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Optimization of tilt angle for solar panel: Case study for Madinah, Saudi Arabia

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ABSTRACT

This article analyzes the optimal choice of the tilt angle for the solar panel in order to collect the maximum solar irradiation. In this paper, the collector surface is assumed to be facing toward equator. The study is based upon the measured values of daily global and diffuse solar radiation on a horizontal surface. It is shown that the optimal angle of tilt (β_{opt}) for each month, allows us to collected the maximum solar energy for Madinah site. Annual optimum tilt angle is found to be approximately equal to latitude of the location. It is found that the loss in the amount of collected energy when using the yearly average fixed angle is around 8% compared with the monthly optimum tilt β_{opt}.

1. Introduction

The amount of solar energy incident on a solar collector in various time scales is a complex function of many factors including the local radiation climatology, the orientation and tilt of the exposed collector surface and the ground reflection properties. The performance of a solar collector is highly influenced by its orientation and its angle of tilt with the horizon. This is due to the fact that both the orientation and tilt angle change the solar radiation reaching the surface of the collector.

Over the last few years, many authors have presented models to predict solar radiation on inclined surfaces. Some of these models apply to specific cases; some require special measurements and some are limited in their scope. These models use the same method of calculating beam and ground reflected radiation on a tilted surface. The only difference exists in the treatment of the diffuse radiation. The approximation commonly used for converting the diffuse component value for a horizontal surface to that for a tilted one is that sky radiation is isotropically distributed at all times [1–3]. However, theoretical as well as experimental results have shown that this simplifying assumption is generally far from reality [4]. Thus, it appears that sky radiance should be treated as anisotropic, particularly because of the strong forward scattering effect of aerosols [5–8]. Reviews on transforming data recorded by horizontal pyranometers to data that would have been received by tilted surfaces are given by many researches [9–14]. From the previous reviews, one concludes that there is a wide range of models recommended by different investigators for year round application.

The best way to collect maximum daily energy is to use tracking systems. A tracker is a mechanical device that follows the direction of the sun on its daily sweep across the sky. The trackers are expensive, need energy for their operation and are not always applicable. Therefore, it is often practicable to orient the solar collector at an optimum tilt angle, β_{opt} and to correct the tilt from time to time. Several interesting articles have been devoted to this problem. Most of these articles treat the problem qualitatively and quantitatively [15–17], while others articles give an analytical treatment [18–21]. It is reported in the literature that in the northern hemisphere, the optimum orientation is south facing and the optimum tilt angle depends only on the latitude. No definite value is given by researchers for the optimum tilt angle. Further review of literature shows that there is a wide range of optimum tilt angle (β_{opt}) as recommended by different authors, and they are mostly for specific locations [22–31].

A simple mathematical procedure for the estimation of the optimal tilt angle of a collector is presented based on the monthly horizontal radiation [32]. As specified by the authors, this method gives a good estimation of the optimal tilt angle, except for places with a considerably lower clearness index. Chang [33] analyzed the gain in extraterrestrial radiation received by a single-axis tracked panel relative to a fixed panel over a specific period of time. The results show that the angle the tracked panel has to rotate by is 0° at solar noon, and increases towards dawn or dusk. The incident an-

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Nomenclature

H_B	daily beam radiation incident on an inclined surface, W h/m^2/day
H_b	daily beam radiation incident on a horizontal surface, W h/m^2/day
H_D	daily sky-diffuse radiation incident on an inclined surface, W h/m^2/day
H_d	daily diffuse radiation incident on a horizontal surface, W h/m^2/day
H_g	daily global radiation incident on a horizontal surface, W h/m^2/day
H_0	extra-terrestrial daily radiation incident on a horizontal surface, W h/m^2/day
H_R	daily ground reflected radiation incident on an inclined surface, W h/m^2/day
H_T	daily global radiation on a tilted surface, W h/m^2/day
n	nth day of the year
R_b	ratio of average daily beam radiation incident on an inclined surface to that on a horizontal surface
R_D	the actual sun–earth distance
R_d	ratio of average daily diffuse radiation incident on an inclined surface to that on a horizontal surface
R_{mD}	the mean sun–earth distance
α	azimuthal angle, °
β	surface slope from the horizontal, °
δ	declination, radian
Φ	latitude, °
θ	zenith angle and the sun's position relative to the north–south axis, °
ρ	ground albedo
ω	hour angle, radian
ω_{sr}	sunrise hour angle, °
ω_{ss}	sunset hour angle, °

gle of sunlight upon the tracked panel is always smaller than that upon the fixed panel, except at solar noon. The electric energy from a photovoltaic module was calculated theoretically at different azimuths and tilt angles in Taiwan [34]. The results show that the optimal tilt angle obtained from the observed data is flatter than those from other two radiation types and becomes flatter while the panel deviates from due south.

A parabolic solar cooker with automatic two axes sun tracking system was designed and tested to overcome the need for frequent tracking and standing in the sun, facing all concentrating solar cookers with manual tracking, and a programmable logic controller was used to control the motion of the solar cooker [35]. The results showed that the water temperature inside the cooker's tube reached 90 °C in typical summer days, when the maximum registered ambient temperature was 36 °C.

This paper deals with the optimum slope and orientation of a surface receiving a maximum solar radiation. We should be able to determine the optimum slope of the collector at any latitude, for any surface azimuth angle, and on any day of the year. Thus, the present study aims to develop a methodology to determine the optimum tilt angle (β_{opt}) for any location in the word. Moreover, the aim is to apply the present methodology by computing the optimum tilt angle for the main Saudi Arabian zones and especially for Madinah location. We begin with measured hourly global and diffuse radiation received on a horizontal surface [36,37]. These quantities are then transposed onto an inclined plane by a mathematical procedure. The optimum tilt angle was computed by searching for the values for which the total radiation on the collector surface is a maximum for a particular day or a specific period. The β_{opt} obtained for each month of the year allows us to collect the maximum solar energy for Madinah site.

The next section presents the solar radiation basics. Section 3 describes the modeling used to estimate the total solar radiation on tilt surface. The results and discussion are given in Section 4.

2. Solar radiation basic

Solar radiation incident outside the earth's atmosphere is called extraterrestrial radiation. On average the extraterrestrial irradiance is 1367 W/m^2. The extraterrestrial radiation I_0 is given as follows:

$$I_0 = 1367\left(\frac{R_{mD}}{R_D}\right)^2 \tag{1}$$

where R_{mD} is the mean sun–earth distance and R_D is the actual sun–earth distance depending on the day of the year. The earth's axis is tilted approximately 23.45° with respect to the earth's orbit around the sun. As the earth moves around the sun, the axis is fixed if viewed from space. The declination of the sun is the angle between a plane perpendicular to a line between the earth and the sun and the earth's axis. An approximate formula for the declination of the sun is given as follows [2]:

$$\delta = \frac{23.45\pi}{180}\,\mathrm{Sin}\left(\frac{2\pi(284+n)}{365}\right) \tag{2}$$

where n is the nth day of the year.

2.1. Zenith azimuthal and hour angles

To describe the sun's path across the sky one needs to know the angle of the sun relative to a line perpendicular to the earth's surface. This is called the zenith angle (θ) and the sun's position relative to the north–south axis, the azimuthal angle (α). The hour angle (ω) is easier to use than the azimuthal angle because the hour angle is measured in the plane of the "apparent" orbit of the sun as it moves across the sky (Fig. 1).

2.2. Solar and local standard time

The local time is the same in the entire time zone whereas solar time relates to the position of the sun with respect to the observer, and that is different depending on the exact longitude where solar time is calculated. To adjust solar time for longitude one must subtract ($Long_{local}Long_{sm}$)/15 (units are hours) from the local time.

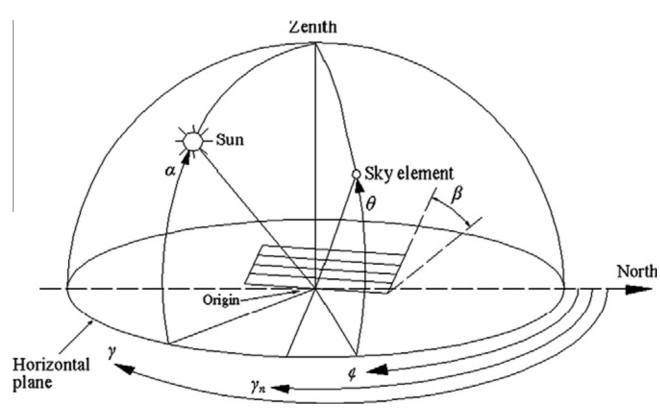

Fig. 1. Zenith, azimuthal, and hour angles.

$Long_{local}$ is the longitude of the observer in degrees and $Long_{sm}$ is the longitude for the standard meridian for the observer's time zone.

2.3. Equation of time

As the earth moves around the sun, solar time changes slightly with respect to local standard time. This time difference is called the equation of time and can be an important factor when determining the position of the sun for solar energy calculations. An approximate formula for the equation of time (E_{qt}) in minutes is given as follows:

$$E_{qt} = -14.2\,\mathrm{Sin}\left(\frac{\pi(n+7)}{111}\right) \quad \text{for } 1 \leqslant n \leqslant 106 \tag{3}$$

$$E_{qt} = 4.0\,\mathrm{Sin}\left(\frac{\pi(n-106)}{59}\right) \quad \text{for } 107 \leqslant n \leqslant 166 \tag{4}$$

$$E_{qt} = -6.5\,\mathrm{Sin}\left(\frac{\pi(n-166)}{80}\right) \quad \text{for } 167 \leqslant n \leqslant 246 \tag{5}$$

$$E_{qt} = 16.4\,\mathrm{Sin}\left(\frac{\pi(n-247)}{113}\right) \quad \text{for } 247 \leqslant n \leqslant 365 \tag{6}$$

Using the longitude correction and the equation of time, the relationship between the solar time and local standard time is given as follows:

$$T_{Solar} = T_{Local} + \frac{E_{qt}}{60} + \frac{(Long_{sm} - Long_{local})}{15} \tag{7}$$

Values are in hours. Since equations use sine and cosine functions it is conceptually easier to calculate using the hour angle (ω) instead of time. The relationship between hour angle and time is given by the following relation:

$$\omega = \pi\frac{(12 - T_{Solar})}{12} \tag{8}$$

The hour angle is in units of radians.

With the above information, one can calculate the cosine of the zenith angle:

$$\mathrm{Cos}(Z) = \mathrm{Sin}(\Phi)\mathrm{Sin}(\delta) + \mathrm{Cos}(\Phi)\mathrm{Cos}(\delta)\mathrm{Cos}(\omega) \tag{9}$$

where Φ is the latitude of the location of interest.

2.4. Sunrise and sunset times

Sunrise and sunset occur when the sun is at the horizon and hence the cosine of the zenith angle is zero. Setting the cosine of the zenith angle to zero in the relation (9), we get the following equation:

$$\omega_{sr,ss} = \mathrm{Arccos}(-\tan(\Phi)\tan(\delta)) \tag{10}$$

where ω_{sr} is the sunrise hour angle and ω_{ss} is the sunset hour angle.

The sunrise and sunset hour angles are not exactly the same value as the sunrise and sunset times that appear in the relation (10). The sunrise will be earlier and the sunset times will be later. The reason for this difference is that the sunlight is refracted as it moves through the earth's atmosphere and the sun appears slightly higher in the sky than simple geometrical calculations indicate.

2.5. Global, beam and diffuse irradiance

The incident solar radiation reaches the earth's surface without being significantly scattered and coming from the direction of the sun, is called direct normal irradiance (or beam irradiance). Some of the scattered sunlight is scattered back into space and some of it also reaches the surface of the earth. The scattered radiation reaching the earth's surface is called diffuse radiation. Some radiation is also scattered off the earth's surface and then re-scattered by the atmosphere to the observer. This is also part of the diffuse radiation the observer sees. This amount can be significant in areas in which the ground is covered with snow.

The total solar radiation on a horizontal surface is called global irradiance and is the sum of incident diffuse radiation plus the direct normal irradiance projected onto the horizontal surface. If the surface under study is tilted with respect to the horizontal, the total irradiance is the incident diffuse radiation plus the direct normal irradiance projected onto the tilted surface plus ground reflected irradiance that is incident on the tilted surface.

3. Modeling

As most published meteorological data give the total radiation on horizontal surfaces, correlation procedures are required to obtain insolation values on tilted surfaces from horizontal radiation. Monthly average daily total radiation on a tilted surface (H_T) is normally estimated by individually considering the direct beam (H_B), diffuse (H_D) and reflected components (H_R) of the radiation on a tilted surface. Thus for a surface tilted at a slope angle from the horizontal, the incident total radiation is given by the relation:

$$H_T = H_B + H_D + H_R \tag{11}$$

Several models have been proposed by various investigators [7–14] to calculate global radiation on tilted surfaces from the available data on a horizontal surface. The only difference among the models appears in the assessment of sky-diffuse component. Based on the assumptions made, the estimation models can be classified into isotropic [1] and anisotropic [7,8] ones. The daily beam radiation received on an inclined surface can be expressed as:

$$H_B = (H_g - H_d)R_b \tag{12}$$

where H_g and H_d are the monthly mean daily global and diffuse radiation on a horizontal surface, and R_b is the ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface. The daily ground reflected radiation can be written as:

$$H_R = H_g\rho\frac{(1 - \mathrm{Cos}\,\beta)}{2} \tag{13}$$

where β is the tilt angle of the solar panel. Liu and Jordan [1] have suggested that R_b can be estimated by assuming that it has the value which would be obtained if there were no atmosphere. For surfaces in the northern hemisphere, sloped towards the equator, the equation for R_b is given as below [1] and is used in the present study.

$$R_b = \frac{\mathrm{Cos}(\phi-\beta)\mathrm{Cos}\,\delta\,\mathrm{Sin}\,\omega_{SS} + \omega_{SS}\,\mathrm{Sin}(\phi-\beta)\mathrm{Sin}\,\delta}{\mathrm{Cos}\,\phi\,\mathrm{Cos}\,\delta\,\mathrm{Sin}\,\omega_{SS} + \omega_{SS}\,\mathrm{Sin}\,\phi\,\mathrm{Sin}\,\delta} \tag{14}$$

where ω_{ss} is the sunset hour angle for the tilted surface for the mean day of the month, given by the relation (10). For surfaces in the southern hemisphere, sloped towards the equator, the equation for R_b is given as below [1].

$$R_b = \frac{\mathrm{Cos}(\phi+\beta)\mathrm{Cos}\,\delta\,\mathrm{Sin}\,\omega_{SS} + \omega_{SS}\,\mathrm{Sin}(\phi+\beta)\mathrm{Sin}\,\delta}{\mathrm{Cos}\,\phi\,\mathrm{Cos}\,\delta\,\mathrm{Sin}\,\omega_{SS} + \omega_{SS}\,\mathrm{Sin}\,\phi\,\mathrm{Sin}\,\delta} \tag{15}$$

where Φ is the latitude and δ is the declination

The declination of the sun is the angle between a plane perpendicular to a line between the earth and the sun and the earth's axis. An approximate formula for the declination of the sun is given by the relation (2).

3.1. Diffuse radiation models

The methods to estimate the ratio of diffuse solar radiation on a tilted surface to that of a horizontal are classified as isotropic and anisotropic models. The isotropic models assume that the intensity of diffuse sky radiation is uniform over the sky dome. Hence, the diffuse radiation incident on a tilted surface depends on the fraction of the sky dome seen by it. The anisotropic models assume the anisotropy of the diffuse sky radiation in the circumsolar region (sky near the solar disc) plus and isotropically distributed diffuse component from the rest of the sky dome.

The sky-diffuse radiation can be expressed as

$$H_D = R_d H_d \tag{16}$$

where R_d is the ratio of the average daily diffuse radiation on a tilted surface, to that on a horizontal surface.

The diffuse radiation models chosen for study were as follows [9]:

3.1.1. Isotropic models

The isotropic model is given by Badescu model [38] as follow:

$$R_d = \frac{3 + \mathrm{Cos}(2\beta)}{4} \tag{17}$$

Tian et al. model [39] is given by the relation:

$$R_d = 1 - \beta/180 \tag{18}$$

Koronakis model [22] is given as follow:

$$R_d = 1/3[2 + \mathrm{Cos}(\beta)] \tag{19}$$

Liu and Jordan model [1] is given as follow:

$$R_d = \frac{1 + \mathrm{Cos}\ \beta}{2} \tag{20}$$

3.1.2. Anisotropic models

Reindl et al. model [40] is given by the relation:

$$R_d = \frac{H_b}{H_0} R_b + \left(1 - \frac{H_b}{H_0}\right)\left(\frac{1 + \mathrm{Cos}\ \beta}{2}\right)\left(1 + \sqrt{\frac{H_b}{H_g}} \mathrm{Sin}^3\left(\frac{\beta}{2}\right)\right) \tag{21}$$

Skartveit and Olseth model [41] is given as follow:

$$R_d = \frac{H_b}{H_0} R_b + \Omega\ \mathrm{Cos}\ \beta + \left(1 - \frac{H_b}{H_0} - \Omega\right)\left(\frac{1 + \mathrm{Cos}\ \beta}{2}\right) \tag{22}$$

where

$$\Omega = \left\{\mathrm{Max}\left[0, \left(0.3 - 2\frac{H_b}{H_0}\right)\right]\right\} \tag{23}$$

Steven and Unsworth model [42] is given as follow:

$$R_d = 0.51 R_b + \frac{1 + \mathrm{Cos}\ \beta}{2} - \frac{1.74}{1.26\pi}\left[\mathrm{Sin}\ \beta - \left(\beta\frac{\pi}{180}\right)\mathrm{Cos}\ \beta - \pi\ \mathrm{Sin}^2\left(\frac{\beta}{2}\right)\right] \tag{24}$$

Hay model [7] is given by the relation:

$$R_d = \frac{H_b}{H_0} R_b + \left(1 - \frac{H_b}{H_0}\right)\left(\frac{1 + \mathrm{Cos}\ \beta}{2}\right) \tag{25}$$

3.2. Total radiation on a tilted surface

Total radiation on a tilted surface, can thus be expressed as:

$$H_T = (H_g - H_d) R_b + H_g \rho \frac{1 - \mathrm{Cos}\ \beta}{2} + H_d R_d \tag{26}$$

As no information is available on ground albedo, ρ values are assumed to be 0.2. According to Eq. (26), we need the direct and diffuse components of global radiation for estimating global solar radiation on tilted surfaces.

4. Results and discussion

For Saudi stations, the historical data used in this study are available from 1998 to 2002 at the National Renewable Energy Laboratory (NREL) website. The present database includes global irradiance (H_g), diffuse irradiance (H_d), direct normal irradiance (H_b), air temperature (T) and relative humidity (H_u). All these data have been collected each 5 min since 1998 until 2002. In addition, we have deduced the sunshine duration (S) which is defined as the time interval when direct solar radiation exceeds 120 W m^{-2}) [36].

4.1. Madinah station data

Fig. 2 shows the daily global solar radiation H_g and the daily extraterrestrial radiation H_0 on a horizontal surface in the city of Madinah in Saudi Arabia. The average winter value of H_g is 5 kW h/m^2/day and its average summer value is 7.5 kW h/m^2/day. Fig. 3 shows the beam, the diffuse and the global monthly average irradiation on a horizontal surface. In summer months, the beam component is more dominant than diffuse component and thus the main contribution comes from the beam component. In winter months, the beam radiation represents nearly 60% of global radiation while diffuse radiation represents nearly 40% of global radiation.

4.2. Methodology

Using Eqs. (11)–(26), total solar radiation falling on tilted surface was computed for different tilt angles (0° until 90°) for each month of the year for Madinah station. Using Matlab software package, graphs were plotted between the total irradiation versus tilt angle for each month. Second order polynomial equations were developed to fit the curves. These polynomial equations were differentiated with respect to tilt angle and then equated to zero to obtain the optimum tilt angle corresponding to maximum insolation. Thus optimum tilt angle was computed for each month and for each station.

Computer program in Matlab were developed using the above formulate to calculate the monthly average daily total radiation on a surface facing towards equator as the tilt angle is changed from 0° to 90°. The solar reflectivity (ρ) was assumed to be 0.2.

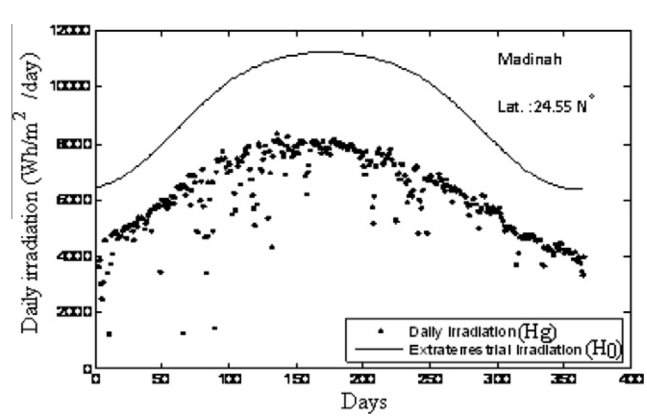

Fig. 2. Daily global radiation (H_G) and daily extra-terrestrial daily radiation (H_0) on a horizontal surface.

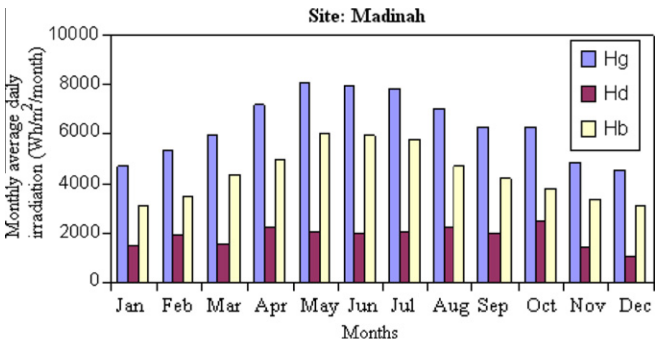

Fig. 3. Monthly average daily global irradiation (H_g), diffuse irradiation (H_d) and beam irradiation (H_b) on a horizontal surface in Madinah.

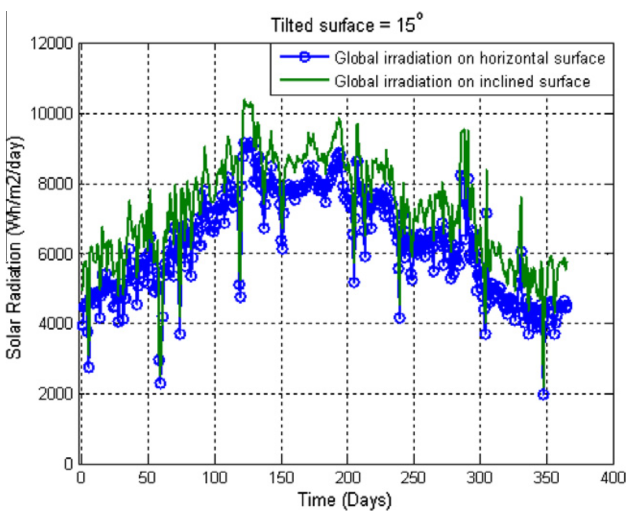

Fig. 4a. Daily global solar radiation (H_g) on a horizontal surface and daily total solar radiation (H_T) on tilted surface ($\beta = 15°$) in Madinah.

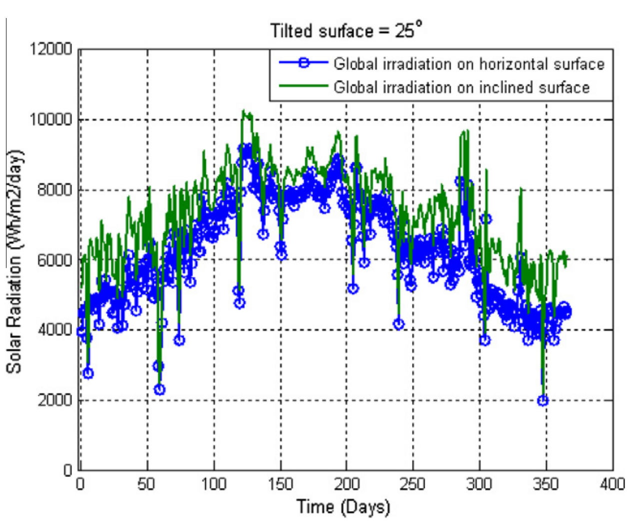

Fig. 4b. Daily global solar radiation (H_g) on a horizontal surface and daily total solar radiation (H_T) on tilted surface ($\beta = 25°$) in Madinah.

Figs. 4a–4d show the average daily total solar radiation at Madinah on a south facing surface for different angle of panel tilt. It is clear from these graphs that a unique β_{opt} exists for each month of the year for which the solar radiation is at a peak for the given month. Similar trend has been observed for all other Saudi stations

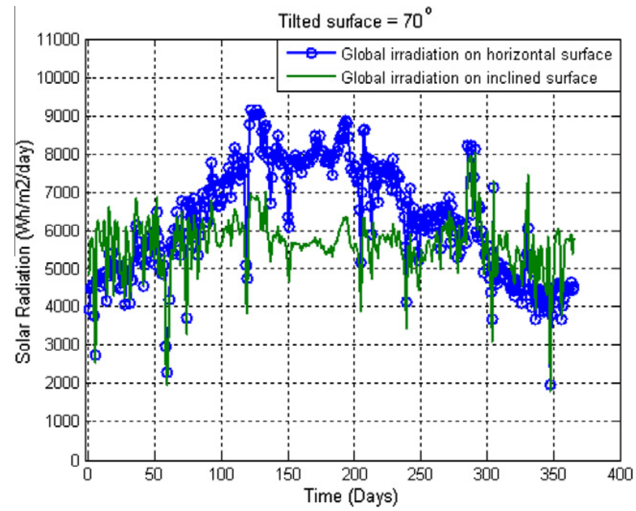

Fig. 4c. Daily global solar radiation (H_g) on a horizontal surface and daily total solar radiation (H_T) on tilted surface ($\beta = 70°$) in Madinah.

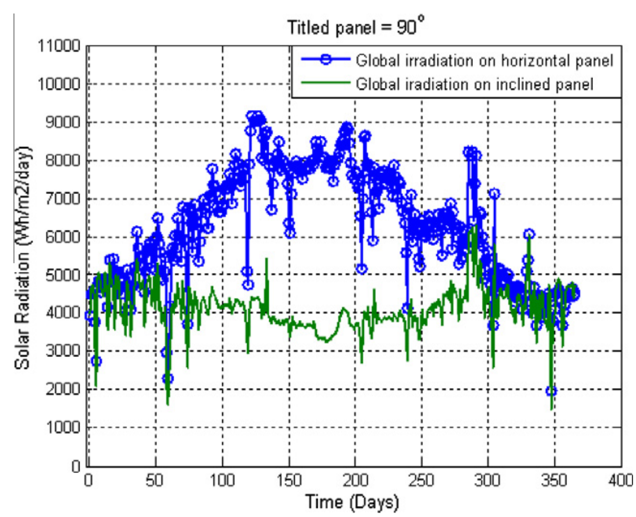

Fig. 4d. Daily global solar radiation (H_g) on a horizontal surface and daily total solar radiation (H_T) on tilted surface ($\beta = 90°$) in Madinah.

selected under present study. Graphs for other stations have not been shown in order to avoid repetition.

The optimum angle of tilt of a flat-plate collector in January is 40° and the total monthly solar irradiation falling on the collector surface at this tilt is 6828.80 W h/m^2/month. The optimum tilt angle in June is 10° and the total monthly solar radiation at this angle is 9047.03 W h/m^2/month. The optimum tilt angle then increases during the winter months and reaches a maximum of 40° in December which collects 6579.12 W h/m^2/month of solar energy.

Fig. 5 shows the average daily total solar irradiation with the tilt angles varying from 0° to 90° at Madinah site on a south facing surface. Fig. 6 shows the tilt angles for each month of the year when the collector panel is titled at the optimum angle at Madinah site. The seasonal average was calculated by finding the average value of the tilt angle for each season and the implementation of this requires the collector tilt to be changed four times a year. In spring the tilt should be 17°, in summer 12°, in autumn 28° and in winter 37°. The yearly average tilt was calculated by finding the average value of the tilt angles for all months of the year. The yearly average tilt was found to be 23.5° and this result in a fixed tilt throughout the year. Fig. 7 shows the total monthly daily solar irradiation

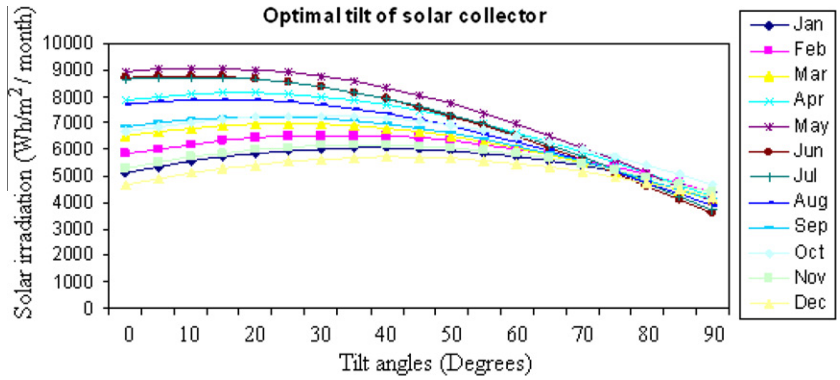

Fig. 5. Monthly average daily total solar irradiation on a south facing surface in Madinah over the year for different tilt varying from 0° to 90°.

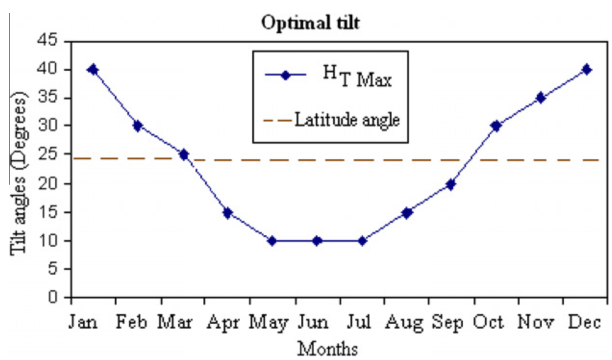

Fig. 6. Optimum average tilt angle for each month of the year at Madinah site.

Fig. 8. Horizontal Single Axis Trackers.

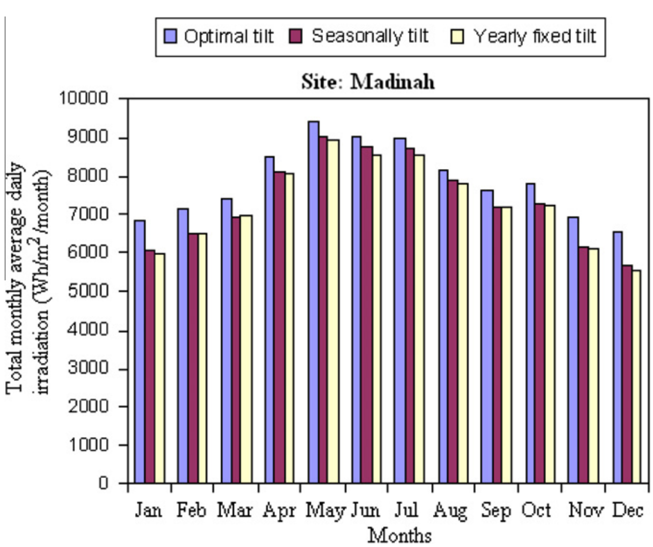

Fig. 7. Total monthly solar radiation for optimum, seasonally and yearly fixed tilt angles.

collected for the optimum tilt angles, the seasonal average tilt angles and for the yearly average angle (latitude). When the monthly optimum tilt angle was used, the yearly collected solar energy was 7876.49 W h/m^2/month. With the seasonally adjusted tilt angles, the yearly collected solar energy was 7362.19 W h/m^2/month. Finally, with the yearly average tilt angle, the yearly collected solar energy was 7283.39 W h/m^2/month.

There are several common implementations of single-axis trackers. These include Horizontal Single Axis Trackers, Vertical Single Axis Trackers, and Tilted Single Axis Trackers. The orientation of the module with respect to the tracker axis is important when modeling performance.

In our case, we opt for the Horizontal Single Axis Trackers (Fig. 8) by choosing the seasonally adjusted tilt angles as indicated in Fig. 9.

5. Conclusion

The optimum tilt is different for each months of the year. The collected solar energy will be greater if we choose the optimum panel tilt for each month. Also, we have found that the yearly average of optimum tilt is equal to the latitude of the site.

The results show that the average optimum tilt angle at Madinah for the winter months is 37° and for the summer months is

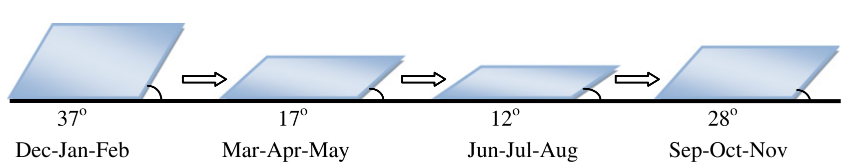

Fig. 9. The seasonally adjusted tilt angles.

12°. So, the yearly average tilt panel is 23.5° which nearly corresponding to the latitude of Madinah site (24.5°). This, in general, is in agreement with the results of many other researchers [15,16].

The loss of energy when using the yearly average fixed angle is around 8% compared with the optimum tilt for each month at Madinah. It can be concluded that a yearly average fixed tilt can be used in many general applications in order to keep the manufacturing and installation costs of collectors low. For higher efficiency, the collector should be designed such that the angle of tilt can easily be changed at least on a seasonal basis, if not monthly. Alternatively, solar tracking systems can be used in industrial installations where higher efficiency is required.

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