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Estimation of Solar Irradiance on Inclined Surfaces Facing South in Tanta, Egypt

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Abstract-The purpose of this work is to investigate a computer program by using Pascal language to estimate the solar irradiance on inclined surfaces. The global solar irradiance on horizontal surfaces is measured for Tanta of latitude (30 47) and longitude (30 99) during the period (2008-2009). The computer program has been prepared to calculate the monthly average daily irradiance and hourly solar irradiance on inclined surfaces from the measured horizontal global solar irradiance data. Hourly diffuse solar irradiance and the average monthly daily diffuse solar irradiance are estimated using (Miguel et al.[9]) correlation and (El-Sebaii and et al.[10]) correlation for Tanta Egypt, by using a computer programs. The method presented can be used to estimate hourly, global, diffuse solar radiation for horizontal surfaces and total solar radiation on inclined and vertical surfaces at different orientations with greater accuracy for any location.

Keywords*:* Solar radiation, inclined surfaces, tilting angle, diffuse radiatio***, c***omputer program

1. Introduction

A variety of numerical models for calculating the solar irradiance for an inclined surface are described and evaluated using data for any location on the land. Where all the hourly models have a common approach for calculating the direct component of the solar irradiance there is a variety of methods for calculating the diffuse irradiance based on the portion of the sky hemisphere within the field of view of the surface. A less significant distinction between the models is in the methods used to calculate the amount of radiation received as a result of reflection from adjacent surfaces. [1].

The hourly solar radiation data required for solar energy system design evaluation and performance studies is generally not available for a number of sites especially in remote locations. As such accurate determination of hourly solar radiation data, is important both at horizontal; surfaces and inclined surfaces. A model to estimate global solar radiation using temperature and sunshine hour data has been developed (Chandel et al. [2]) which is used to calculate the hourly solar radiation Data. The hourly solar radiation has also been calculated using Gueymard [3] daily integration approach from the measured daily solar radiation data. These two predicted hourly solar radiation data values are compared with measured hourly values to test the accuracy of the models. The total solar radiation on the inclined surfaces and vertical surfaces for different orientations, have also been estimated. The estimated values are found to be in close agreement with measured values. The method presented can be used to estimate hourly, global, diffuse solar radiation for horizontal surfaces and total solar radiation on inclined and vertical surfaces at different orientations with greater accuracy for any location.

The solar radiation that reaches the outer atmosphere is subjected to absorption, reflection, and transmission processes through the atmosphere before reaching the earth’s surface [3]. The knowledge of global solar radiation is extremely important for the optimal design and the prediction of the solar energy conversion system performance [4]. The calculation of hourly solar radiation on tilted surfaces is important in many practical applications of solar energy. Usually hourly global solar radiation is measured on a horizontal plane, while radiation on tilted or variably orientated vertical surfaces is calculated by means of empirical models [5]. To calculate inclined insolation, it is necessary to know beam and diffuse components. However, as most weather stations provide only global irradiance data on a horizontal surface, the diffuse irradiance on horizontal surface and global irradiance on tilted surfaces are not available for almost all locations in the world, and have to be estimated from theoretical models [6].

In this paper, a computer program by using Pascal language to estimate the solar irradiance on inclined surfaces. The global solar irradiance on horizontal surfaces is measured for Tanta of latitude ($30^o 41'$) during the period (2008-2009). Also, the programs have been prepared to calculate the monthly average daily irradiance and hourly solar irradiance on inclined surfaces from the measured horizontal global solar irradiance data. The hourly diffuse solar irradiance and the average monthly daily diffuse solar irradiance will be calculated.

2. Methods of Investigation.

2.1. Measurements of global solar irradiance

In this work, the global solar irradiance during the 12-month period from July 2008 to July 2009 has been measured by using the Epply-Precision spectral Pyranometer (E-PSP) which is situated on the top of Faculty of Science, Tanta University, Tanta of latitude ($30^o 41'$).

2.2. Determination of hourly solar irradiance on an inclined surface.

Solar hourly irradiance on an inclined surface (I_t) has been calculated and plotted for Tanta through the whole year (2008-2009). Computer program using Pascal language is prepared for calculating the global hourly solar irradiance on a tilted surface, using the measured data of global solar irradiance on horizontal surface and by using the following equations:-

The number of day light hours is given by,

$$N = \frac{2}{15}\cos^{-1}(-\tan\varphi\tan\delta) \qquad (1)$$

Equation (2) represents the hourly clearness index K_T [7]:

$$K_T = \frac{I_{gh}}{I_o} \qquad (2)$$

The hourly values of beam and diffuse components of solar irradiance from hourly global solar irradiance have been calculated by using Miguel et al. correlation [8,9]:

$$\frac{I_d}{I_{gh}} = \begin{cases} 0.995 - 0.081k \\ 0.724 + 2.738k_T - 8.32k_T^2 + 4.967k_T^3 \\ 0.18 \end{cases}$$

$$\left.\begin{matrix} if\ k_T < 0.21, \\ if\ 0.21 \le k_T \le 0.76, \\ if\ k_T > 0.76. \end{matrix}\right\} \quad (3)$$

The beam irradiance incident on a tilted surface is given as:

$$I_b = I_{gh} - I_d \quad (4)$$

The total solar irradiance incident on a tilted surface is written as:

$$I_t = I_b R_b + I_d R_d + R_r (I_b + I_d) \quad (5)$$

Where R_b, R_d, R_r are known as conversion factors for beam, diffuse and reflected components [7]. They are given as:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \quad (6)$$

$$R_d = \frac{1 + \cos\beta}{2} \quad (7)$$

$$R_r = \rho' \left(\frac{1 + \cos\beta}{2} \right) \quad (8)$$

Where ρ' is the reflectivity of the ground? In this work $\rho' = 0.2$.

The effective ratio of solar energy incident on a tilted surface to that on a horizontal surface, is

$$R_t = \frac{I_t}{I_{gh}} \quad (9)$$

$$Kav_T = \frac{H_{gh}}{Hav_o} \quad (10)$$

where H_{gh} is the monthly average daily total solar irradiance on a horizontal surface.

The monthly average daily diffuse component of solar irradiance has been calculated by using El-Sebaii and Trabea correlation [10][15] which is represented by the following equation

$$\frac{H_d}{H_{gh}} = 1.242 - 1.337 Kav_T \text{ ,RC=0.78} \quad (11)$$

The monthly average daily beam irradiance can be calculated from,

$$H_b = H_{gh} - H_d \quad (12)$$

If both the diffuse and ground-reflected solar irradiance are assumed to be isotropic, then, in a manner analogous to Eq. 12, the monthly mean solar irradiance on a tilted surface can be expressed as

$$H_t = H_b R_b + H_d R_d + R_r H_{gh} \quad (13)$$

With

$$R_{av} = \frac{H_t}{H_{gh}} \quad (14)$$

where R_{av} is the monthly conversion factor for average daily total solar irradiance.

3. Discussions of Results

3.1. Determination of hourly solar irradiance on inclined surface

Fig. 1 till Fig. 4 illustrate the variation of hourly values of solar irradiance on tilted surfaces I_t and hourly global solar irradiance on horizontal surfaces I_{gh} with the time of day during the period July 2008 to July 2009.

From the results of these figures, it is evident that in January 2009 there are big differences between the values of $\mathbf{I_{t1}}$ and $\mathbf{I_{gh1}}$. The sky is cloudy that leads to increasing the diffuse component which increases the values of $\mathbf{I_{t1}}$. These results agree with previous work [11, 12]. After solar noon, both of them have the same values. In February 2009, there are few differences between the values of I_{t2} and I_{gh2}. After solar noon, both of them have nearly the same values. In March 2009 there are few differences between the values of I_{t3} and I_{gh3} all the day. In April 2009 there are few differences between the values of I_{t4} and I_{gh4}. After solar noon, both of them have the same values. In May and June 2009 there are some differences between the values of hourly solar irradiance on tilted surfaces and hourly global solar irradiance on horizontal surfaces all the day.

It is also noticed that in July 2008, August 2008 and July 2009 there are few differences between the values of hourly solar irradiance on tilted surfaces and hourly global solar irradiance on horizontal surfaces. After 5pm, the differences between these values become large. In September 2009, there are some differences between the values of I_{t9} and I_{gh9}. After 5pm, both of them have the same values. In October and November 2008 there are large differences between the values of hourly solar irradiance on tilted surfaces and hourly global solar irradiance on horizontal surfaces. After 3pm there are few differences between these values. In December 2008, there are large differences between I_{t12} and I_{gh12}, while after solar noon, there are some differences between the values.

Fig.1. to Fig.4, illustrate the maximum hourly solar irradiance on a tilted surface facing south is 1152.97 Wm^{-2} in March. The minimum hourly solar irradiance on a tilted surface facing south is 223.69 Wm^{-2} in December.

Also, it is clear that the solar irradiance measurements are strongly affected by clouds. Surface measurements of the diffuse component of solar irradiance are particularly sensitive to cloud amount. The clouds are divided into (i) a cloudless day and (ii) an overcast morning and an afternoon with broken clouds. In many cloudy days, the conditions varied throughout the day from overcast in the morning, with cloud gradually breaking up throughout the afternoon to the early evening when the clouds are cleared completely.

During the overcast sky conditions, the values of I_{gh} are small compared to the clear sky case and almost equal to diffuse solar irradiance, which fluctuates more in the clear sky case. During the afternoon the cloud becomes broken. The values of I_{gh} are greater than diffuse solar irradiance when the sun is directly visible. When cloud obscures the sun, however, the values of I_{gh} are reduced and matched the diffuse solar irradiance. These results agree with those reported in the literature [13]. It is also obvious that in summer (July, August and September), there are little differences between values of I_t and I_{gh}. During summer season, the clouds are much less.

Finally, it is concluded that the effects of optically dense clouds on solar irradiance levels can cause almost total reduction in the direct component and an appreciable increase in diffuse component of solar irradiance [14].

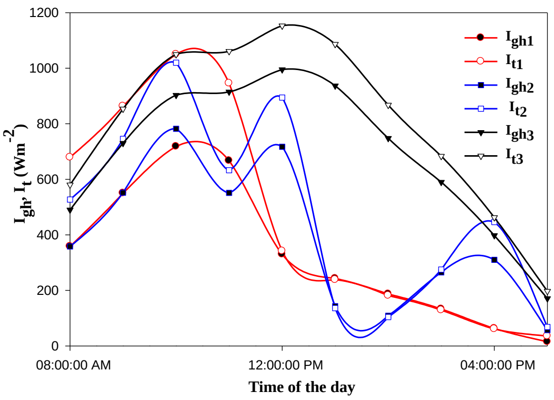

Fig. 1: Hourly solar irradiance on tilted surface I_t and global solar irradiance on horizontal surface I_{gh} with time of the day in winter (January-1, February-2 and March-3 of 2009).

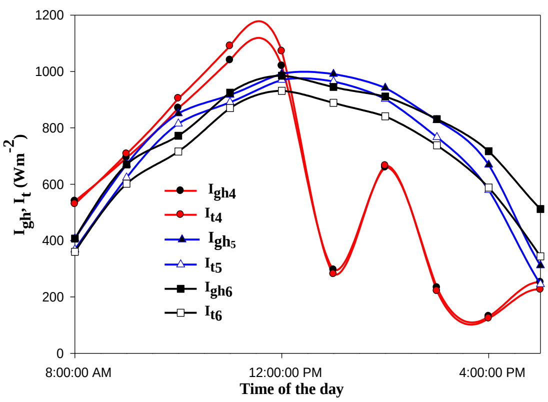

Fig. 2: Hourly solar irradiance on tilted surface I_t and global solar irradiance on horizontal surface I_{gh} with time of the day in spring (April-4, May-5 and June-6 of 2009).

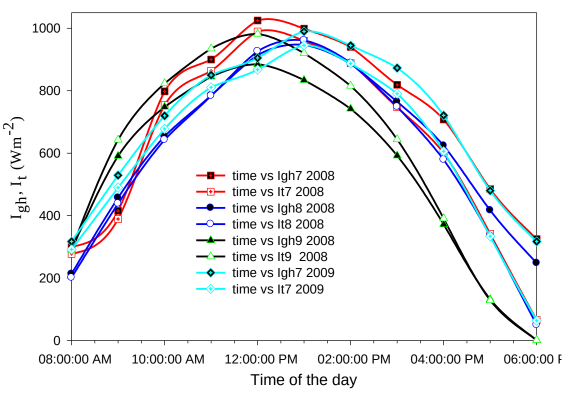

Fig. 3. Hourly solar irradiance on tilted surface I_t and global solar irradiance on horizontal surface I_{gh} with time of the day in summer (July-7, August-8 and September-9 of 2008 and July-7 of 2009).

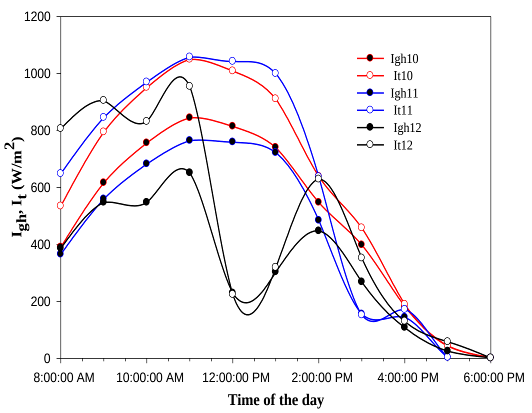

Fig. 4. Hourly solar irradiance on tilted surface I_t and global solar irradiance on horizontal surface I_{gh} with time of the day in autumn (October-10, November-11 and December-12 of 2008).

Table 1 shows the effective ratio R_t of solar energy incident on a tilted surface to that on a horizontal surface in winter and spring. From the results of Table 1, it is clear that the sunset times in January, February, March, April, May and June are 6PM, 6PM, 7PM, 7PM, 7PM and 7PM, respectively.

Table 2 shows the effective ratio of solar energy incident on a tilted surface to that on a horizontal surface R_t in summer and autumn. It is obvious from the results of Table 2 that the sunset times in July, August, September, October, November and December are 8 PM, 8 PM, 6 PM, 6 PM, 6 PM and 6 PM, respectively. The results of Table 1 and Table 2 indicate that in winter and autumn, the sun leaves early an hour or more than in summer and spring. The numbers of day light hours in July and August are about 13.8 hours and the numbers of day light hours in October, November, December, January and February are 11.2 hours. The day light hours in March, April, May and June are 12.8 hours. The number of day light hours varies in every season because the distance between the sun and the earth also varies. The number of day light hours in every month in this year has been calculated by using Eq (1).

The monthly average clearness index Kav_T and Rav for the months from August 2008 to July 2009 are illustrated in Table 3.

Table 1. R_t (The effective ratio of solar energy incident on a tilted surface to that on a horizontal surface) values in winter and spring for a day / every month from Sunrise to Sunset

Winter & Spring	Jan. 18	Feb. 17	Mar. 16	April 15	May 15	June 12
Time	$R_{t\,1}$	$R_{t\,2}$	$R_{t\,3}$	$R_{t\,4}$	$R_{t\,5}$	$R_{t\,6}$
8 AM	1.89	1.47	1.184	0.981	0.904	0.885
9 AM	1.57	1.35	1.169	1.02	0.93	0.898
10 AM	1.46	1.3	1.163	1.039	0.958	0.927
11 AM	1.41	1.14	1.16	1.048	0.972	0.941
12 noon	1.03	1.24	1.159	1.051	0.978	0.946
1 PM	0.98	0.95	1.16	0.95	0.973	0.941
2 PM	0.97	0.95	1.16	1.009	0.958	0.923
3 PM	0.97	1.03	1.159	0.95	0.927	0.888
4 PM	0.971	1.43	1.163	0.947	0.866	0.82
5 PM	2.382	1.19	1.154	0.897	0.785	0.672
6 PM	-	-	1.066	0.883	0.327	0.201
7 PM	-	-	-	-	-	-

Table 2. R_t (The effective ratio of solar energy incident on a tilted surface to that on a horizontal surface) values in summer and autumn for a day in every month from sunrise to sunset

Summer & Autumn (2008)	July 17	Aug. 16	Sep. 15	Oct. 15	Nov. 14	Dec. 10	July 17 2009
Time	$R_{t\,7}$	$R_{t\,8}$	$R_{t\,9}$	$R_{t\,10}$	$R_{t\,11}$	$R_{t\,12}$	$R_{t\,7}$
8 AM	0.925	0.945	1.005	1.369	1.775	2.088	0.919
9 AM	0.937	0.96	1.088	1.289	1.512	1.654	0.925
10 AM	0.945	0.983	1.101	1.257	1.421	1.519	0.941
11 AM	0.96	0.999	1.106	1.243	1.384	1.465	0.954
12 noon	0.966	1.013	1.11	1.239	1.373	0.977	0.958
1 PM	0.961	1.015	1.104	1.23	1.384	1.053	0.955
2 PM	0.945	1.003	1.099	1.166	1.316	1.406	0.939
3 PM	0.912	0.979	1.088	1.15	0.979	1.312	0.905
4 PM	0.848	0.928	1.05	1.04	1.189	1.203	0.84
5 PM	0.704	0.804	0.974	0.974	0.986	2.35	0.695
6 PM	0.201	0.201	-	-	-	-	0.201
7 PM	-	0.945	-	-	-	-	0.919
8 PM	-	-	-	-	-	-	-

3.2. Monthly average daily solar irradiance on tilted surfaces

Fig.5. illustrates the variation of average monthly daily solar irradiance on a tilted surface, average monthly global solar irradiance, the average monthly of daily beam, daily diffuse and reflected component of solar irradiance on a tilted surface facing south during a whole year in Tanta β equals the latitude of Tanta. It is obvious that the value of the ground reflected component

of solar irradiance may be neglected compared to the beam and diffuse components. The maximum value of H_t has been obtained as 29.25 (MJ/m^{2}day) during March. The minimum value of H_t has been determined to be 15.54 (MJ/m^2 day) during January.

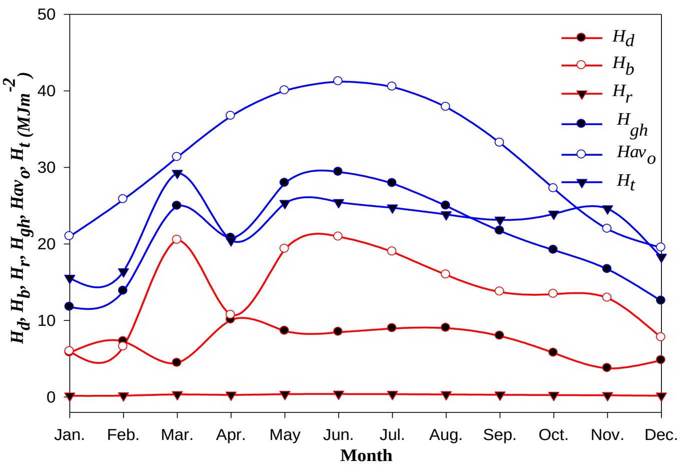

Fig. 5. The average monthly solar irradiance on tilted surface H_{av} , average monthly global solar irradiance H_{gh}, the average monthly of beam H_b, diffuse H_d and reflected H_r components of solar irradiance on tilted surface for the months of the years (2008-2009)

Table 3. The monthly average clearness index Kav_T and R_{av} for the months from August 2008 to July 2009

Month	Year	Kav_T	R_{av}
August	2008	0.659	0.955
September	2008	0.654	1.066
October	2008	0.705	1.246
November	2008	0.761	1.474
December	2008	0.644	1.457
January	2009	0.56	1.322
February	2009	0.536	1.185
March	2009	0.796	1.173
April	2009	0.566	0.984
May	2009	0.698	0.906
June	2009	0.713	0.865
July	2009	0.689	0.886

4. Conclusions

The global solar irradiance on horizontal surfaces has been measured. Computer programs have been prepared to calculate the monthly average daily solar irradiance and hourly solar irradiance on inclined surfaces from the global solar irradiance. The hourly diffuse solar radiation and the average monthly daily diffuse solar irradiance are estimated using Miguel et al. correlation and El-Sebaii and Trabea correlation for Egypt, respectively. From the obtained results, it may be concluded that the maximum hourly solar irradiance on a tilted surface facing south is 1152.97 Wm^{-2} in March and the minimum hourly solar radiation on a tilting surface facing south is 223.69 Wm^{-2} in December. The value of the ground reflected component may be neglected compared to the beam and diffuse components. The maximum value of H_t is 29.25 (MJ/m^{2}day) during March. The minimum value of H_t is 15.54 (MJ/m^2 day) during January. Also, the effective ratio of solar energy incident on a tilted surface to that on a horizontal surface and the monthly average clearness index Kav_T and R_{av} for the months from August 2008 to July 2009 were estimated.

Appendix A

I_o, the extraterrestrial radiation on a horizontal surface for a period defined by hour angles ω_1 and ω_2 which define an hour (where ω_2 is larger) [7]:

$$I_o = \frac{12\times3600}{\pi} G_{sc}\left(1+0.033\cos\frac{360n}{365}\right)\left(\cos\varphi\cos\delta(\sin\omega_2-\sin\omega_1)+\frac{2\pi(\omega_2-\omega_1)}{360}\sin\varphi\sin\delta\right) \tag{A1}$$

Where G_{sc} is the solar constant (normally taken as1367W/m^2), n is the day of the year

The monthly average daily

extraterrestrial radiation on a horizontal surface Hav_o

$$Hav_o = \frac{24\times3600}{\pi} G_{sc}\left(1+0.033\cos\frac{360 n_{av}}{365}\right)$$

$$\left(\cos\varphi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\sin\varphi\sin\delta\right) \qquad \text{(A)}$$

where n_{av} is average day of the month and ω_s is the sunset hour angle, in degrees.

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