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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:

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

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]:

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

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.

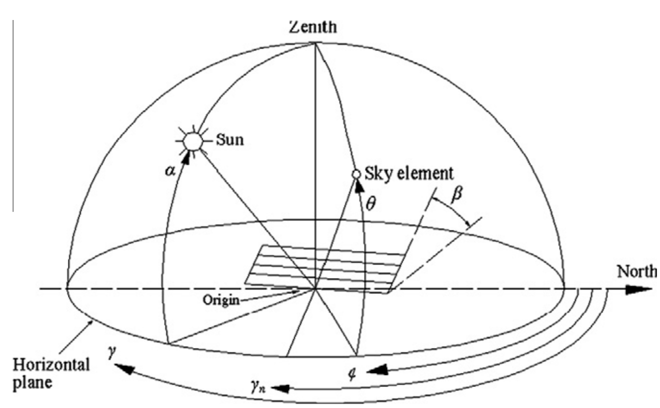

Fig. 1. Zenith, azimuthal, and hour angles.