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Effects of Tilt Angle on Flat-Plate Solar Thermal Collector Systems

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Authors' contributions

This work was carried out in collaboration between all authors. Authors AG and AK designed the study, performed the statistical analysis, wrote the protocol. Authors IFY and GTS managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aims: The performance of a solar collector is highly influenced by its orientation and its angle of tilt with the horizon. Both the orientation and tilt angle change the solar radiation reaching the surface of the collector. Previous studies show that south is the optimum orientation direction. By utilizing maximum solar energy through the optimum tilt, we are able to harness the energy needed without polluting our environment. It reduces the CO_2 emissions in the atmosphere which is a major culprit for Global warming.
Study Design: In this study, the optimum tilt angle for the south facing single axis solar collector has been determined in order to maximize the system performance.
Place and Duration of Study: Department of Mechanical Engineering, Akdeniz University, 2014-2015.
Methodology: The equations which calculate total solar radiation falling on tilted surface for optimum tilt angle the monthly, the seasonally, the semi-annually, the annually, latitude ±15° and latitude are solved with a computer code which is written in MATLAB and should be modular to

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allow users to update component modules easily as new findings become available.
Results: The results convey that the optimum tilt angle changed between 1° (June) and 65° (December) throughout year in Antalya, Turkey. The loss in the amount of collected energy is around 1% if the angle of tilt is adjusted seasonally instead of using β_{opt} for each month of the year.
Conclusion: Energy loss when using the yearly average fixed angle is approximately 7% compared with the monthly optimum tilt.

Keywords: Solar energy; alternative energy; tilt angle; south facing.

1. INTRODUCTION

Two important factors which affect the efficiency of solar surfaces are angle and orientation. In some cases, it possible to have a number of limitations to adjust the solar collector or panel at the excellent orientation and tilt angle. If the case is so, then tilt angle and orientation ought to be adjusted to maximize solar radiation. It is known from previous studies that south is the optimum direction [1,2]. Since the flat plate solar collectors are positioned at an angle to the horizontal, it is crucial to find out the optimum tilt angle in order to maximize the amount of collected energy. By utilizing maximum solar energy through the optimum tilt, we are able to harness the energy needed without polluting our environment. It reduces the CO_2 emissions in the atmosphere which is a major culprit for Global warming. By reducing CO_2 emissions in the atmosphere, carbon credit can also be earned which is an international issue now a day [3].

The orientation and its angle of tilt with the horizon are two major factors that determine the performance of a solar collector .This is caused by the fact that both the orientation and tilt angle affect the amount of solar radiation reaching the surface of the collector. A lot of empirical correlations for estimating the optimal tilt-angle can be seen in the literature [4-8]. It is reported in the literature that the optimum orientation of the PV array should be directly towards the equator, facing south in the northern hemisphere and the optimum tilt angle depends only on the latitude (ϕ). For example, Lunde [9] and Garg [10] β_{opt} = ±15°, Duffie and Beckman [11] suggested β_{opt} = (ϕ±15°) ±15° and Heywood [12] concluded that β_{opt} = (ϕ±15°), where ϕ latitude of the location and where plus, and minus signs is used in winter and summer respectively [2]. Many papers in the literature suggest different recommendations for the optimum tilt, based only on the latitude [8,13]. In practice, the collector plates are customarily oriented south facing and at a fixed tilt to ensure maximum average amount of collected solar energy over a year [3]. Monthly averages of the daily solar radiation incident upon a horizontal surface are available in the literature for many locations [4,14-16]. However, radiation data on tilted surfaces is not generally available. From this point of view, in this study, the optimum tilt angle for the south facing single axis solar collector has been computed to achieve the maximum yield in order to maximize the system performance in Antalya, Turkey. Total solar radiation on the solar collector surface with an optimum tilt angle is computed and analyzed for specific periods (monthly, seasonal, semi-annual, annual) for the variations of tilt angle β between ϕ –15° and ϕ + 15°.

2. THEORETICAL ANALYSIS

The monthly average values of solar radiation incident on surfaces of various orientations are required for solar energy applications. The monthly averages of the daily solar radiation incident upon a horizontal surface are available for many locations. However, radiation data on tilted surfaces are generally not available. A simple method to estimate the average daily radiation for each calendar month on surfaces facing directly towards the equator has been developed by Liu and Jordan [17].

The tilt angle (β) of any collector is defined as the angle between the plane of the collector surface and the horizon. When β is positive, the orientation of the surface is toward the equator, and when negative, it is toward the pole.

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 [11].

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

where n is the number of the day of year starting from the first day of January (n=1 on January 1st and n=365 on December 31st , February 29th is ignored).

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, we get the following equation [11],

$$\omega = \cos^{-1}(-\tan\phi \tan\delta) \qquad (2)$$

The monthly average daily radiation on a horizontal surface (H), the fraction of the mean daily extraterrestrial radiation (H_0), the monthly average daily diffuse radiation (H_D) [17],

$$H_0 = \frac{24}{\pi} G_{sc}(1+0.033\cos(\frac{360n}{365})(\cos\phi\cos\delta\sin\omega + \frac{\pi\omega}{180}\sin\phi\sin\delta) \qquad (3)$$

where G_{sc} is the solar constant (1367 W/m^2), ϕ is the latitude of the Antalya.

Extraterrestrial radiation is solar radiation incident occurring outside the earth’s atmosphere. On average the extraterrestrial irradiance is 1367 W/m^2. The monthly average daily solar radiation on tilted surface (H_T), may be expressed as follow (Liu and Jordan, 1960) [17],

$$H_T = (H - H_D)R_b + \frac{H_D}{2}(1+\cos\beta) + \frac{H\rho}{2}(1-\cos\beta) \qquad (4)$$

where ρ is ground reflectance (≈0.2).

Liu and Jordan [17] have suggested that can be estimated to be the ratio of extraterrestrial radiation on the tilted surface to that on a horizontal surface for each month. For a surface facing directly towards the equator,

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega' + (\pi/180)\omega'\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega + (\pi/180)\omega\sin\phi\sin\delta} \qquad (5)$$

ω' where is the sunset hour angle for the tilted surface given by

$$\omega' = \min\begin{bmatrix} \omega = \cos^{-1}(-\tan\phi\tan\delta) \\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta) \end{bmatrix} \qquad (6)$$

where “min” means the smaller of the two items in the bracket [2].

3. METHODOLOGY

The equations which calculate total solar radiation (monthly, the seasonally, the semi-annually, the annually) falling on tilted surface for optimum tilt angle of latitude ±15° and latitude are solved with a computer code which is written in MATLAB and should be modular to allow users to update component modules easily as new findings become available. All graphs plotted with Grapher 10. The calculations begin with measured hourly global and diffuse radiation received on a horizontal surface.

A mathematical procedure is then used to transpose these quantities onto an inclined plane. The optimum tilt angle was determined by figuring out the values for which the total radiation on the collector surface is a maximum for a particular day or a specific period. In this regard, the calculations were made for a south facing solar collector for 365 days. The tilt angle is changed from 0° to 90°. The solar reflectivity (ρ) was assumed to be 0.2. The β_{opt} obtained for a specific period allows us to collect the maximum solar energy for Antalya, Turkey.

4. RESULTS AND DISCUSSION

The main purpose of this study is to determine and analyze the optimum tilt angle for solar collectors in Antalya, which is located in the southern part of Turkey and is the seventh biggest city in the country by population which is a main touristic attraction point by the south coast facing the Mediterranean.

Turkey lies in a sunny belt between 36° and 42°N latitudes and is geographically well positioned with respect to solar energy potential. Turkey's yearly average total sunshine duration is 2640 h and the yearly average solar radiation is 4719.6 MJ/m^2 yr (12.96 MJ/m^2 day) [18]. Antalya has a high potential for solar energy production (Fig. 1) and the daily sunshine duration is very long. Fig. 2 show sunshine duration throughout the year in Antalya [19].

Table 1 show optimum tilt angles and Table 2 and Figs. 3-4 show calculated solar radiation on tilted surface for optimum tilt angles. The optimum angle of tilt of a flat-plate collector in January is 63° and the total monthly solar irradiation falling on the collector surface at this tilt is 529.11 MJ/m^2-month. The optimum tilt angle in July is 1° and the total monthly solar radiation at this angle is 701.05 MJ/m^2-month. The optimum tilt angle increases during the winter months and reaches a maximum of 65° in December which collects 517.75 MJ/m^2-month of solar energy.

Fig. 5 shows the average seasonally total radiation derived on a south facing surface on optimum tilt angle. The seasonal average was calculated by finding the average value of the tilt angle for each season and the application of this requires the collector tilt to be rearranged four times a year. In spring the tilt should be 22°, in summer 4°, in autumn 48° and in winter 61°. The figures clearly show that a unique optimum tilt angle exists for each month of the season that corresponds to the maximum point of each curve.

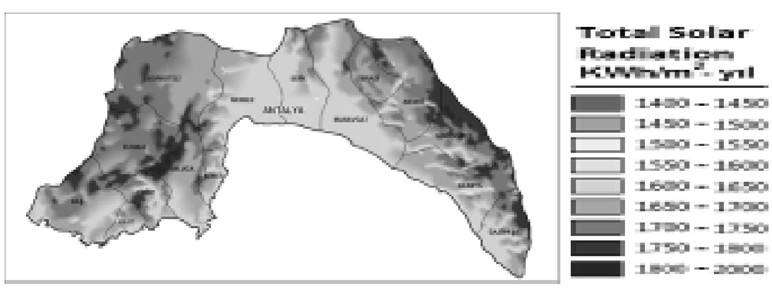

Fig. 1. Solar map of Antalya

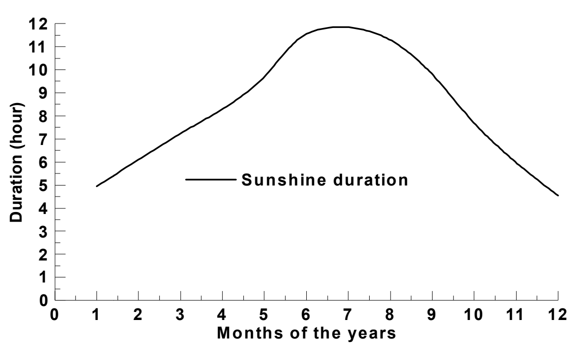

Fig. 2. Sunshine duration throughout the year

Table 1. Monthly, seasonally, semi-annually, annually, latitude±15 and latitude optimum tilt angles

Months	Monthly	Seasonally	Semi-annually	Annually	Ø±15	Ø
Jan	63	61	54	33	51,89	36,89
Feb	54	61	54	33	51,89	36,89
Mar	39	22	13	33	21,89	36,89
Apr	21	22	13	33	21,89	36,89
May	5	22	13	33	21,89	36,89
Jun	1	4	13	33	21,89	36,89
Jul	1	4	13	33	21,89	36,89
Aug	15	4	13	33	21,89	36,89
Sep	33	48	54	33	51,89	36,89
Oct	50	48	54	33	51,89	36,89
Nov	61	48	54	33	51,89	36,89
Dec	65	61	54	33	51,89	36,89

Table 2. Solar radiations on tilted surface for optimum tilt angles (MJ)

Months	Monthly	Seasonally	Semi-annually	Annually	Ø	Ø±15
Jan	529,11	528,89	523,66	467,77	482,49	520,74
Feb	503,55	500,46	503,55	474,94	484,45	503,24
Mar	589,77	568,62	541,05	587,05	589,41	568,35
Apr	614,37	614,27	610,11	603,91	596,23	614,29
May	687,87	667,37	683,19	633,07	617,17	667,63
Jun	694,99	692,44	678,16	610,15	591,40	654,01
Jul	701,05	700,07	690,07	629,37	611,66	669,57
Aug	647,92	640,07	647,76	623,85	612,72	644,13
Sep	577,99	561,41	546,23	577,99	576,68	552,11
Oct	562,17	562,00	560,82	542,56	550,64	561,82
Nov	516,12	504,93	512,95	464,22	477,52	510,68
Dec	517,75	516,54	509,05	447,27	462,96	505,47
Total	7142,66	7057,06	7006,61	6662,16	6559,32	6972,04

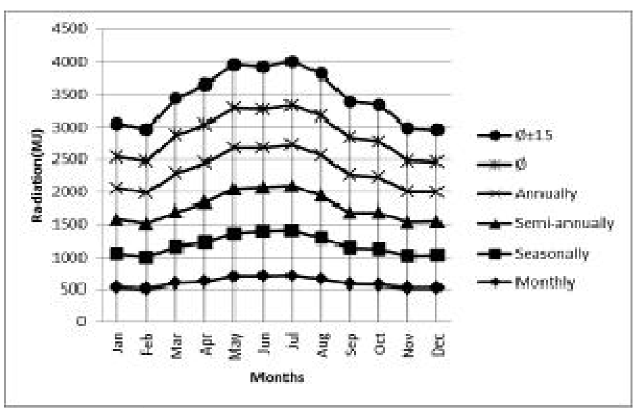

Fig. 3. Monthly, seasonally, semi-annually, annually, latitude ±15 and latitude optimum tilt angles

Fig. 6 shows the average semi-annually total radiation derived on a south facing surface on optimum tilt angle. It is clear from the figures that a unique optimum tilt angle exists for each 6 months of the year that corresponds to the maximum point of each curve.

Fig. 7 shows the average annually total radiation derived on a south facing surface on optimum tilt angle. The yearly average tilt was calculated by finding the average value of the tilt angles for all months of the year. The yearly-average optimum tilt angle was 33° and the yearly collected solar energy was 6662.16 MJ/m^2-year for a south facing solar collector which nearly corresponding to the latitude of Antalya (36.89°). This is in agreement with the results of many other researchers. It is clear from the figure that there is a unique optimum tilt angle exists for each month of the year that corresponds to the maximum point of each curve.

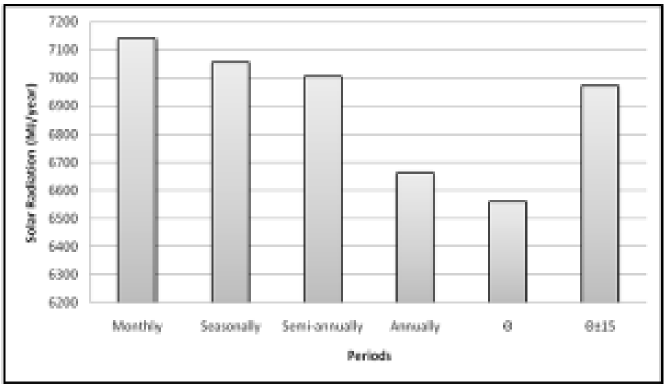

Fig. 4. Solar radiations on tilted surface for optimum tilt angles

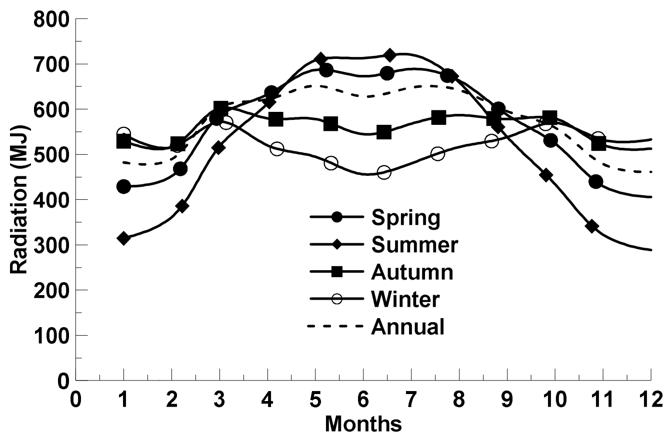

Fig 5. Seasonally average solar radiation availability of tilted surfaces

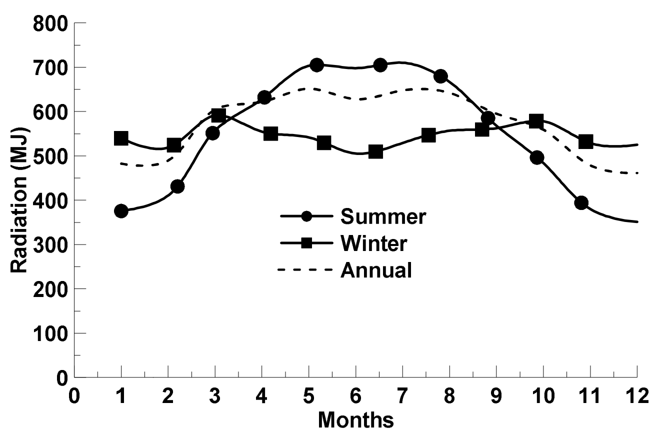

Fig. 6. Semi-annually average solar radiation availability of tilted surfaces

Fig. 8 shows the average monthly total radiation at Antalya on a south facing surfaces for latitude angle and latitude angle±15 of panel tilt. It is clear from this graph that there is a unique tilt angle for each month of the year for which the solar radiation is at a peak for the given month.

Fig. 9 shows the results obtained that variation of monthly optimum tilt angle for Antalya.

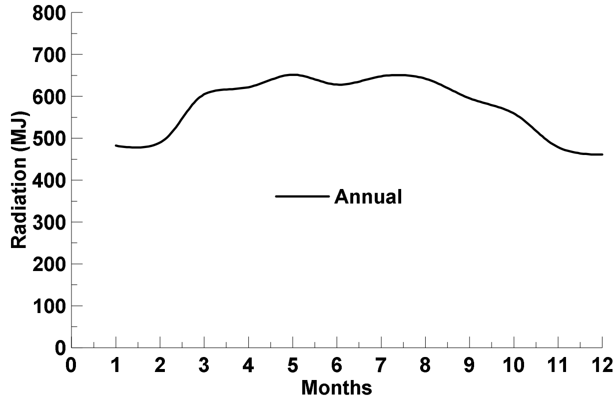

Fig. 7. Annually average solar radiation availability of tilted surfaces

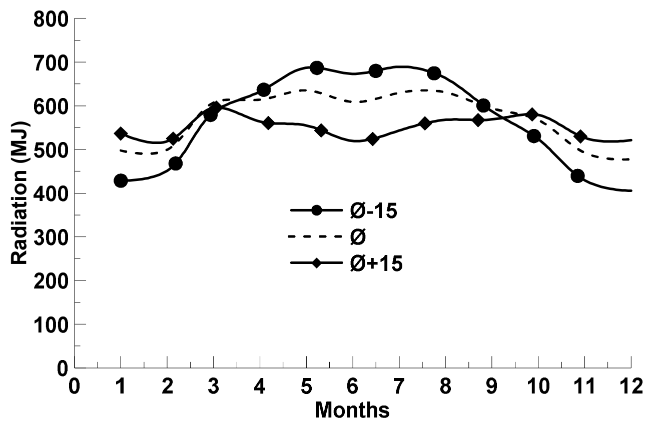

Fig 8. Monthly average solar radiation for latitude angle and latitude angle±15

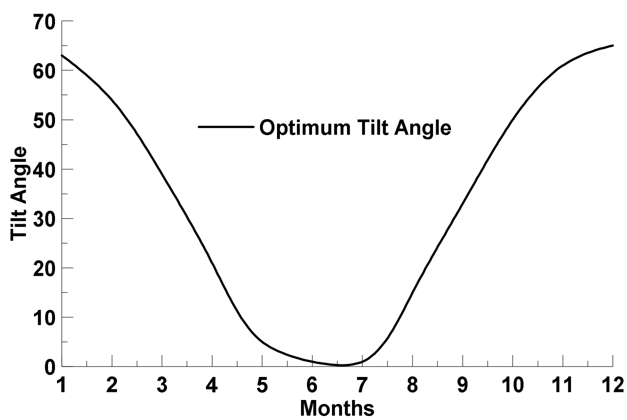

Fig. 9. The variation of monthly optimum tilt angle for Antalya

When the monthly optimum tilt angle was used, the yearly collected solar energy was 7142.66 MJ/m^2-year. The solar collector should be mounted at the monthly tilt angle and the slope adjusted every month. This would allow an increase in the efficiency of the solar collector more than 7% over that of a similar fixed solar collector at the optimum annual tilt angle in Antalya.

When the seasonally optimum tilt angle was used, the yearly collected solar energy was 7057.07 MJ/m^2 -year. The solar collector would be mounted at the seasonally tilt angle and the slope adjusted every season. This will allow an increase in the efficiency of the solar collector more than 5% over that of a similar fixed solar collector at the optimum annual tilt angle in Antalya.

5. CONCLUSION

The optimum tilt angle is different for each month of the year. The collected solar energy amount will be higher if the optimum tilt angle for each month is chosen. Also it has been found that the optimum tilt angle in June and July becomes 1°. The optimum tilt angle then escalates during the winter months and reaches a maximum of 65° in December. The results show that the average optimum tilt angle for the summer months is 4° and for the winter months 61°. Finally, the yearly-average optimum tilt angle found to be 33° and the yearly collected solar energy was 6662.16 MJ/m^2-year for a south facing solar collector which nearly corresponding to the latitude of Antalya (36.89°). This is in agreement with the results of many other researchers.

This study shows the importance of accurate slope angle and orientation. The position of the solar collectors can be easily adjusted when the supporting structure is designed accordingly. We can conclude that a yearly average fixed tilt may be utilized in many general applications (e.g. domestic water heating) in order to alleviate and downsize the manufacturing and installation costs of collectors low. In order to get the highest efficiency, the collectors need to be designed so that the tilt angle can be altered effortlessly at least on a seasonal basis, if not monthly. Alternatively, solar tracking systems effective tools to be used in industrial installations where higher efficiency is required.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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