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Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey

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Abstract

The performance of a photovoltaic (PV) panel is affected by its orientation and its tilt angle with the horizontal plane. This is because both of these parameters change the amount of solar energy received by the surface of the PV panel. A mathematical model was used to estimate the total solar radiation on the tilted PV surface, and to determine optimum tilt angles for a PV panel installed in Sanliurfa, Turkey. The optimum tilt angles were determined by searching for the values of angles for which the total radiation on the PV surface was maximum for the period studied. The study also investigated the effect of two-axis solar tracking on energy gain compared to a fixed PV panel. This study determined that the monthly optimum tilt angle for a PV panel changes throughout the year with its minimum value as 13° in June and maximum value as 61° in December. The results showed that the gains in the amount of solar radiation throughout the year received by the PV panel mounted at monthly optimum tilt angles with respect to seasonal optimum angles and tilt angel equal to latitude were 1.1% and 3.9%, respectively. Furthermore, daily average of 29.3% gain in total solar radiation results in an daily average of 34.6% gain in generated power with two-axis solar tracking compared to a south facing PV panel fixed at 14° tilt angle on a particular day in July in Sanliurfa, Turkey.

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Nomenclature

H	direct-beam radiation normal to the horizontal surface (W m^{-2})
H_n	direct-beam radiation solar radiation (W m^{-2})
H_b	direct-beam radiation perpendicular to tilted surface (W m^{-2})
H_d	diffuse radiation on the horizontal surface (W m^{-2})
$H_{d,p}$	diffuse radiation on the tilted surface (W m^{-2})
H_{gr}	ground reflected radiation on the tilted surface (W m^{-2})
R_b	the ratio of beam radiation on tilted surface to that on horizontal (dimensionless)
ρ_g	ground reflectance (dimensionless)
H_T	total global solar radiation on the surface (W m^{-2})
S	tilt angle of PV panel ($^\circ$)
n	day of year
I	current (A)
I_{mp}	maximum power current (A)
I_{sc}	short circuit current (A)
V	voltage (V)
T_a	air temperature ($^\circ$C)
T_p	panel temperature ($^\circ$C)
V_a	air velocity (m s^{-1})
V_{oc}	open circuit voltage (V)
V_{mp}	maximum power voltage (V)
W_p	peak power (W)

Greek letters

δ	declination angle ($^\circ$)
β	solar azimuth angle ($^\circ$)
γ	solar surface azimuth angle ($^\circ$)
ω	solar hour angle ($^\circ$)
α	solar altitude angle ($^\circ$)
θ_I	solar incidence angle ($^\circ$)
θ_Z	solar zenith angle ($^\circ$)
ϕ	latitude of the location ($^\circ$)

Keywords: PV system performance; PV system optimization; Tracking; Optimum tilt angle

1. Introduction

Solar cells change the received solar energy into electricity, thus they have received attention as clean energy devices which do not release hazardous pollutants into the environment. The efficiency of the photovoltaic (PV) systems has been increased, while their production cost reduced which contributed to the expansion of PV systems globally [1]. Energy production using PV power system and utilization of the energy produced by this system in agricultural applications, especially in places which receive abundant amounts of solar radiation, are one of the best alternative and clean energy production techniques.

For the optimum design of PV systems for any application, it is important to determine their performance at the site of installation. The amount of power produced by a PV panel depends upon the amount of sunlight it is exposed to. More light means more power. To intercept the most sunlight, a PV panel must be positioned so that the sun's rays arrive at the panel directly; perpendicular to its surface. When a PV panel is not aimed directly at the sun, it does not intercept as much light as it can. And consequently, it does not produce as much power as it can. The best way to collect maximum daily energy is to use tracking systems. How much a tracker will enhance a particular PV system's performance depends upon the application and local conditions. Furthermore, the decisions have also to be made on trade-off between the cost of the tracking system and the savings provided by using fewer amount of PV modules to obtain a certain amount of power. The trackers are often expensive and are not always applicable. Thus, the optimum slopes of PV panels at any latitude, for any surface azimuth angels and on a day or in a month of a year, have to be determined for design purposes. Definite value is rarely given by researchers for optimum tilt angles. Lunde [2] suggested $S_{\mathrm{opt}} = \phi \pm 15^{\circ}$, Duffie and Beckman [3] $S_{\mathrm{opt}} = (\phi + 15^{\circ}) \pm 15^{\circ}$ and Lewis [4] reported $S_{\mathrm{opt}} = \phi \pm 8^{\circ}$.

Sanliurfa city, located in Southestern Anatolia Region in Turkey, has a great solar radiation potential, as the number of sun hours (Fig. 1) is large. Furthermore, the amount of solar intensity in Sanliurfa is about 5.1 kW m^{-2} based on averages of long years (1981–2002). These data show that solar energy could be

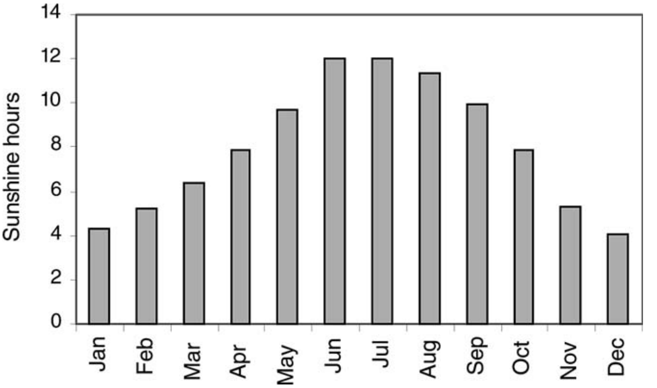

Fig. 1. Annual variation of daily sunshine hours in Sanliurfa, Turkey (average 1981–2002) (Sanliurfa Meteorological Station, 2002).

used for certain applications, especially in agriculture. One of the problems faced in this region is that electricity cut-off is large especially in rural areas. In addition, there has been increasing interest from growers in the region about the utilization of PV systems to irrigate small areas with drip irrigation systems and using solar energy for drying purposes. Therefore, the goal of this study was to determine optimum panel tilt angles and to investigate the effects of panel tilt angles, fixed and two-axis tracking of sun rays on the amount of solar radiation received by a PV panel and the power generation with theoretical calculations and experiments.

2. Materials and methods

2.1. Experimental site and PV module

The experiment was conducted on the roof of one of the research facilities of Solar Energy Research Center at Harran University located in Sanliurfa (37°N, 38°E).

Two single crystalline PV module (Model AP-120, AstroPower, Inc., Deleware, USA), each rating 120 W peak power, were used for the experiments. Table 1 shows the electrical parameters for the PV modules.

During the experiment, first PV panel (PV_F) was mounted at a fixed tilt angle of 14° facing true south, while two-axis solar tracking was applied to the second panel (PV_T) following azimuth and altitude angles of the sun throughout the day (Fig. 2).

2.2. Measuring system

Measurements included current (I) and voltage (V) readings of panels, air temperature (T_a), air velocity (V_a), panel temperature (T_p), radiation (H_T) on horizontal surface and in a perpendicular direction on the fixed and tracking panel and tilt angles of the tracking panel (S).

Table 1
Typical electrical parameters for experimental PV modules

Peak power[a] (Wp)	W	120
Open circuit voltage (V_{oc})	V	21.0
Max. power voltage (V_{mp})	V	16.9
Short circuit current (I_{sc})	A	7.7
Max. power current (I_{mp})	A	7.1
Short circuit temp. coefficient	mA °C^{-1}	+3.5
Open circuit voltage coefficient	V °C^{-1}	−0.08
Max. series fuse	A	15

Standard test conditions (defined as: irradiance = 1000 W m^{-2}; cell temperature = 25 °C; AM 1.5G solar spectrum).

[a] Rated power tolerance ± 10%.

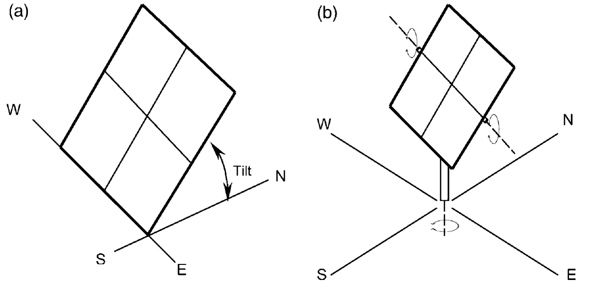

Fig. 2. Schematics of fixed (a) vs. two-axis (b) solar tracking mounts.

I–V readings through the panels were monitored by four digital multimeter under varying load resistances applied by two load resistors to have detailed information about PV panel power output. Air temperature was measured by a K type thermocouple, air velocity with an anemometer and a radiometer was used to monitor the radiation. Fig. 3 illustrates the schematics of the measuring system.

Continuous measurements were carried out on a clear-sunny day from 6 a.m. until 6 p.m. with a time interval of 1 h on 18.06.2003. All the measurements were synchronized and recorded for data processing. Solar radiation measurements were obtained on the horizontal plane and on the planes of the fixed and tracking panels perpendicular to the sun's rays to determine the performance of the system under fixed and tracking positions. In a separate experimental trial, tilt angle effect on the amount of radiation and power generation of the PV panels was investigated by changing the tilt angle of the fixed panel (facing true south) from 0° to 60° from the horizontal plane at solar noon.

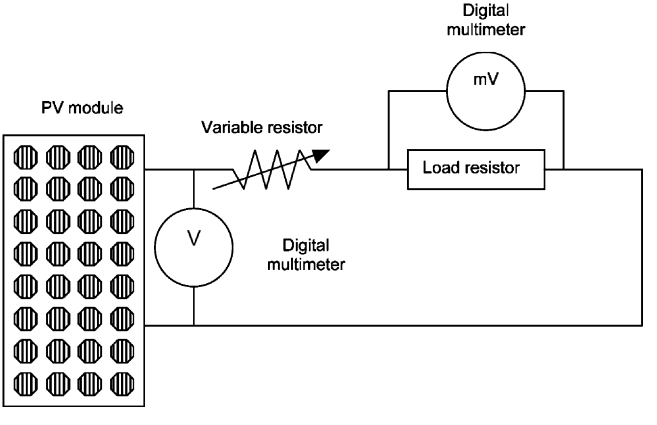

Fig. 3. Schematic circuit diagram of PV module measurement system.

2.3. Solar radiation on a tilted south facing and two-axis tracking surface

The declination is the angular position of the sun at solar noon with respect to the plane of the equator. Its value is given by

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \tag{1}$$

The solar hour angle (ω) is the angular displacement of the sun east or west of the local meridian; morning positive, afternoon negative and zero at solar noon. The hour angle is determined as

$$\omega = \frac{\text{minutes before noon}}{4} \tag{2}$$

Solar altitude angle (α) is the angle between the sun's rays and the horizontal plane and its value is determined by

$$\alpha = \sin^{-1}([\cos(\phi)\cos(\delta)\cos(\omega)]) + [\sin(\phi)\sin(\delta)] \tag{3}$$

The azimuth angle (β) is the angle between true north and the projection of the suns rays onto the horizontal. The azimuth angle can be calculated by

$$\beta = \cos^{-1}\left(\frac{[\sin(\alpha)\sin(\phi)] - \sin(\delta)}{\cos(\alpha)\cos(\phi)}\right) \tag{4}$$

The zenith angle (θ_Z) is the angular distance of the sun from the local vertical. The zenith angle is directly related to the solar elevation angle by

$$\theta_Z = 90 - \alpha \tag{5}$$

Surface azimuth angle (γ) is the angle between the normal of the panel surface and the local meridian

$$\gamma = 0 \quad \text{for south facing surface} \tag{6}$$

$$\gamma = 180 - \beta \quad \text{for two-axis tracking surface} \tag{7}$$

Solar incidence angle (θ_I) is the angle between the normal of the panel and the sun's rays. The general formula for this angle is

$$\begin{aligned}\theta_I = \cos^{-1}([&\sin(\delta)\sin(\phi)\cos(S)]) - [\sin(\delta)\cos(\phi)\sin(S)\cos(\gamma)]\\ &+ [\cos(\delta)\cos(\phi)\cos(S)\cos(\omega)] + [\cos(\delta)\sin(\phi)\sin(S)\cos(\gamma)\cos(\omega)]\\ &+ [\cos(\delta)\sin(S)\sin(\gamma)\sin(\omega)]\end{aligned} \tag{8}$$

For a surface facing true south, $\gamma = 0$ is used in Eq. (6). For two-axis tracking system, $\theta_I = 0$. The tilt angle of the two-axis tracking panel was determined by

$$S = 90 - \alpha = \theta_Z \tag{9}$$

The relationship between the intensity of the direct-beam radiation normal to the horizontal surface (H) and the max. direct-beam solar radiation (H_n) is

$$H_n = \frac{H}{\cos(\theta_Z)} \tag{10}$$

The amount of direct-beam solar radiation perpendicular to the tilted surface (H_b) is determined by

$$H_b = H_n \cos(\theta_I) \tag{11}$$

R_b is the ratio of beam radiation on the PV panel to that on the horizontal, which can be expressed as

$$R_b = \frac{H_b}{H} = \frac{\cos(\theta_I)}{\cos(\theta_Z)} \tag{12}$$

Thus, the direct-beam radiation perpendicular to the tilted panel can also take the form as

$$H_b = HR_b \tag{13}$$

Tilted surfaces can only see some part of the sky. The amount of the sky seen by the tilted surface is expressed as $(1 + \cos(S))/2$. Hence, the diffuse radiation on the plane of the tilted surface is determined as

$$H_{d,p} = H_d \frac{(1 + \cos(S))}{2} \tag{14}$$

where H_d is the diffuse radiation on the horizontal surface. The portion of the ground seen by the tilted surface is defined by $(1 - \cos(S)) * \rho_g/2$. Thus, ground reflected radiation on the tilted surface is determined by

$$H_{gr} = (H + H_d)\left(\frac{1 - \cos(S)}{2}\right)\rho_g \tag{15}$$

Total radiation received on the plane of the tilted PV panel is the summation of direct-beam, diffuse and ground reflected radiations on the tilted panel as

$$H_T = H_b + H_{d,p} + H_{gr} \tag{16}$$

3. Results and discussions

3.1. Monthly and seasonal optimum tilt angles

The effect of tilt angle on maximum total radiation received by a surface facing true south at solar noon was investigated for the course of a full calendar year. The effect of tilt angle from 0° to 60° from the horizontal plane is shown in Fig. 4. From this comparison, it was determined that maximum radiation on the south facing surface at solar noon was obtained with 30–40° and 50° tilt angles from

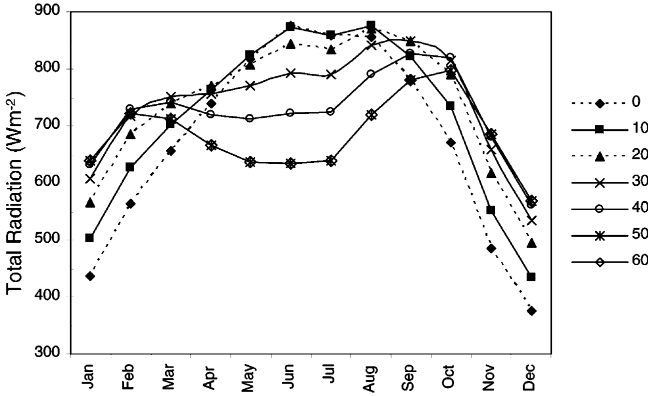

Fig. 4. The effect of tilt angle on maximum radiation for a south facing surface.

January to March; with 0–10–20° from April to August and 40–50–60° from September to December. In other words, higher tilt angles during fall and winter and lower tilt angles during the summer allow maximum radiation to be received by the surface.

In a different analysis, the optimum monthly tilt angle was found by searching for the values for which H_T is a maximum (Fig. 5). Monthly adjustments of approximately 10° from January to May, 4–7° from May to July and 10° from July to November were found to be necessary to obtain maximum radiation on the surface of the panel.

Researchers have reported that changing the tilt angle to its daily and monthly optimum values throughout the year does not seem to be practical, another possibility, such as changing the tilt angle once in a season [5]. Nijegorodov and Jain [6] reported that the output of the PV arrays could be increased by 20–25% at almost

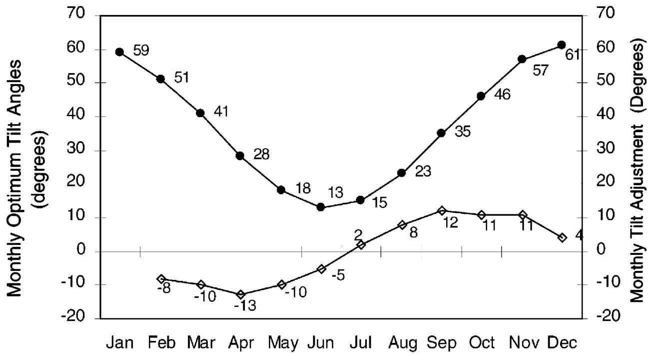

Fig. 5. Optimum monthly tilt angles and monthly tilt adjustments for the course of a full year.

no investment if they could be installed at a slope equal to the mean monthly slope for the site of application and the slope adjusted once a month. Thus, an analysis was performed to determine % gain or loss in solar radiation by comparing the amount of solar radiation received by the surface tilted at the monthly optimum tilt angles (HT_{opt}), seasonal optimum tilt angles (HT_s) (as averages of monthly optimum angles for four month periods) and at tilt angle equal to the latitude of the location (HT_ϕ) with respect to the horizontal surface (HT_h), tilt angle equals to zero (Fig. 6). The results demonstrated that a gain in the amount of solar radiation received by the surface mounted at monthly optimum tilt angles lies in the range of 2.4–47.7% (average of 21.8% for whole year). This indicates that the efficiency of solar collection at the optimum tilt angle is increased compared to the horizontal position. It can be pointed out that the optimum tilt angle increases towards the beginning and end of each year. Therefore, this is the time when greatest improvements are made on the amount of solar radiation incident on the panel tilted at an optimum angle. The installation of the panel at seasonal optimum tilt angles and tilt angle equal to latitude instead of horizontally represents an increase of about 20.9% and 18.6%, respectively, for whole year in the amount of solar radiation received. The gains in the amount of solar radiation throughout the year received by the surface mounted at monthly optimum tilt angles with respect to seasonal optimum angles and tilt angel equal to latitude were 1.1% and 3.9%, respectively. Furthermore, installation at seasonal optimum angles increased the amount of solar radiation received by the surface at about 2.8% compared to tilt angle equal to latitude of the location. Yakup and Malik [5] recommended that the solar collectors should be mounted at the monthly average tilt angle and the slope adjusted every month. Their study indicated that such installation would allow an increase in the efficiency of the collector more than 4.4% over that of a similar collector fixed at the annual tilt angle.

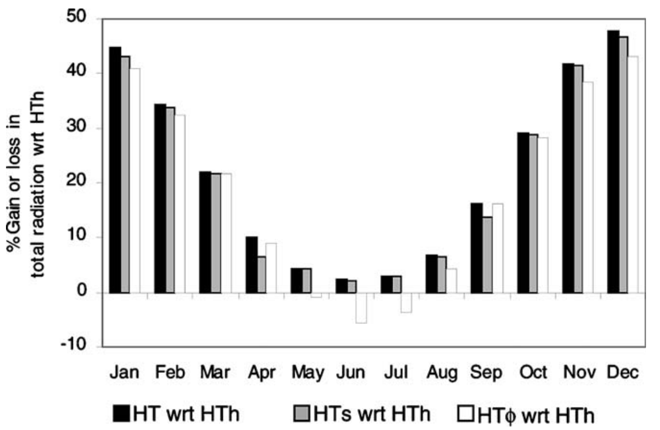

Fig. 6. Comparison of amount of solar radiation on the panel surface tilted at the monthly optimum angles, seasonal optimum angles and tilt angle equal to latitude with the horizontal surface.

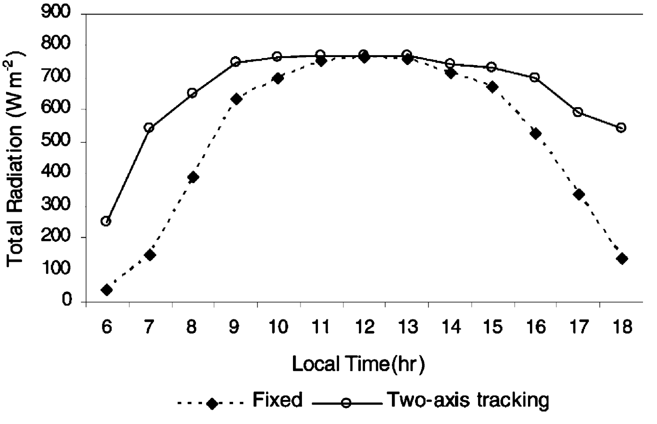

Fig. 7. Hourly total radiation received by fixed and two-axis tracking panel on 18.06.2003 in Sanliurfa.

3.2. Fixed vs. two-axis solar tracking

In order to see the effect of solar tracking on the energy generated by the PV panel, an experiment was conducted on a clear day on 18.06.2003 from 6 a.m. to 6 p.m. with one panel fixed tilt angle of 14° facing true south while two-axis solar tracking was applied to the second panel (PV_T) following azimuth and altitude angles of the sun throughout the day.

Fig. 7 illustrates the amount of total solar radiation measured in perpendicular direction to the plane of fixed and two-axis tracking panel on 18.06.2003. It is clear that there is a substantial amount of solar radiation which could be utilized to generate electricity during the early morning and late afternoon hours.

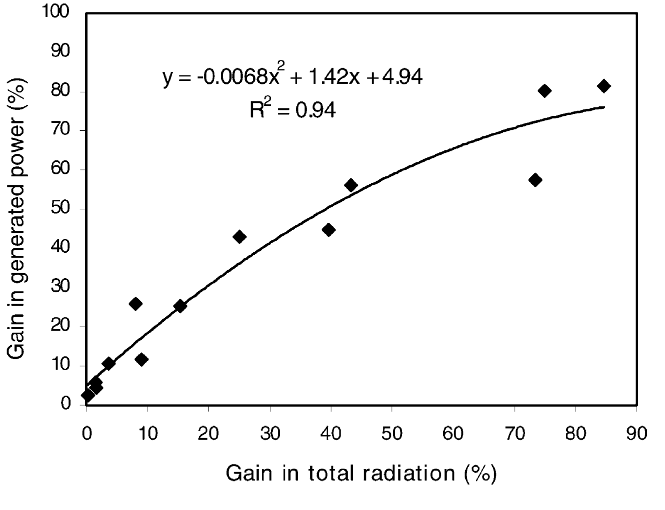

Fig. 8. Gain in total solar radiation vs. gain in generated power by PV panels.

Gain in the amount of solar radiation received by two-axis tracking PV panel to that on the fixed panel varied from 0.25% to 84.6% throughout the day which corresponded to 2.5–81.4% gain in the generated power. Furthermore, daily average of 29.3% gain in total solar radiation resulted in an daily average of 34.6% gain in generated power on this particular experimental day (Fig. 8). Vilela et al. [7] investigated the effect of one-axis east–west tracking on solar radiation received by a PV panel compared to fixed installation. Their results showed that the irradiation collected by the tracker plane is 19–24% higher than the one collected by the fixed system.

4. Conclusions

The optimum values of tilt angles and orientation of an PV panel in Sanliurfa, Turkey, were determined using a mathematical model and by a computer package. This study determined that the monthly optimum tilt angle for an PV panel changes throughout the year, with its minimum value as 13° in June and maximum value as 61° in December.

Adjustments of optimum tilt angles play a significant role to maximize the energy received by the PV panel and energy generation. The gains in the amount of solar radiation throughout the year received by the PV panel mounted at monthly optimum tilt angles with respect to seasonal optimum angles and tilt angle equal to latitude were 1.1% and 3.9%, respectively.

Daily average of 29.3% gain in total solar radiation results in an daily average of 34.6% gain in generated power with two-axis solar tracking compared to a south facing PV panel fixed at 14° tilt angle on a particular day in July in Sanliurfa, Turkey. The effect of two-axis tracking on solar radiation capture and power generation by the PV panel has to be determined for each month of the year. The electricity generation and the life cycle cost of tracking system have to be compared to determine if two-axis tracking is feasible and practical.

The mathematical model utilized in this study can be used to compute the optimum tilt angle and maximum amount of solar radiation on a PV panel installed in other locations.

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