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Estimation of Optimum Tilt Angles for Solar Collector and Gained Energy at Cairo, Egypt

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Abstract

The solar energy incident on any fixed solar collector, for thermal or electrical purposes, is highly affected by the tilt angle of the collector over the horizontal surface. The tilt angle of any solar system is a function of the site parameters and the time through the year due to the continuous daily and seasonally movements of the earth with respect to the sun. This paper presents a theoretical study for detecting the effect of tilt angle on the incident solar energy on a solar collector and consequently determines the optimum tilt angles for each month, season and through the year. The mathematical model is based on the monthly average hourly measured values for diffuse and global solar radiation on horizontal surface in the test field of Solar Energy Department, NRC, Cairo, Egypt. The calculations also use the beam radiation on the horizontal as the difference between the measured global and diffuse values. The results showed that optimum fixed tilt angle through the year ranges from 28^o-30^o and the corresponding solar energy gain over that of the horizontal is 10%. For non-fixed systems, changing the tilt angle monthly, seasonally, two times per year and yearly can increase the collected solar energy over that of the optimal fixed tilt (30^o) by 5.5%, 4.6% and 4%, respectively.

Keywords: *Solar radiation, Radiation conversion models, Collector tilt angles, Solar angles, Solar energy gains.*

1. Introduction

Due to the continuous diminishes in the world conventional energy with the great demand of energy for development strategies and the world concerns about environmental pollution, the solar energy as a renewable source has been utilized and become one of the most important alternative safe sources for solving these problems [1]. In this manner, solar energy can help in supporting the required energy in many applications either thermal or electrical. In thermal applications, it can be used in water heating, agriculture and medical products drying, air heating and conditioning, solar cooking, solar desalination, water treatment and greenhouse applications [2]. Electricity also can be generated using solar energy as direct generation in photovoltaic systems or as indirect generation such as in concentrated solar power stations [3]. In all applications, solar as a source of energy has many advantages such as; clean without any impact on the environment, renewable, safe, low maintenance, technology development and the generated energy can be used directly at the site without need any expensive and complicated transmissions [4].

In all solar installations, the orientation of the solar system with respect to the sun's position is the major factor affecting the output energy and hence the overall system performance. As the performance of the solar system depends on the amount of solar energy reached to its surface, maximizing the energy received by the system is very important [5]. The amount of solar irradiation incident on an arbitrary solar system is a function of several parameters such as; total radiation on a horizontal surface, diffuse radiation, surround ground reflected radiation, system location, day number and system orientation. Orientation which is very important factor for designing and installating the solar systems is mainly a function of the system tilt angle and facing [6].

Solar system can be installed either fixed or movable to maximize the amount of solar energy received via keeping the incident solar beam radiation normal to the system surface as possible. In the fixed system, the solar collector is mounted on a fixed structure facing directly south or north according to the geographic location in northern or southern hemisphere, respectively. Also, it can be tilted over the horizontal surface by a tilt angle according to the site latitude and the time. This orientation can help in reducing the incident angle of the solar beam according to the orientation position [7]. The advantages of the fixed system arise from increasing the solar radiation on the system over that of the horizontal one by amount of 6-12% according to the site location without any movements, which reduce the system maintenance, moving complexity and problems [8]. In the movable (tracking) system, the solar collector movement is continuously adjusted according to the nature of the solar motion in one or two axes (according to the daily and seasonally movements of the sun) in order to align the solar collector with the solar radiation beam as possible. This tracking can maximize the solar energy falling on the system surface by amount of 20-42% depending on the location and the nature of the tracking [9]. Although tracking the solar system increases the incident solar energy, but it still has some limitations due to the complexity resulting from the gears, motors or operation maintenance [10].

Different researches studied the optimum tilt angle of the solar collector over the horizontal surface and the corresponding energy gain over the world in theoretical or practical basis using either theoretical models for getting solar radiation components or using the measured radiation values on a horizontal surface. Ghosh et al., [11] studied the optimum tilt angle for the solar collector located at latitude of 23.73 ^{o}N. They reported that the annual optimum tilt angle is about 28^{o} and that for summer and winter are 10^{0} and 40^{o}, respectively. In Syria, Sheiker [12] designed a mathematical model for getting the monthly optimum tilt angles and the corresponding energy benefits concluding that daily adjusting the tilt angle increases the system overall radiation by amount of 30% more than that of the horizontal one. In Athens, Rapits et al., [13] simulated the solar energy gain from adjusting the tilt angle depending on simulation models using the measured horizontal radiation and showed that the energy gain from changing the tilt by ±8^{o} reaches 10% over that of the fixed at 38^{o} and the optimum tilt angles is 30^{o}. In India, based on measurements of the global and diffuse radiation on horizontal surface the estimated optimum tilt angles are 27.62^{o} and 27.95^{o} for 27.89^{o} (Aligarh) and 28.61^{o} (Delhi), respectively. Also, the solar radiation gains over that of the horizontal are 6.5%, 11.6% and 12.9% for the yearly, seasonally and monthly adjusted tilt angles [14]. The same study is presented for Algerian zone of 27.88^{o} N latitude based on actual measurements and showed that the optimum tilt angles are 3.5^{o} and 49.2^{o} for summer and winter periods, respectively, and the semi-annual energy gain over that of the horizontal is 19.24%, which is also more than that of the annual tilt [15]. The effect of changing the tilt angle in the PV system performance is also studied for various sites in Saudi Arabia using simulation program based on the measured horizontal solar radiation. The study concluded that about 99% of the energy captured by daily adjusting the tilt angle can be achieved by varying the system tilt angle for only 6 times per year [16]. In Turkey, the optimum tilt angle is determined for eight cities between latitude 36^{o}-41^{o} depending on the measured solar radiation in these sites. The study showed that the optimum tilt angle reached zero in summer months (June & July), which is the minimum value and increased in winter to its maximum value in December by about 60^{o} [17]. In Abu Dhabi, Jafar kazemi [18] concluded that the optimum tilt angle ranges from -9^{o} to 52^{o} and the facing south fixed solar system performance can be optimized by adjusting the tilt angle two times per year one for summer and the other for winter. A theoretical model for getting the winter optimum tilt angle for a fixed PV installation was developed in Nigeria by Ikeodem [19] which showed that tilting the system by 24.7^{o} over the horizontal can get the maximum radiation in winter. In Iran, Moghadam [20] concluded that adjusting the PV system tilt angle twice per year could increase the total energy output by 8% than the optimal fixed one. In US, lave [21] revealed that adjusting the fixed solar system to its optimum tilt can get energy gain by 10-25% over that of the horizontal according to the latitude of the system. For summer and winter seasons, the optimum tilt angles studied in Cyprus [22] and Malaysia [23] are 14 or 48 and 0 or 27 for two countries, respectively. Ullah et al. [24] reported that the annual optimum tilt angle in Lahore-Pakistan is 31.5^{o} while it ranges between 0^{o} and 50.5^{o} for summer and winter seasons. Finally, the neural networks also are used in optimizing the global solar radiation by getting the optimal tilt angle in Mashad-Iran [25].

The present paper uses the measured monthly average global and diffuse radiation in Wh/m^{2}/day incident on a horizontal surface for estimating the optimum tilt angles over the horizontal plane for an arbitrary fixed solar system. The measured radiation values are taken from the weather station in the test field of Solar Energy Department, NRC, Cairo, Egypt located in; 30°2'39" North, 31°14'9" East and Elevation of 22 m. The paper also calculates in monthly average the daily global solar radiation on a tilted surface based on the optimum tilt angle for; every month, every three months, two times per year or yearly. Also, it gives the gains in the collected solar radiation resulting from varying the tilt angle across the year over that of the fixed tilt and horizontal. In this study, the incident angle of the beam solar radiation on the tilted surface is firstly calculated using the desired location in terms of latitude & longitude and time in terms of the day number of the year. Then, converting the beam and diffuse radiation of the horizontal to that of the tilted surface.

2. Incident angle

The main factor affecting the amount of total solar radiation received by an arbitrary surface or solar collector located in a certain latitude and longitude is the sun position with respect to that surface. The position of the sun with respect to any surface is a function of different parameters such as; time of the year, system tilt angle, geographic location, and the other solar angles shown in Fig. 1.

The angle of incidence of the solar beam in any surface is the angle between the normal to the system surface and the solar beam. Minimizing the incident angle, increasing the total system radiation, so tilting the solar system or moving to track the sun attempted to keep this angle as minimum as possible. The general form of the incident angle of the solar beam on a surface is given as follows [26];

$$\begin{aligned}\cos\Theta &= \sin\varphi\cdot\sin\delta\cdot\cos\beta - \cos\varphi\cdot\sin\delta\cdot\sin\beta\cdot\cos Z_S \\ &+ \cos\varphi\cdot\cos\delta\cdot\cos\omega\cdot\cos\beta + \sin\varphi\cdot\cos\delta\cdot\cos\omega\cdot\sin\beta\cdot\cos Z_S \\ &+ \cos\delta\cdot\sin\omega\cdot\sin\beta\cdot\sin Z_S \qquad (1)\end{aligned}$$

Where the angles in equation (1) are; latitude angle (φ), declination angle (δ), tilt angle (β), surface azimuth angle (Z_S) and hour angle (ω).

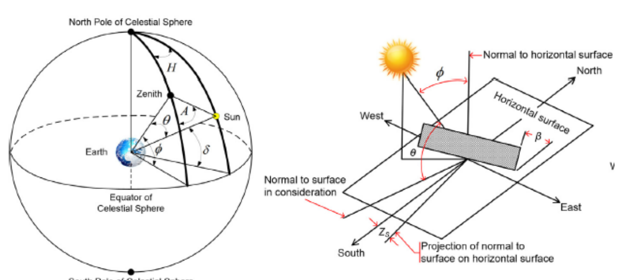

Fig. 1: Solar angles affecting the incident angle of the beam radiation on a tilted surface [26].

2.1 latitude angle (φ)

It represents the distance in degrees on the earth's surface from the equator, south or north as shown in Fig. 1. The system tilt angle is related to the location latitude. High latitude angles require large tilt angle for optimum system operation. Also, according to the change of the sun elevation angles (height of the sun), the tilt angle varies between different seasons thorough the year.

2.2 Declination angle (δ)

It is the angle between the sun at solar noon with respect to the equator. During the year it ranges between ±23.45o. Fig. 2 shows the variation of the declination angle through the year. It can be calculated in radians according to the day number (N=1 to 365 starting from first of January) from the following relation [24];

$$\delta = \frac{23.45\cdot\pi}{180}\cdot\sin\left(\frac{2\pi(284+N)}{365}\right) \qquad (2)$$

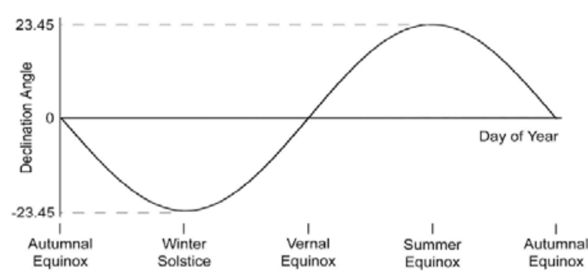

Fig. 2: Variation of the declination angle through the year.

2.3 Tilt angle (β)

It is the angle that the collector surface can be tilted over the horizontal to reduce the incident angle of the sun beam. As shown in Fig. 1, it is the angle between the normal to the center of the earth and the normal to the surface. If the solar system is installed horizontally, then the tilt angle will be zero. The solar surface can be tilted from 0o to 90o in northern hemisphere and from 0o to -90o in southern hemisphere [24].

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2.4 Surface azimuth angle (Z_S)

It is the angular displacement between the projection of the normal to the surface on the horizontal plane with the south direction. When the system is oriented to the south, the surface azimuth is zero, -90o to west and 90o to east.

2.5. Hour angle (ω)

It measures the angle between the longitude of the site on the earth and that of the parallel to the sun. Since the earth rotates complete revolution every day, the displacement of the sun is 15o per hour. At noon it equals zero, negative morning and positive afternoon [28]. The hour angle can be calculated from the following relation;

$$\sin\omega = \frac{\sin\alpha - \sin\delta \cdot \sin\varphi}{\cos\delta \cdot \cos\varphi} \qquad (3)$$

2.6 Solar altitude angle (α)

It represents the height of the sun over the horizontal surface or it is the angle between the line pointed directly to the sun and the horizontal surface. It can be derived from the following relation;

$$\sin\omega = \sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cos\omega \qquad (4)$$

Eq. (1) is the general form of the incident angle of the solar beam on any surface on the earth. If the solar system is facing directly to south direction, then the system azimuth angle (ZS) equals zero. Then the new form of the incident angle will be;

$$\cos\theta = \sin\varphi \cdot \sin\delta \cdot \cos\beta - \cos\varphi \cdot \sin\delta \cdot \sin\beta + \cos\varphi \cdot \cos\delta \cdot \cos\omega \cdot \cos\beta + \sin\varphi \cdot \cos\delta \cdot \cos\omega \cdot \sin\beta \qquad (5)$$

3. Solar radiation

The global solar radiation incident on any arbitrary tilted surface is composed of three components; direct (Gbβ), diffuse (Gdβ) and ground reflected (Grβ) components. All these components can be calculated on the tilted surface from the measured solar radiation of beam, global and diffuse on a horizontal plate using the incident angle Eqs. (1-5). Eq. 6 represents the three components of the total radiation on a tilted surface while Fig. 3 illustrates these components [29].

$$G_{g\beta} = G_{b\beta} + G_{d\beta} + G_{r\beta} \qquad (6)$$

3.1 Direct radiation

Direct radiation incident on any tilted surface on the earth is the radiation that directly hits the surface without suffering any scattering or deviation by the obstacles such as atmosphere water vapor or air dusts. The value of this radiation component is directly affected by the incident angle between the beam radiation and the system surface [30].

$$G_{b\beta} = G_b \cdot \cos\theta \qquad (7)$$

Where Gb is the beam radiation on a horizontal surface.

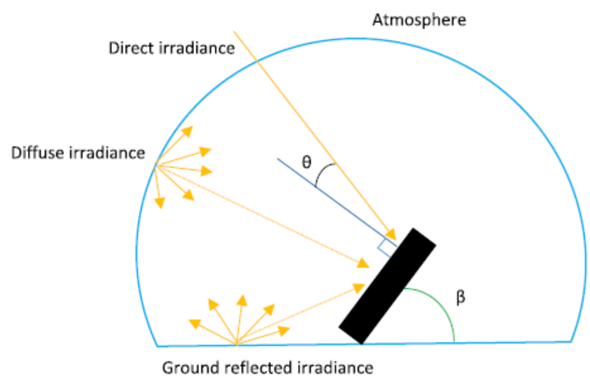

Fig. 3: Solar radiation components incident on a tilted surface [29].

3.2. Diffuse radiation

Diffuse radiation on any tilted surface on the earth is the radiation hits the surface after changing its direction due to continuous scattering by the water vapor of the atmosphere or other obstacles in the air. Different models are used to convert the horizontal diffuse radiation into a tilt surface one.

$$G_{d\beta} = \frac{G_{dh}(1+\cos\beta)}{2} \cdot \left[1+F\cdot\sin^3(\beta/2)\right]\cdot\left[1+F\cdot\cos^2(\theta)\cos^3(\alpha)\right] \qquad (8)$$

$$F = 1-\left(\frac{G_{dh}}{G_{gh}}\right)^2 \qquad (9)$$

Where; Gdh is the diffuse radiation measured on a horizontal surface. Ggh is the global or total radiation measured on horizontal surface. F is a factor representing the amount of the sky diffuses to global radiation of the horizontal surface. When the diffuse radiation is small compared to the global, then the sky can be considered clear and F equals unity (Anisotropic sky diffuse radiation model [31]). On contrary, when the diffuse in large with respect to global radiation, the sky seems to be not clear and F will be small (Isotropic diffuse radiation model [32]).

3.3 Reflected radiation

The third component of the total radiation on a tilted surface comes from the reflection of the solar beam by the ground. The amount of the reflected radiation is mainly depending on the nature of the ground such as; agriculture land, water, concrete or snow. Accordingly, different models tried to get the reflected radiation component on a tilted surface with different accuracies such as the isotropic model, as follows [33];

$$G_{r\beta} = \frac{\sigma \cdot G_{gh}(1-\cos\beta)}{2} \qquad (10)$$

Where σ is the ground reflected albedo, which represents the ratio of the reflected radiation to that of the total on a horizontal surface. Helwa et al., [33] reported that for concrete ground it can be taken accurately as 20%. From Eq. 10, it can be seen that the reflected radiation will not be zero is the solar surface is installed horizontally, which will reduce the total system radiation. Also, the amount of this radiation component increase by increasing the system tilt angle, and reaching its maximum at 90o tilt angle.

4. Measurements

Three solar radiation components are measured, averaged and stored as daily solar radiation energy based on monthly average in wh/m2/day using the weather station couples with data acquisition system installed in the test field of SED, NRC, Cairo, Egypt (30°2'39" North, 31°14'9" East). The measured components are the global and diffuse solar radiation on a horizontal plane using a kipp and Zonen pyranometers with and without shadow ring for global and diffuse radiation, respectively as shown in Fig. 4. The beam solar radiation was calculated as the difference between the measured global and diffuse components [14]. Fig. 5 indicates the measured solar radiation components on a horizontal surface as monthly average Wh/m^2/day.

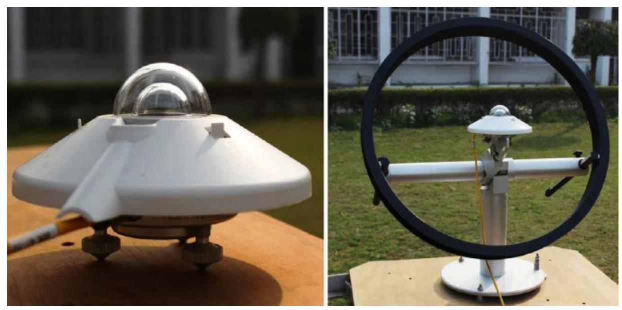

Fig. 4: Pyranometers with and without shadow ring for global and diffuse radiation measurements.

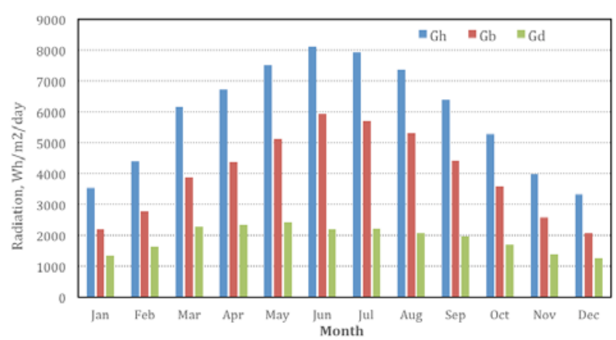

Fig. 5: Beam, diffuse and global solar radiation measured on a horizontal surface.

Fig. 5 shows that the chosen site (Cairo) has high solar radiation values on the horizontal surface reaches about 8 and 6 kWh/m2/day in summer months for global horizontal and beam radiations, respectively. The yearly average horizontal radiation per day is about 5.9 kWh/m2/day. The percentage of the diffuse to the global on a horizontal

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surface showed in Fig. 6. The diffuse radiation increases in the winter period reached its maximum of about 38% of the global radiation, while this percentage reduced to about 27% in summer. The yearly average diffuse to global radiation on horizontal is about 32%.

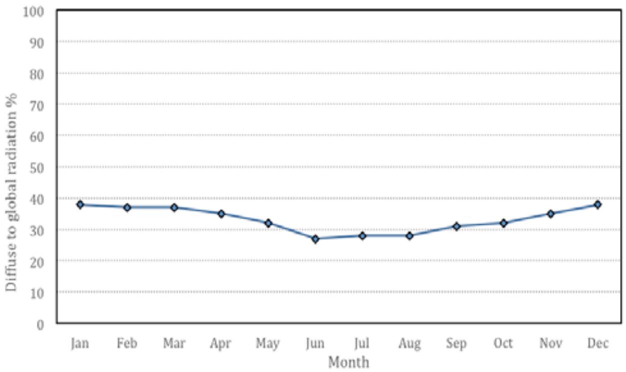

Fig.6: Percentage of the diffuse to global radiation on horizontal surface.

5. Methodology

The methodology for getting the solar radiation on a titled surface from that on a horizontal surface and hence get the optimum tilt angle of the fixed inclined solar collectors and the corresponding gain in the amount of solar energy captured by the tilted collector is carried out as follows;

i. Using the measured values for global (G_{gh}), diffuse (G_{dh}) on a horizontal plane and beam (G_b) as inputs radiation values in monthly average basis for daily solar energy in Wh/m^2/day. Also, the site latitude and longitude with the day number are used for getting the incident angle on a tilted surface.

ii. Assume tilt angle stating from o^o to 60^o with step of 1^o to get the incident angle of the beam radiation on the tilted surface for each case using Eqs. (2-5).

iii. Calculate the direct radiation on a tilted surface ($G_{d\beta}$) by Eq. (7), Diffuse radiation ($G_{d\beta}$) by Eq. (8), Ground reflected radiation ($G_{r\beta}$) by Eq. (10) and the global tilted radiation ($G_{g\beta}$) by Eq. (6).

iv. Change the day number and repeat the steps from (ii) till the end of the year.

6. Results and discussions

The total daily solar radiation in Wh/m2/day based on monthly average have been calculated for the tilted surface at different tilt angles from 00 to 90o with a step of 1o for all months of the year. Fig. 7 indicates the total solar radiation on a tilted surface through the year at different tilt angles. The figure shows that the total radiation on a tilted surface increase as the tilt angle decreases in summer months reaching its maximum at zero tilt angle. While in winter, the small tilt angles decrease the collected solar energy. The total radiation on a tilted surface through the year corresponding to the different tilt angles were displayed for first and last six months of the year in Figs. 8&9, respectively. From the figures, it can be shown that the total radiation collected in summer (Jun., Jul. and Aug.) decrease as the tilt angle increases while it increase for winter (Nov., Dec. and Jan.) with the increase of tilt angle to the optimum tilt and then decrease again. The figures declare that there is an optimum tilt angle for maximizing the collected solar energy on a tilted surface for each month, which is larger in winter months than in summer ones.

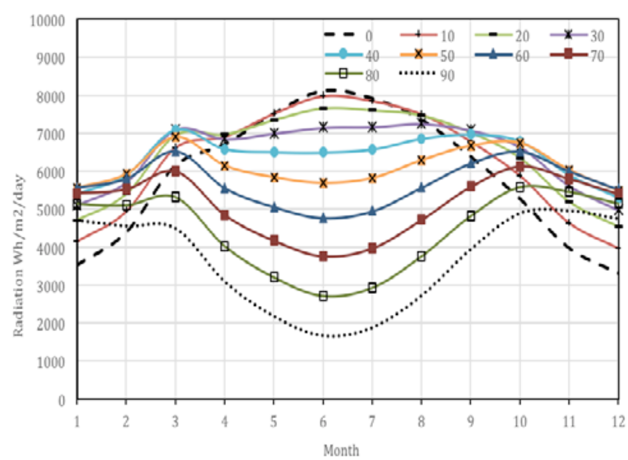

Fig. 7: Total solar radiation on a tilted surface through the year at different tilt angles.

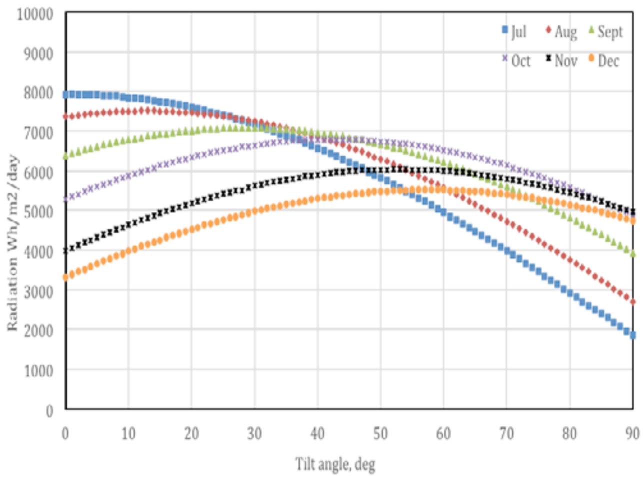

Fig. 8: Total radiation on a tilted surface with the tilt angle for first six months of the year.

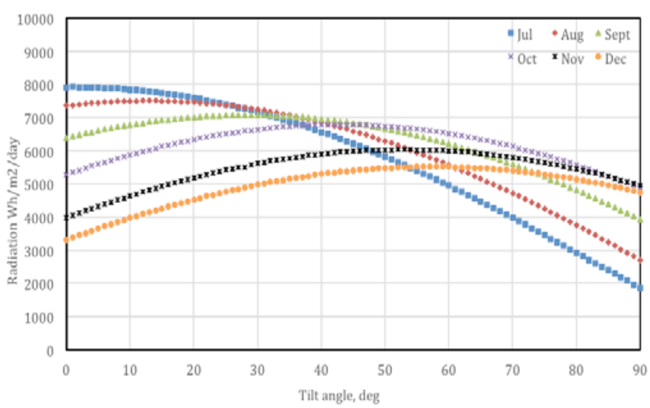

Fig. 9: Total radiation on a tilted surface with the tilt angle for last six months of the year.

The yearly average daily solar radiation in Wh/m^2/day on a tilted surface with different tilt angles is presented in Fig. 10. From the figure, it is clear that the yearly solar radiation on a tilted surface differs with the tilt angle and there is optimum tilt angle for maximizing the solar energy captured by the tilted surface between 28^o-30^0 as shown in the figure. The deviations from these tilt angles decrease the annual solar radiation. Fig. 11 shows the yearly average daily solar radiation on a tilted surface for 28^o, 29^o and 30^0 tilt angles. It is clear from the figure that tilting the solar collector by 28^o, 29^o or 30^o can capture the same maximum yearly solar energy, which reaches to 6480 Wh/m^2/day.

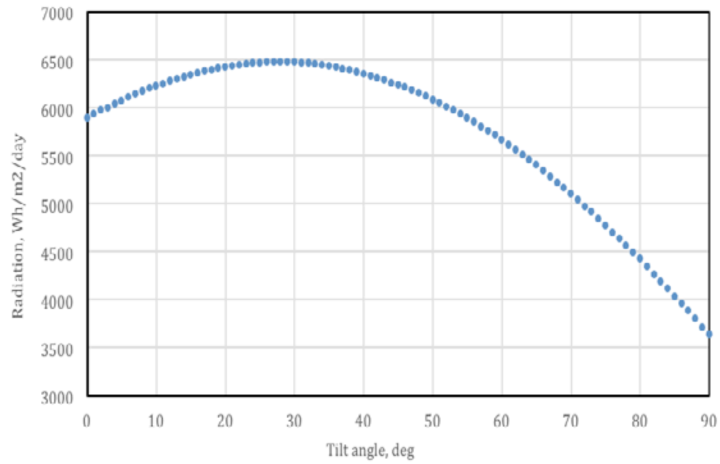

Fig. 10: Yearly average daily solar radiation on a tilted surface with different tilt angles.

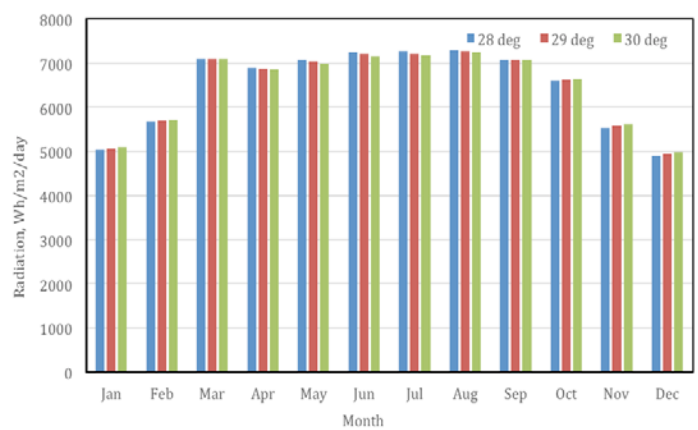

Fig. 11: Yearly average daily solar radiation on a tilted surface for 28^o, 29^o and 30^o

Fig. 12 indicates the monthly and yearly optimum tilt angle for the solar collector through the year and Fig. 13 shows the seasonally and semi-annually optimum tilt angles. As shown before, there is an optimum tilt angle for collecting maximum solar energy for each month reaching its maximum of 57o at December and its minimum of 0o and 1o at June and July, respectively. In the semi-annually optimum tilt angle, the tilt angle can be adjusted twice through the year which are the small one about 10o for summer and the other of 48o for winter as shown in Fig. 13.

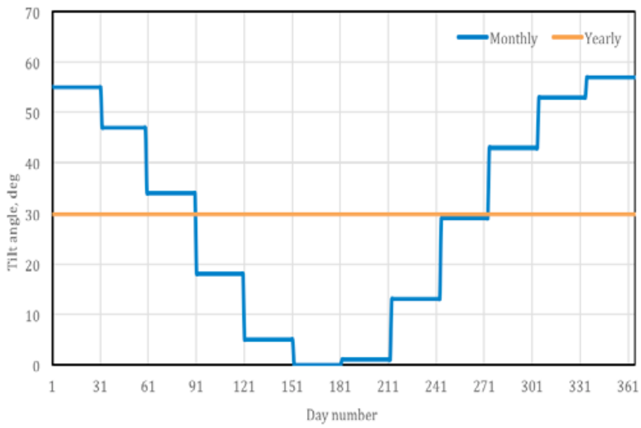

Fig. 12: Monthly variation of the optimum tilt angle through the year.

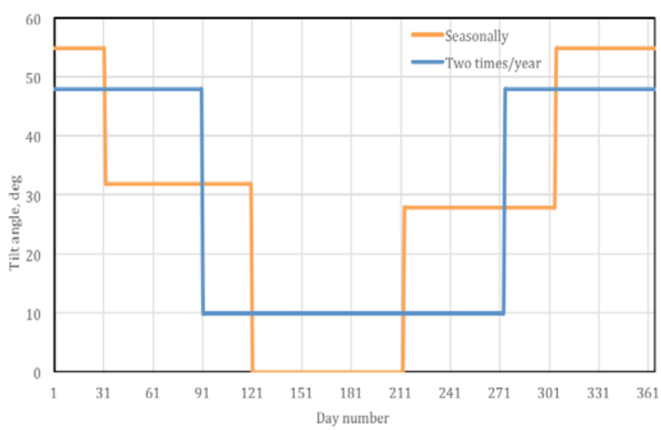

Fig. 13: Seasonally and semi-annually variation of the tilt angle through the year.

For comparison, the collected solar energy by both horizontal and tilted surface at yearly optimum tilt angle of 30o is shown in Fig. 14, while Fig. 15 expresses the same results for other optimum tilt angles such as seasonally, semi-annually and annually. Table 1 indicates the optimum tilt angles and the corresponding monthly average daily collected solar energy for each optimum tilt and Table 2 presents the yearly average gains of solar energy collected by each optimum tilt configuration.

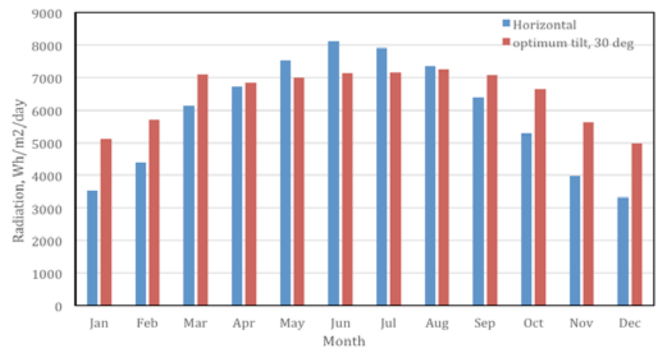

Fig. 14: Monthly average solar radiation from horizontal and yearly optimum tilt surfaces through the year.

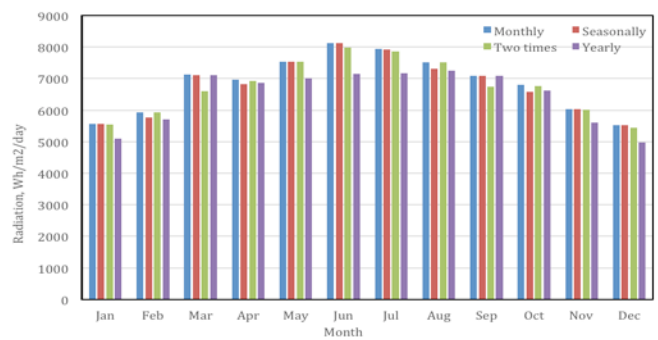

Fig. 15: Monthly average solar radiation at monthly, seasonally, semi-annually and yearly optimum tilt angle through the year.

Table 1: Monthly, seasonally, semi-annually and yearly optimum tilt angle of the solar collector and the corresponding average daily collected solar energy

Month	**Optimum tilt deg**	**Radiation at opt. tilt Wh/m^2/day**	**Seasonally opt. tilt deg**	**Radiation at seasonally opt. tilt Wh/m^2/day**	**Two times tilt per year deg**	**Radiation at two times tilt Wh/m^2/day**	**Fixed tilt at 30^o deg**	**Radiation at fixed tilt at 30^o Wh/m^2/day**
Jan.	55	5570	55	5570	48	5540	30	5110
Feb.	47	5940	32	5770	48	5940	30	5720
March	34	7120	32	7110	10	6620	30	7100
Apr.	18	6960	32	6810	10	6910	30	6850
May	5	7540	0	7520	10	7520	30	7000
Jun.	0	8120	0	8120	10	7980	30	7150
Jul.	1	7930	0	7920	10	7850	30	7170
Aug.	13	7510	28	7300	10	7500	30	7250
Sept.	29	7080	28	7080	48	6740	30	7080
Oct.	43	6790	28	6600	48	6760	30	6640
Nov.	53	6040	55	6030	48	6020	30	5620
Dec.	57	5520	55	5520	48	5450	30	4980

Table 2: Yearly average solar energy gains between different optimum tilt angles.

Optimum tilt	Yearly average radiation $Wh/m^2/day$	gain over horizontal	Radiation gain over fixed tilt
Monthly	6834	16 %	5.5 %
Seasonally	6779	15 %	4.6 %
Two times	6736	14 %	4 %
Fixed, 30^o	6480	10 %	
Horizontal	5900		

From the above figures and tables, it can be shown that;

i. In Cairo, there is high amount of the incident solar energy on the horizontal surface through the year with annual average of 5900 $Wh/m^2/day$, which can be considered one of the largest radiation values over the world.

ii. Tilting the solar collector by 30^o fixed tilt through the year increases the received average daily solar energy by 10% over that of the horizontal surface.

iii. Changing the tilt angle of the solar collector one time per month to its monthly optimum tilt increases the annual average solar energy captured to 6834 $Wh/m^2/day$ with gains of 16% and 5.5% over that of the horizontal and annual optimum tilt surfaces, respectively.

iv. Changing the solar collector four times per year using the optimum angle for each season as shown in Tables 1&2 rises the annual average solar energy captured to 6779 $Wh/m^2/day$ with gains of 15% and 4.6% over that of the horizontal and annual optimum tilt surfaces, respectively.

v. Changing the solar collector two times per year using the two optimum angles (10^o and 48^o for summer and winter months, respectively) increases the annual average solar energy captured to 6736 $Wh/m^2/day$ with gains of 14% and 4% over that of the horizontal and annual optimum tilt surfaces, respectively.

7. Conclusion

The present paper is a mathematical calculation based on measured values of the average daily global and diffuse solar radiation on horizontal surface to get the annual, seasonal, semiannual and monthly optimal tilt angles and the corresponding solar energy gains in Cairo, Egypt. The model uses the measured radiation values and site parameters with the solar geometry to get the tilted radiation and the different optimum tilt angles. The obtained results showed that tilting the solar collector increases the total solar energy captured by different gains according to the optimum tilt used. The annual optimum tilt was 28^o-30^o that gives energy gain of 10% over that of the horizontal surface. While tilting the solar collector twice though the year increases the solar energy received by about 14% over that of the horizontal and 4% over that of the annual fixed optimum tilt. Changing the collector optimum tilt angles four times per year or monthly give energy gains of 15% and 16% over that of the horizontal and 4.6% and 5.5% over that of the annual fixed optimum tilt.

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