Prediction of total solar irradiance on tilted greenhouse surfaces

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Abstract: Solar radiation is the driving force for the surface energy balance in buildings such as greenhouses. The 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 the tilted surfaces based on the solar global and diffuse radiation intensities on horizontal surfaces. In this work, a south-facing thermal box inclined at 26.5° from the horizontal was used for solar radiation measurements. Additionally, the recorded solar radiation data were retrieved for the study location and used to develop an empirical correlation. The derived 4th order polynomial correlation related the diffuse fraction to the clearness index. The conversion factors for the beam, the diffuse and the reflected solar radiation components were essential in the prediction of the total solar irradiance on the tilted surface. The measured solar radiation data were then compared with the simulated total irradiance on the tilted surface. The model performance was assessed using both graphical and statistical methods. Overall, the diffuse-to-global solar radiation correlation has proved to be a useful technique providing reliable results. The locally calibrated data led to a clear improvement in the estimated total solar radiation. Generally, reliance on indirect techniques of solar radiation estimation is gaining importance especially for data-scarce regions where measurement is quite infrequent.

Keywords: solar radiation, greenhouses, tilted surface, diffuse fraction, clearness index

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1 Introduction

Solar energy is nowadays one of the most promising renewable energy sources in the world (Sawin, 2013). Quantitative assessment of the solar irradiance incident on tilted surfaces is of critical importance for energy-efficient control of the indoor climate of buildings such as greenhouses (Gulin et al., 2013). The solar radiation incident on external greenhouse surfaces can be broken down into three main components (Figure 1): direct (beam) radiation emanating from the region of the sky near to the sun's disc, diffuse radiation from the sky vault, and radiation scattered or reflected by the ground (Garg and Prakash, 2000; Al-Ajlan et al., 2003). 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 (Evseev and Kudish, 2009). However, this is not the case regarding the diffuse radiation component since the diffuse radiation rays have no defined source (Evseev and Kudish, 2009). Most solar energy systems (e.g. greenhouses) are designed with tilted collected surfaces (Pandey and Katiyar, 2013). 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 (Von Elsner et al., 2000). Therefore, it is necessary to have knowledge about the availability and to be able to estimate the solar radiation on tilted surfaces.

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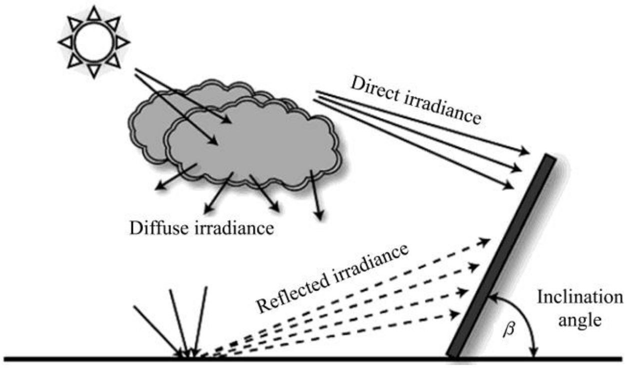

Figure 1 Solar irradiance components (source: modified after Gulin et al., 2013)

The techniques for estimating the hourly global solar radiation on a horizontal surface have been elaborated and proposed by many researchers (Abdullah and Ali, 2012; Gueymard, 1993; Davies and MacKay, 1989). These techniques are based either on the analysis of recorded data or on the analysis of meteorological data (Abdullah and Ali, 2012). 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 (1.496×10^8 km). The I_{sc} is valued at 1367 W m^{-2} (Sukhatme, 2003; Iqbal, 1983) 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 (Howell et al., 2011).

Global solar radiation data is mostly available from the weather stations worldwide. However, in some areas, the solar radiation is infrequently measured (Shamim et al., 2015) and thus reliable radiation prediction models are essential. The diffuse-to-global solar radiation correlation is one such indirect technique which is gaining importance in terms of prediction. This correlation has been extensively used with high accuracy in simulations (Liu and Jordan, 1960; Jacovides, 2006). The correlation relates the diffuse fraction and the clearness index using global and diffuse radiation measurements on a horizontal surface. However, the correlation is location-dependent and the empirical coefficients need to be determined for every study location. Hence, based on the local calibration coefficients, this study aims at estimating the total solar irradiance on tilted greenhouse surfaces.

2 Materials and methods

2.1 Experimental setup

A thermal box (Figure 2) 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 cover material (4 mm normal single greenhouse float glass) was inclined at 26.5° to the south and had a length of 2 m and a width of 1.5 m with steel glazing bars. 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 thermal box was also useful for the longwave radiation exchange measurement (Ronoh and Rath, 2015).

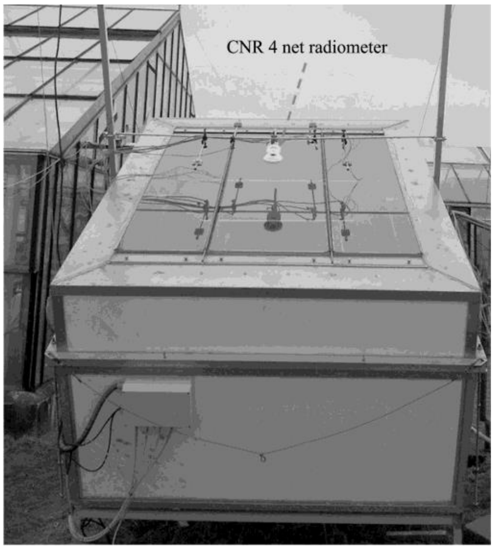

Figure 2 Thermal box system for thermal radiation measurements

2.2 Data acquisition

Upward and downward facing solar radiation components were independently measured with a CNR 4 net radiometer (Kipp & Zonen, Delft, and The Netherlands). The CNR 4 measures the energy that is received from the whole hemisphere (Kipp & Zonen, 2009). 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 newly acquired CNR 4 net radiometer, the original calibration coefficients from the company Kipp & Zonen (Delft, The Netherlands) were used. For the shortwave detector (pyranometer), the sensitivity values of the upper and the lower sensors were 13.58 µV Wm^{-2} and 10.83 µV Wm^{-2}, respectively.

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

2.3 Mathematical modelling of total solar irradiance

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:

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

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 one 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 using the following equation (El-Sebaii et al., 2010; Duffie and Beckman, 1991):

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

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 (Sukhatme, 2003; Ezekoye and Enebe, 2006):

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

The hour angle ω is computed as a function of the hour of the day in 24 hour time H_t as (Sukhatme, 2003):

$$\omega = \frac{H_t - 12}{24} \cdot 360° \tag{4}$$

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 (Abdullah and Ali, 2012). According to Honsberg and Bowden (2012), the local solar time (*LST*) can be found by using two corrections to adjust the local time (*LT*).

$$LST = LT + \frac{TC}{60} \tag{5}$$

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 (Duffie and Beckman, 1991; Goswami et al., 2000; Honsberg and Bowden, 2012) and also incorporates the equation of time (EoT) (in minutes).

$$TC = 4(L_{st} - L_{loc}) + EoT \tag{6}$$

where, L_{st} is the standard meridian for the local time zone and L_{loc} is the longitude of the location.

The *EoT* is calculated from the following expression (Honsberg and Bowden, 2012):

$$EoT = 9.87 \cdot \sin(2 \cdot B) - 7.53 \cdot \cos(B) - 1.5 \cdot \sin(B) \tag{7}$$

where, the coefficient B is given by:

$$B = \frac{360}{365} \cdot (n_d - 81) \tag{8}$$

Due to a limited availability of diffuse radiation data, decomposition models have been developed to predict the diffuse radiation using the measured global data (Wong and Chow, 2001). These models are based on some key parameters which include the clearness index and the diffuse fraction. There is a need to recalibrate these parameters for the study location in order to account for local climatic differences (Jacovides et al., 2006). The relationship between the diffuse fraction F_d and the clearness index I_c was established by using daily diffuse and global radiation data for the five-year period (2009 to 2013). The data was obtained from the Institute of

Meteorology and Climatology, Leibniz Universität Hannover.

The hourly clearness index I_c 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 (El-Sebaii et al., 2010; Abdullah and Ali, 2012):

$$I_c = \frac{I_{g,h}}{I_o} \tag{9}$$

The diffuse fraction F_d expresses the ratio of diffuse-to-global solar radiation (Jacovides et al., 2006). The diffuse radiation is that portion of solar radiation that is scattered downwards by the molecules in the atmosphere. The diffuse radiation on a horizontal surface $I_{d,h}$ was therefore calculated as:

$$I_{d,h} = I_{g,h} \cdot F_d \tag{10}$$

The beam radiation reaching a unit area of a horizontal surface on the earth in the absence of the atmosphere $I_{b,h}$ can be expressed by Ibrahim et al. (2011):

$$I_{b,h} = I_{g,h} - I_{d,h} \tag{11}$$

According to Jawarneh et al. (2012) and Jacovides et al. (2006), 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.

$$F_d = a_0 + a_1 \cdot I_c + a_2 \cdot I_c^2 + a_3 \cdot I_c^3 + a_4 \cdot I_c^4 \tag{12}$$

The coefficients a_0, a_1, a_2, a_3 and a_4 are empirical constants which can be experimentally obtained for the study location.

According to El-Sebaii et al. (2010), an estimation of total solar radiation incident on tilted surfaces can be expressed as:

$$I_{t,t} = I_{b,h} \cdot \psi_b + I_{d,h} \cdot \psi_d + I_{g,h} \cdot \rho_g \cdot \psi_r \tag{13}$$

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 (Yang et al., 2012). These radiation conversion factors are given by El-Sebaii et al. (2010):

$$\psi_b = \frac{\cos\theta}{\cos\theta_z} \tag{14}$$

$$\psi_d = \frac{1-\cos\beta}{2} \tag{15}$$

$$\psi_r = \frac{1+\cos\beta}{2} \tag{16}$$

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

An overview of the solar angles involved in calculating the amount of solar irradiance on tilted surfaces is shown in Figure 3. The incidence angle θ for a surface inclined to the south towards the equator (northern hemisphere) is dependent on the inclination angle (Twidell and Weir, 2005). The zenith angle θ_z is the angle between the line that points to the sun and the vertical. At solar noon θ_z is zero, while in the sunrise and sunset this angle is 90°. The solar azimuth angle γ is the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative and west positive (Sahin and Sen, 2008). This angle is only measured in the horizontal plane and thus neglects the height of the sun. The solar altitude α (also known as solar elevation angle) is the angle between the horizon and the centre of the sun's disc.

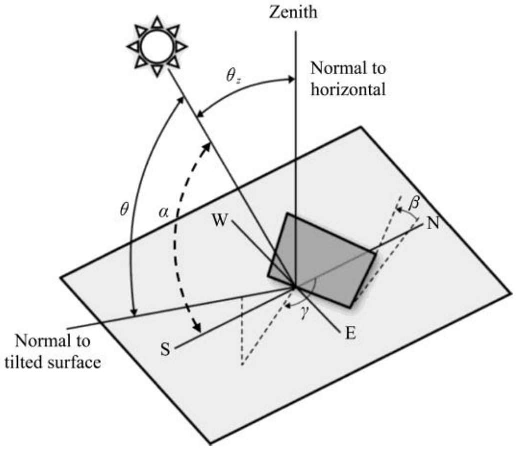

Figure 3 Detailed description of solar angles for a tilted surface (source: modified after Twidell and Weir, 2005)

The incidence angle, the solar altitude, the zenith angle and the solar azimuth angle are generally expressed as (Yang et al., 2012; Shamim et al., 2015; Twidell and Weir, 2005; Bolsenga, 1979):

$$\theta = \arccos(\cos\delta \cdot \cos(\varphi-\beta) \cdot \cos\omega + \sin\delta \cdot \sin(\varphi-\beta)) \tag{17}$$

$$\theta_z = \arccos\left(\cos\delta \cdot \cos\varphi \cdot \cos\omega + \sin\delta \cdot \sin\varphi\right) \quad (18)$$

$$\alpha = \arcsin(\cos\delta \cdot \cos\varphi \cdot \cos\omega + \sin\delta \cdot \sin\varphi) \quad (19)$$

$$\gamma = \arccos\left(\frac{\sin\delta \cdot \cos\varphi - \cos\delta \cdot \sin\varphi \cdot \cos\omega}{\cos\alpha}\right) \quad (20)$$

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

$$I_{ref,t} = \alpha_s \cdot I_{t,t} \quad (21)$$

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 (Campbell and Norman, 1998; Scharmer and Greif, 2000). This value is therefore applicable for fields where grass is present.

3 Results and discussion

A comparison of the measured solar radiation incident on the tilted glass-covered surface, the horizontal global radiation on the horizontal plane and the diffuse solar flux from the sky is presented in Figure 4. 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 irradiance on the south-facing tilted surface I_t was always higher than the horizontal global radiation I_{gh}. The diffuse horizontal solar radiation I_d was notably close to the I_{gh} values, especially after the 150th hour number.

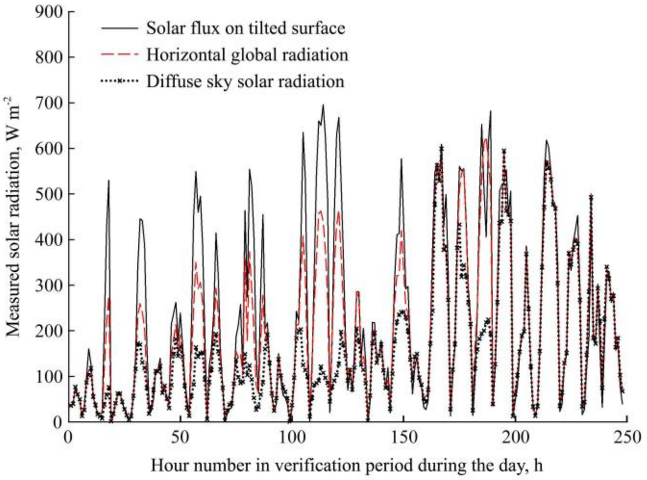

Figure 4 Variation of measured solar radiation incident on horizontal and tilted surfaces

From individual daily global and diffuse solar radiation measurements, the diffuse fraction as a function of the clearness index was computed; the trend is shown in Figure 5. The figure shows the scatter plot of the data and the fitted line (dashed line) resulting from the 4th order polynomial correlation. The correlation fits well for the clearness index I_c in the range of zero and 0.75.

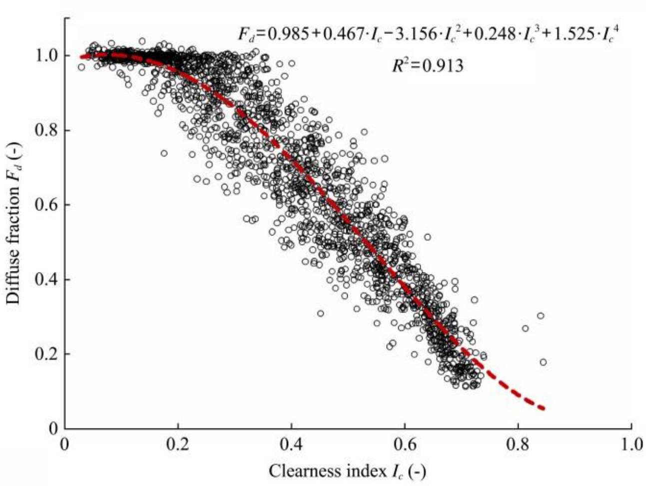

Figure 5 Plot of the relationship between the diffuse fraction and the clearness index

Figure 6 illustrates the comparisons between the solar radiation measured by the two pyranometers of the CNR 4 net radiometer and the corresponding values calculated with the radiation models.

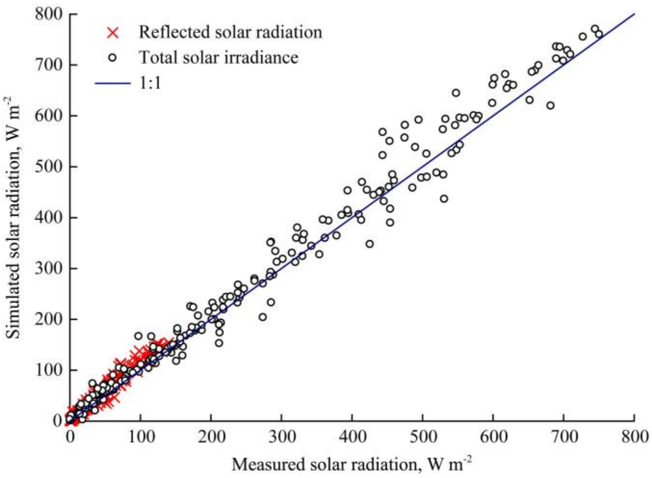

Figure 6 Comparison between the simulated and the measured solar radiation components

The total solar irradiance on the south-facing surface inclined at 26.5° included 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 solar radiation of high magnitude occurred towards the end of the measurement period, i.e. in the early spring period. As seen from the figure, the reflected solar radiation during the entire observation period was generally less than 155 W m^{-2}.

4 Discussion

The diffuse-to-global solar radiation correlation, originally developed by Liu and Jordan (1960), has been used extensively as a technique providing accurate results, although it is latitude-dependent. This empirical procedure involves a one-parameter correlation between the diffuse fraction F_d and the clearness index I_c. The 4th order polynomial expression helps to establish the relationship between the hourly F_d and I_c using the measured data on a horizontal surface (Jacovides et al., 2006). From the available dataset (2009 to 2013), this polynomial expression showed a good agreement for $0 \leq I_c \leq 0.75$ (see Figure 5). Another important observation is that for $I_c > 0.75$, the diffuse fraction F_d does not decrease further. Despite a paucity of data for $I_c > 0.75$, F_d is relatively large at high I_c values. For $I_c > 0.75$, an average F_d value of 0.2 was found to be appropriate and this is in agreement with the value given by Miguel et al. (2001).

During the day, solar radiation is the dominant flux under clear, dry skies (when $I_c \rightarrow 0$). The solar flux is also important with cloudy skies (when $I_c \rightarrow 1$) since cloudiness alters the solar radiation profile through scattering and absorption of the incident solar radiation. 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 (Key and Minnett, 2004). For any given location, the solar radiation reaching the surface decreases with increasing cloud cover. The larger insolation increases the surface temperature (Moene and van Dam, 2014) and this result in high longwave radiation emitted by the surface.

The south-facing surface offers better solar irradiance energy collection and this is evidently true for the study site which is located in the northern hemisphere. The developed solar radiation models with the respective radiation conversion factors compared well with the measurements (see Figure 6). The values of coefficient of determination (R^2) for total solar irradiance on the inclined surface and the reflected component were 0.962 and 0.951, respectively. The results imply that it is practical to calculate the total solar irradiance on any surface (inclined or horizontal) for any location other than the measurement site considered in this study. Based on the global and the diffuse radiation data for any location, the coefficients of the 4th order polynomial correlation relating the diffuse fraction with the clearness index need, however, to be rechecked. It is worth noting that the findings from this study are in line with other results reported in the literature (Miguel et al., 2001; Jacovides et al., 2006; Evseev and Kudish, 2009). For inclined surfaces such as those used in this study, it is necessary to consider the radiation reflected onto the surface by adjacent surfaces. Modifications of the solar radiation models are generally recommended for estimating the hourly, the daily or the monthly averages of solar radiation (direct, diffuse, ground reflected and total) on a tilted surface.

5 Conclusions

In this paper, the solar radiation measurements at the tilted greenhouse surfaces are compared with simulations of the total solar irradiance with the 4th order polynomial correlation. The derived 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 relating the diffuse fraction and the clearness index can efficiently be used for the total solar irradiance computation in other parts of the world. Due to the difference in spatial and temporal resolution, the derived correlation can be further assessed as to whether it is site-specific or generally applicable.

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