south-facing surface inclined at 26.5° includes both the direct and diffuse solar radiation components. Simulation with the appropriate radiation conversion factors gave promising results, especially within the solar radiation range of 0 W/m^2 to 500 W/m^2. The south-facing surface offers better solar radiation energy collection and this is evidently true for the study site which is located in the Northern Hemisphere. The solar radiation of high magnitude occurred towards the end of the measurement period, i.e. in the early spring period. During the day, solar radiation is the dominant flux under clear, dry skies. The solar flux is also important with cloudy skies since cloudiness alters the solar radiation profile through scattering and absorption of the incident solar radiation.

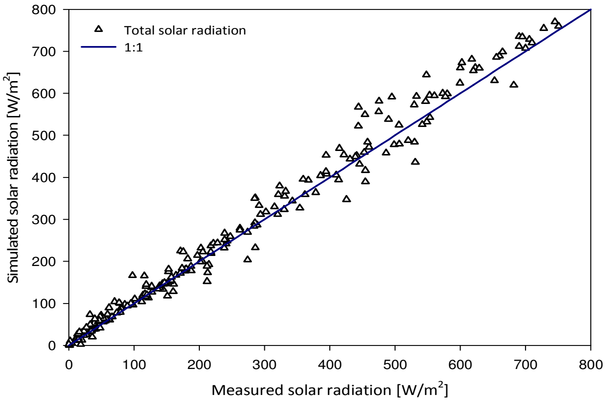

Fig. 4. Comparison between simulated and measured total solar radiation incident on a tilted greenhouse surface

As seen from Fig. 5, the reflected solar radiation during the entire observation period was generally less than 155 W/m^2. A portion of the energy reaching the surface is reflected skyward where it may again interact with the clouds. These radiative interactions constitute the surface cloud radiative forcing over a given area, a factor used to determine the impact of clouds on the irradiance [35].

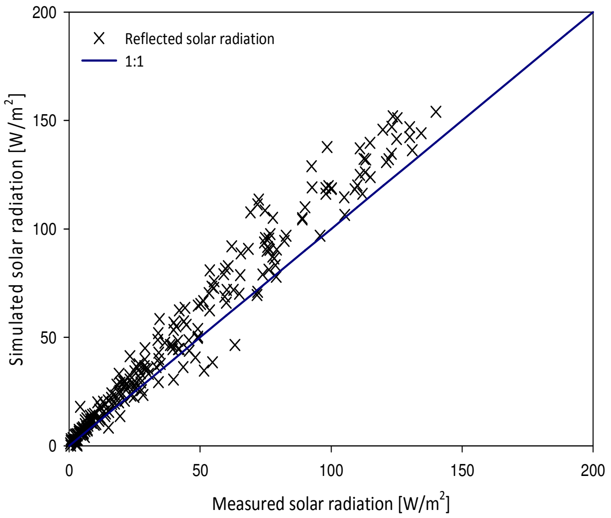

Fig. 5. Comparison between simulated and measured reflected solar radiation

For any given location, the solar radiation reaching the surface decreases with increasing cloud cover. The larger insolation increases the surface temperature [36] and this result in high longwave radiation emitted by the surface to the sky, as reported by [20]. The developed solar radiation models with the respective radiation conversion factors compared well with the measurements (see Figs. 4 and 5). The values of coefficient of determination (R^2) for total solar radiation incident on the inclined roof surface and the reflected component were 0.962 and 0.951, respectively. The results imply that it is possible to accurately calculate the total solar radiation incident on any surface (inclined or horizontal) for any location other than the measurement site considered in this study. This is in agreement with [37] where the 4th order polynomial correlation was successfully applied in prediction of daily and monthly solar radiation in São Paulo City, Brazil. However, the coefficients of the 4th order polynomial correlation relating the diffuse fraction with the clearness index, need to be rechecked. This is achieved through calibration based on the global and the diffuse radiation data for any location. Although it is latitude-dependent, the diffuse-to-global solar radiation correlation has been used extensively as a technique providing accurate results [18, 19, 38]. Hence, the local calibration is critical for accuracy enhancement of the solar radiation models. For inclined surfaces, it is necessary to consider the radiation reflected onto the surface by adjacent surfaces. Modifications of the solar radiation models are generally recommended for better estimation of average (hourly, daily or monthly) solar radiation on a tilted surface.

5. CONCLUSION

From this work, the measured solar radiation incident on the tilted greenhouse roof surfaces compared well with the simulations. The locally calibrated correlation relating the diffuse fraction and the clearness index yields promising results in the prediction of the total solar irradiance. Through a combination of statistical and graphical methods, a relatively high performance of the prediction model was achieved. For energy balance under daytime conditions, the solar irradiance on greenhouse surfaces plays a very important role and should therefore be accounted for precisely. Solar radiation data is readily available from most weather stations particularly for horizontal surfaces and this, together with other parameters, can be used in calculating the total irradiance on tilted surfaces with an acceptable accuracy. In particular, it is believed that the improved polynomial correlation (diffuse fraction as a function of the clearness index) can efficiently be used for the total solar irradiance computation in other parts of the world. However, due to the differences in spatial and temporal resolutions, the polynomial correlation needs to be reassessed so as to establish its general applicability. Generally, reliance on indirect techniques of solar radiation estimation is gaining importance especially for data-scarce regions (such as in Africa) where measurement is quite infrequent.

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