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Research Article

Calculation of the Optimum PV Panel Incline Angle for Mediterranean Climate

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Abstract

Due to the increasing energy needs and the limited resources that are depleted, more importance is given to renewable energy sources and their use with the highest efficiency in many areas. In order to benefit from solar energy, which is one of the most important renewable energy sources, with the highest efficiency, various parameters must be optimized. In this study, the optimization of the photovoltaic (PV) panel angle is emphasized. By using the values of solar radiation incident on the horizontal plane, the optimum PV panel angle for Adana province related to the months was determined according to the south direction. In total, 12 different panel-angle estimation models specific to the region were developed and brought to the literature. When the results are reviewed, it is thought that the usability of these data for designers and academics is appropriate.

Keywords: Energy, panel, solar radiation, mathematical modelling, optimum angle.

Akdeniz İklimi İçin Optimum PV Panel Eğim Açisinin Hesaplanması

Öz

Artan enerji ihtiyaçları ve tükenen kısıtlı kaynaklar sebebiyle birçok alanda yenilenebilir enerji kaynakları ve bunların en yüksek verimle kullanımına daha büyük önem verilmektedir. En önemli yenilenebilir enerji kaynaklarından birisi olan güneş enerjisinden en yüksek verimle yararlanabilmek için çeşitli parametrelerin optimize edilmesi gerekmektedir. Bu çalışmada bahsi geçen parametrelerden panel açısının optimizasyonu üzerine durulmuştur. Yatay düzleme gelen güneş ışınımı değerleri kullanılarak Adana ili için aylara göre optimum panel açısı güney yöne göre belirlenmiştir. Bölgeye özgü 12 farklı panel-açı tahmin modeli geliştirilmiş ve literatüre kazandırılmıştır. Sonuçlar incelendiğinde bu verilerin tasarımcılar ve akademisyenler için kullanılabilirliğinin uygun olduğu düşünülmektedir.

Anahtar Kelimeler: Enerji, panel, güneş ışınımı, matematiksel modelleme, optimum açı.

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1. Introduction

The solar radiation energy falling on the earth every year is about 160 times more than the fossil fuel reservoirs determined so far on earth (Teke et al., 2015). In addition, it is 15,000 times more than the classical energy production facilities on earth would produce in a year (Serrano et al., 2009). In this respect, sensitivity to nature will be ensured by adapting solar energy to a usable energy type suitable for human activities.

As it is known, there are many studies in the literature on PV panel tilt angle (Rusen et al., 2013; Yadav and Chandel 2013; Khatib et al., 2012). These studies aim to obtain electrical energy with maximum efficiency from sunlight by finding the angle values in the regional geography and obtaining the maximum radiation values. For example, (Ulgen, 2006) examined the monthly PV panel tilt angle values for İzmir province in his study and found that the lowest in June is 0°, the highest is 61° in December, and the annual fixed PV panel angle is 30.3. (Benghanem, 2011) determined the panel inclination angles for spring, summer, autumn and winter as 17°, 12°, 28° and 37°, respectively, in a study conducted for Medina. By determining the annual fixed panel angle of 23.5°, an increase in efficiency of up to 8% was achieved compared to the previous situation. (Yılmaz et al., 2016) observed that the panel inclination angles for the province of Batman vary between 1° and 65° per month. In seasonal analyzes, 61°, 22°, 4° and 48° angle values were found for winter, spring, summer and autumn, respectively, and 33° fixed angle values were calculated annually.

(Kallioğlu et al., 2018) in their study for Muğla-Turkey, the annual average panel tilt angle was found to be 32.25°, and if the angles are changed monthly, the annual efficiency increases by 17.03% compared to the horizontal position and the annual average radiation value is 5949 W/m^2-year. (Kallioğlu et al., 2020) also determined the optimum PV panel tilt angles for Antalya, Kayseri and Trabzon (Turkey). In addition, statistical analyzes were made by developing seven different mathematical models that give the optimum tilt angle only depending on the latitude value in the northern hemisphere. All correlations developed are recommended for academic and industrial users.

As can be seen from this and many similar studies, knowing the solar radiation coming to the earth is an essantial factor in determining the design and efficiency of the systems in which solar energy is used. The solar radiation values (instantaneous, hourly and daily) coming to the earth are measured by solar radiation measuring devices at meteorology stations or calculated with the help of mathematical relations developed for this region. Due to the elliptical movement of the earth around the sun, the sunrise and sunset times and the angle of incidence of the sun's rays on the earth change. In order to benefit from the maximum amount of solar energy, the angle of the PV panels should be adjusted perpendicular to the solar radiation.

In this study, Adana region (GPS coordinates with DMS: 37° 0' 0.0000" N and 35° 19' 16.8060" E) with solar energy potential above Turkey's average was selected as the target, and it was aimed that the solar energy investments planned to be made in the region would be more efficient and more profitable. Since the determination of PV panel angles in different regions gives different results even if the latitudes are the same, these calculations need to be made specific to the region. In addition, the best model was created by comparing the results calculated with the equations obtained for the PV panel tilt angle and applying statistical error tests.

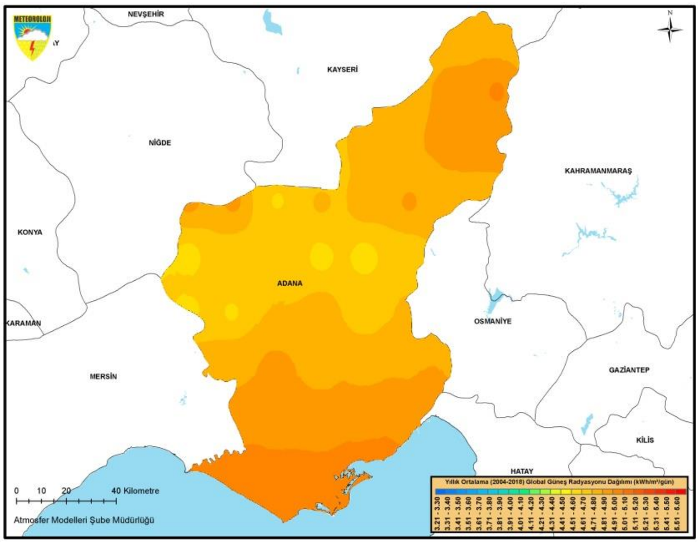


Figure 1. *Solar radiation map of Adana region (the study area)* ***(Provided by*** *Turkish State Meteorological Service)*

2. Material and Method

2.1. Calculation of Optimum PV Angle

The geographical location of the settlement where the plane is located, the number of days in the year and the daily time period are the main factors that affect the amount of radiation used in solar energy calculations. Therefore, this study aims to provide maximum benefit by determining the optimum PV panel angles on a monthly, seasonal and annual basis for the PV panel on the inclined plane.

Solar radiation measurements commonly consist of data recorded in the horizontal plane. In order to calculate the amount of radiation falling on the inclined surface, the daily total radiation value should be re-measured.

The monthly average daily global radiation value (H_T) falling on the inclined plane is given in equation 1. This equation consists of the sum of direct solar radiation (H_B), reflected radiation (H_R) and diffuse radiation (H_S) values (Benghanem, 2011).

$$H_T = H_B + H_R + H_S \quad (1)$$

The value of direct solar radiation (H_B) coming to the inclined surface is given in equation 2. This equation is calculated with the help of monthly total radiation (H) and diffuse radiation (H_D) incident to the horizontal plane.

$$H_B = (H - H_d)R_b \quad (2)$$

The value of R_b in equation 2 is the ratio of the direct radiation incident on the inclined plane to the amount of radiation incident on the horizontal plane and can be calculated with the help of equation 3. This ratio is calculated as a relation of latitude ($\emptyset$), solar declination angle (δ), mean sunrise angle (ω_s) and sunrise angle on inclined plane (ω_s') values (Bakırcı, 2012).

$$R_b = \frac{\cos(\emptyset-\beta)\cos(\delta)\sin(\omega_s') + \omega_s'(\pi/180)\sin(\emptyset-\beta)\sin(\delta)}{\cos(\emptyset)\cos(\delta)\sin(\omega_S) + \omega_S(\pi/180)\sin(\emptyset)\sin(\delta)} \tag{3}$$

The daily amount of radiation reflected from the ground and falling on the inclined surface is calculated by equation 4. ρ in this equation is the reflection coefficient of the ground, and it varies according to the vegetation, altitude, topography and season of the region. In this study, this value was taken as 0.2. β in the equation is the angle of inclination of the panel with the horizontal plane.

$$H_R = H\rho(1-\cos\beta)/2 \tag{4}$$

The amount of diffuse radiation falling on the inclined surface is calculated by equation 5.

$$H_S = H_d\, R_d \tag{5}$$

H_d is the amount of diffuse radiation falling on the horizontal plane and is calculated by equation 6 (Liu and Jordan, 1962).

$$H_d = H(1 - 1{,}13\, H/H_0\,) \tag{6}$$

H_0 in equation 6 is the daily extraterrestrial solar radiation coming to the horizontal surface, and it is a function of the solar constant Gsc, the earth's orbital eccentricity correction factor k, the solar declination (δ), the latitude ($\emptyset$) of the region and the mean sunrise angle (ωs) of the sun and is calculated monthly with the equation (7) (Kallioğlu, 2014; Sharma et al., 2021).

$$H_o = (24/\pi).Gsc\,.k.[cos\,\emptyset.cos\,\delta.sin\,\omega_s + (\pi/180).sin\,\emptyset.sin\,\delta.\omega_s] \tag{7}$$

The solar constant is generally accepted as 1367 W/m^2. Earth's orbital eccentricity correction factor is found in relation to the solar radiation incident on the Earth and the solar radiation coming out of the atmosphere. The correction factor (k) of the solar constant varies according to the days; it is calculated from equation 8, where n is the number of days in the year (1-365).

$$\mathrm{k} = 1 + 0{,}033\cos(\,360\,\mathrm{n}/360) \tag{8}$$

The solar deviation (δ) is calculated by equation 9. The n in this formula represents the number of days from January 1 to the day the declination angle will be calculated. Instead of all the days in a month with solar radiation values, the monthly average declination angle is calculated over the average number of days determined per month (Duffie and Beckman, 1991).

$$\delta = 23{,}45^\circ sin(360\,(n+284)/365\,\,) \tag{9}$$

The angle of sunrise on horizontal (ω_s) and inclined (ω_s') surfaces is calculated by equations 5 and 6, respectively. These relations vary depending on the inclined surface, latitude and solar declination.

$$\omega_s = \cos^{-1}(-\tan\emptyset.\tan\delta) \tag{10}$$

$$\omega_s' = \min\left[\frac{\omega = \cos^{-1}\,(-\tan\emptyset\tan\delta)}{\cos^{-1}(-\tan(\emptyset-\beta)\tan\delta}\right] \tag{11}$$

R_d in equation 5 is the calibre coefficient between the average daily sloped and horizontal surfaces and is calculated with equation number 7.

$$R_d = (1+\cos\beta)\,/2 \tag{12}$$

2.2. Statistical Methods

It is inevitable that the collected information can be understood by others and can be compared with different information obtained by the same means, and this situation has brought the obligation to present the data in a whole and distribution form, according to certain rules. For this purpose, various statistical methods have been developed.

Examining the relationship between variables in these statistical studies is an indispensable part of the scientific method. Whether there is a relationship between two variables, and if there is, determining the level of this relationship is an issue that is frequently encountered in statistical analysis.

In the design and projection of systems working with solar energy, it is necessary to know the solar radiation data of that region. However, due to the inaccessibility of meteorological data and some difficulties encountered, in this study, simple calculation models were determined for the province of Adana to determine the value of the panel angle with the horizontal and its compatibility with the measured values was analyzed. Developed models are linear equation, quadratic polynomial relation and third-degree polynomial relation. These models were tested with four different statistical methods, namely mean bias error (MBE), square root error ($RMSE$), t-statistic ($t-sat$) and coefficient of determination (R^2)

Mean bias error (MBE) provides information about the long-term value of the correlation. A low value of this value is desired, ideally close to zero and calculated by equation 13. In the equation, ci (calculated) indicates the calculated value, while mi (measured) indicates the measured value (Kallioğlu et al., 2017).

$$MBE = \frac{1}{n}\sum\nolimits_{i=1}^{n}(mi-ci) \tag{13}$$

Root mean square error ($RMSE$) statistical data is important in comparing short-term measured and predicted model performance. While it always takes a positive value, its ideal value is close to zero, and it is expressed by equation 14 (Bakirci, 2012).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ci-mi)^2} \tag{14}$$

The t-test method ($t-stat$) is one of the most extensively used methods in hypothesis testing, and by comparing the means of the two groups, it is decided whether the difference is random or statistically reasonable. It is used to determine the statistical significance between the calculated panel angle values and the estimated angle values and is shown in equation 15 (Kallioğlu, 2014).

$$t - stat = \sqrt{\frac{(n-1)\, MBE^2}{RMSE^2 - MBE^2}} \tag{15}$$

The coefficient of determination (R^2) is used to understand the strength of the link between two variables. It is used to determine the linear relationship between the calculated and measured values. The value of this coefficient varies between 0 and 1 ($0 < R^2 < 1$); its ideal value is close to 1 and is expressed by equation 16. The ca and ma in the equation are the averages of the calculated and measured values, respectively (Kallioğlu, 2021; Stone, 1993).

$$R^2 = \frac{\sum_{i=1}^{n}(ci - ca)x(mi - ma)}{\left[\sqrt{\sum_{i=1}^{n}(ci - ca)^2}\right]x\left[\sum_{i=1}^{n}(mi - ma)^2\right]} \tag{16}$$

3. Results and Discussion

In this study, the meteorological data of the Turkish State Meteorological Service were used. The optimum point was determined from the total solar radiation values at different angles (0°-90°) of the solar panel using equations 1-12.

In Table 1, for the city of Adana, H is the monthly average amount of radiation falling on the horizontal plane ($W/m^2 - day$), H_0 is the monthly average amount of radiation outside the atmosphere ($W/m^2 - day$). As a result of the calculations, the monthly average diffuse radiation falling on the H_d horizontal plane ($W/m^2 - day$), the optimum angle values $\beta_{OPT}(°)$ and the amount of radiation falling on the corresponding panel at this angle value H_T ($W/m^2 - day$) are shown monthly.

As can be seen from Table 1, the optimum angle values and the maximum and minimum points of the amount of radiation falling on the PV panel are 0° and 6680 ($W/m^2 - day$) in Adana in June, and $57°$ and 2726 ($W/m^2 - day$) in December, respectively. When looking at the region in general, the optimum angle values vary between 0°- 57°, and the highest angle values are in December-January, while the lowest angle values are in June-July. Angle values decrease in the period from December to June and tend to increase in the period from June to December. The main reason for this situation is that on June 21, the sun's rays reach the Northern Hemisphere at the steepest angle and on December 21, the opposite of this situation, the most oblique angle. This mentioned example can be seen more clearly in Figure 3.

The models developed specifically for Adana are given as equations 17-28, also illustrated with Figure 2. The equations determined for Adana region were tested with statistical methods, and the results are shown in Tables 2 and 3. As one ca

$$\beta = -1{,}2809(\delta) + 29{,}698 \tag{17}$$
$$\beta = -0{,}0081(\delta)^2 - 1{,}2799(\delta) + 31{,}867 \tag{18}$$
$$\beta = 0{,}0001(\delta)^3 - 0{,}0081(\delta)^2 - 1{,}3352(\delta) + 31{,}863 \tag{19}$$
$$\beta = -0{,}0089(H_0) + 104{,}59 \tag{20}$$
$$\beta = -0{,}0000007(H_0)^2 + 0{,}0026(H_0) + 60{,}865 \tag{21}$$
$$\beta = -0{,}00000000003(H_0)^3 - 0{,}00000002(H_0)^2 - 0{,}0027(H_0) + 74{,}269 \tag{22}$$
$$\beta = -0{,}0117(H) + 79{,}967 \tag{23}$$
$$\beta = -0{,}000001(H)^2 + 0{,}0001(H) + 59{,}388 \tag{24}$$
$$\beta = 0{,}0000000002(H)^3 - 0{,}000004(H)^2 + 0{,}0095(H) + 48{,}544 \tag{25}$$
$$\beta = -0{,}0449(Hd) + 109{,}38 \tag{26}$$
$$\beta = -0{,}00002(Hd)^2 + 0{,}0343(Hd) + 45{,}776 \tag{27}$$
$$\beta = -0{,}00000002(H_d)^3 + 0{,}00006(H_d)^2 - 0{,}0962(H_d) + 114{,}8 \tag{28}$$

The compatibility between the estimation results of the models developed specifically for the region and the calculated values was examined by statistical methods. There are 12 linear, 2nd-degree polynomial and 3rd-degree polynomial equations developed specifically for Adana city. Among these equations, the best equation for estimating the PV panel angle for Adana city is equation 22, which is a 3rd-degree polynomial. The coefficient of determination (R^2) values for which the statistical analyzes were examined took the value of 0.9937 for the city of Adana, which is reasonably close to 1. In addition to being simple and usable, the models developed specifically for the city are also strong in providing statistical data. Thus, it can be preferred in determining the free optimum panel angle by using meteorological data when needed.

The relationship between the PV panel tilt angle and the amount of radiation intensity in the regions calculated is shown in Figure 3 between January and December. The figures show the amount of radiation falling on the panel in relation to the angles of the solar panels between 0°-90°. While there is an increase in the amount of radiation until the optimum angle value in the autumn and spring months, a decrease is observed afterwards. A significant decrease in the amount of radiation is observed in the change of the panel angle from 0° to 90° in the summer months. The same situation is observed in the winter months, on the contrary. Considering this variable situation, it should be adjusted monthly in order to use solar energy systems with maximum efficiency. However, if the change in the angle of the panel is not possible, at least a periodic or annual average value for the purpose of use can be determined. The variation of monthly, seasonal and annual panel angles of Adana city is also shown in Figure 3.

Considering similar studies, the PV panel inclination angle, which is accepted in solar energy applications, is generally adjusted to latitude in annual applications, latitude + 15 degrees in summer applications and latitude-15 in winter applications. Figure 3 shows the changes in the amount of radiation for these applications, as well as the optimum and seasonal angles of the months.

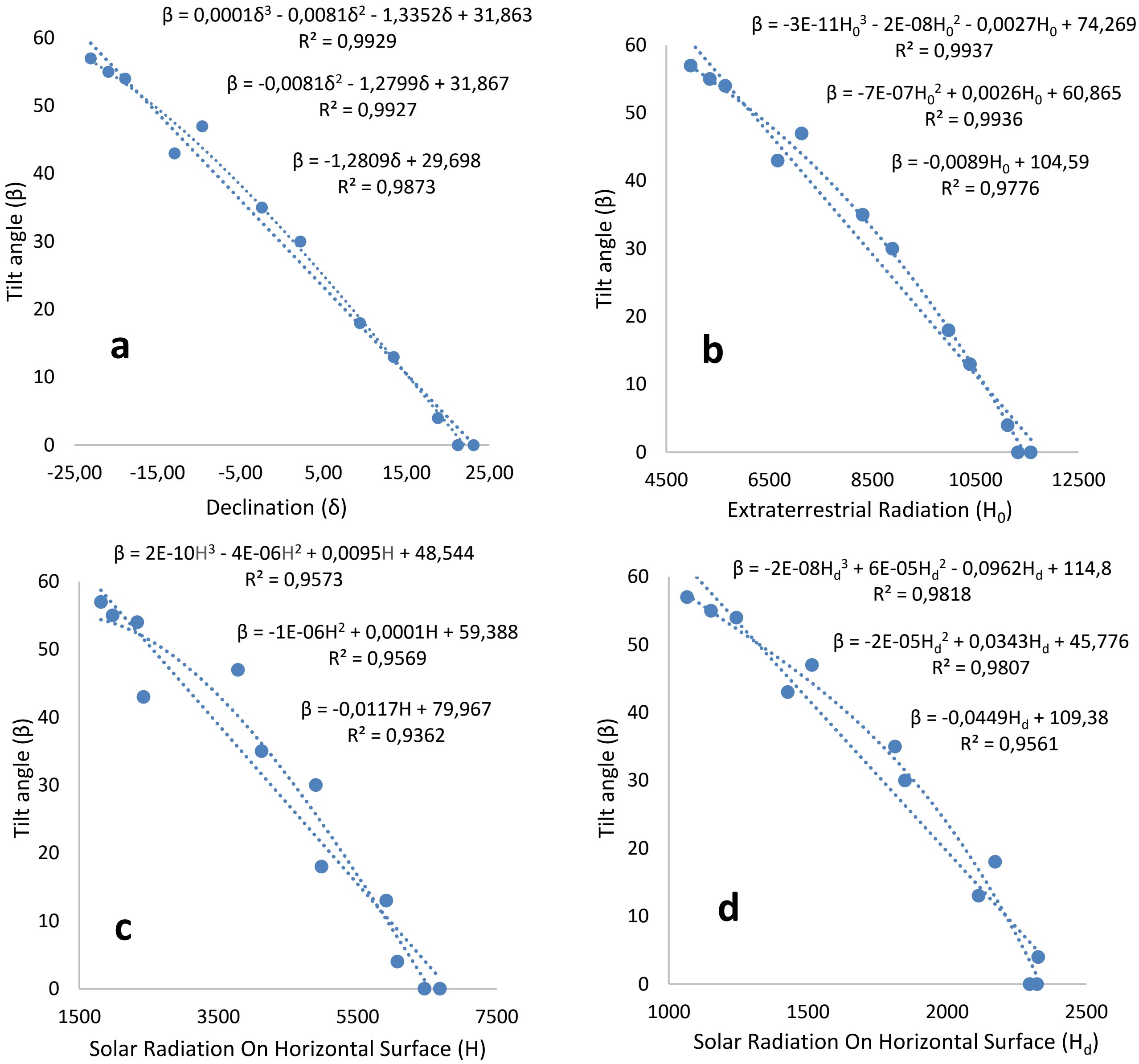


***Figure 2**. Models developed specifically for Adana region a)δ b)H_0 c)H d)H_d*

***Table1**. Optimum Tilt Angle and Radiation Amount Relation by Month*
(Monthly average radiation falling on the horizontal plane $W/m^2 - day$)
*(H value is Provided by **Turkish State Meteorological Service**)*

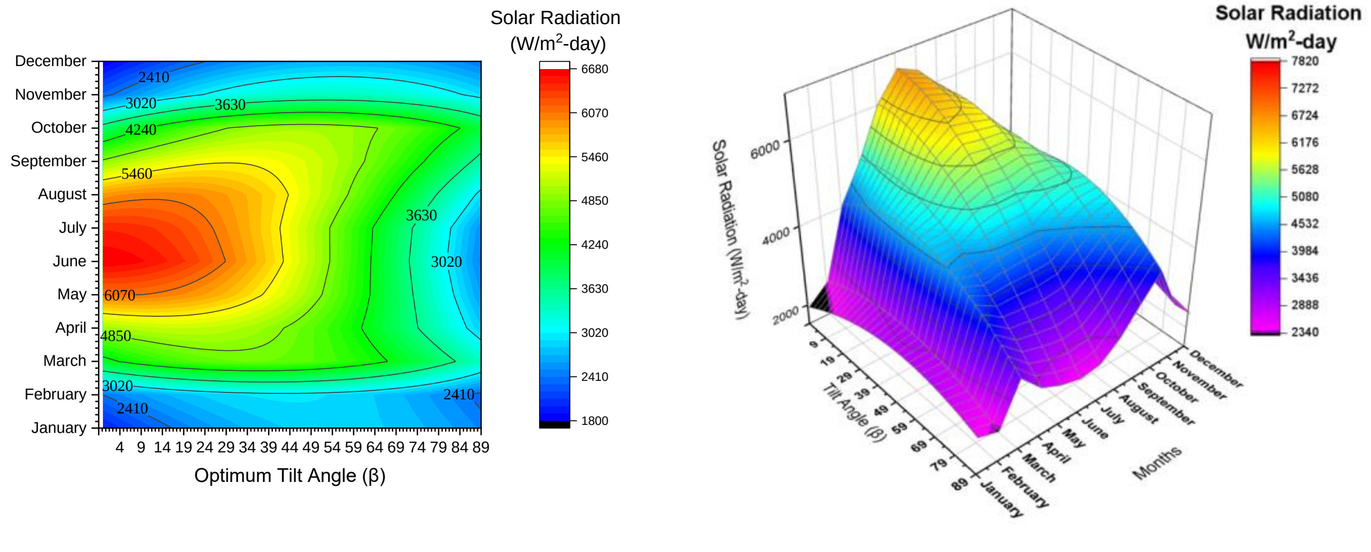
Location	Months	H_0	H	H_d	K_T	$\beta_{OPT}(^0)$	H_T
	Jan.	5343	1980	1151	0,37	55	2859
	Feb.	6662	2420	1427	0,36	43	2946
	Mar.	8313	4120	1813	0,50	35	4752
	Apr.	9980	4980	2172	0,50	18	5156
	May	11122	6070	2327	0,55	4	6080
Adana	Jun.	11574	6680	2323	0,58	0	6680
	Jul.	11325	6460	2296	0,57	0	6460
	Aug.	10393	5910	2112	0,57	13	6022
	Sep.	8890	4900	1848	0,55	30	5441
	Oct.	7127	3780	1515	0,53	47	5037
	Nov.	5642	2330	1243	0,41	54	3369
	Dec.	4970	1810	1065	0,36	57	2726

***Table 2.** Estimated PV Panel Tilt Angles*

	Months	Calculate	Eq.(16)	Eq.(17)	Eq.(18)	Eq.(19)	Eq.(20)	Eq.(21)	Eq.(22)	Eq.(23)	Eq.(24)	Eq.(25)	Eq.(26)	Eq.(27)
Adana	Jan.	55	56	55	55	57	55	55	57	56	53	58	59	53
	Feb.	43	46	47	48	45	47	47	52	54	51	45	54	42
	Mar.	35	33	35	35	31	34	33	32	43	34	28	42	18
	Apr.	18	18	19	19	16	17	16	22	35	21	12	26	-16
	May	4	6	5	5	6	3	0	9	23	4	5	17	-36
	Jun.	0	0	-2	-2	2	-3	-6	2	15	-7	5	18	-36
	Jul.	0	3	1	1	4	1	-2	4	18	-3	6	19	-32
	Aug.	13	12	13	13	12	12	10	11	25	6	15	29	-9
	Sep.	30	27	29	29	25	29	28	23	36	23	26	41	16
	Oct.	47	42	43	44	41	44	43	36	45	38	41	52	37
	Nov.	54	54	53	54	54	53	53	53	54	51	54	58	50
	Dec.	57	59	57	57	60	56	57	59	56	54	62	60	56

***Table 3.** Statistical Comparison of Estimated Angles*

Location	Eq. No	MBE	RMSE	t-statistic	R^2
Adana	17	0,0005	2,3708	0,0007	0,9873
	18	-0,0073	1,7968	0,0136	0,9927
	19	-0,0061	1,7899	0,0113	0,9929
	20	0,2376	3,1636	0,2498	0,9776
	21	0,6227	1,8395	1,1934	0,9936
	22	1,9478	2,9836	2,8583	0,9937
	23	-0,1463	5,3221	0,0912	0,9362
	24	-8,7598	11,5184	3,8845	0,9569
	25	2,5708	5,2594	1,8583	0,9572
	26	-0,0506	4,4109	0,0380	0,9561
	27	-9,8069	11,2378	5,9273	0,9803
	28	17,7488	22,6282	4,1939	0,9813



a) *2D map* b) *3D map*

***Figure 3**. Variation of inclination angle in Adana according to months (January- December):*

As Figure 4 also shows, the relationship between the panel angle change and the amount of radiation varies in different periods. While this change in the period between March and October can be more clearly defined, the change in radiation intensity between October and March is more uncertain. The main reason for this situation can be explained by the high radiation intensity and the angle of incidence of the sun's rays in the period from the beginning of the Spring Equinox on March 21 to the beginning of the Autumn Equinox on September 23. In general, when all regions between March and October are examined, the maximum amount of radiation is at the optimum angle value. This value is followed by seasonal angle, latitude-15, annual mean angle, latitude angle, latitude+15, respectively. In the period between October and March, the optimum angle is latitude+15, latitude angle, annual average angle and latitude-15.

4. Conclusions and Recommendations

In this study, the optimum panel angle was determined for Adana province, which is one of the provinces most suitable for solar energy investments in the southern region of Turkey. When these data are considered in general, the inclination angles have varied according to the months and the lowest is 0° while the

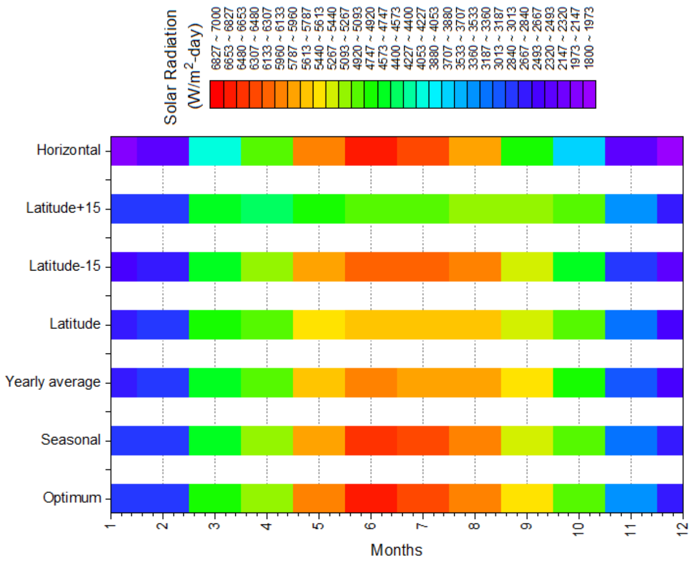


Figure 4. Relationship between the panel angle change and the amount of radiation varies in different periods.

the highest degree, around 57° degrees. The seasonally appropriate slope angle values are 51° in winter, 19° in spring, 4° in summer, 44° in autumn, and the annual average is around 29.66°. According to the optimum monthly panel angle, the increase in production efficiency is 50,61% in the winter months compared to the first situation and does not change in the summer months. In the case of adjusting the annual panel inclination angle, an efficiency increase of around 6.66% was achieved compared to the original condition (Horizontal plane). When the results are analyzed, monthly adjustment of the panel tilt angles provides maximum benefit from solar radiation. However, in cases where monthly angle change is not possible, climatic conditions are an important factor. For example, if the weather is cloudy in December and January in a region, the module should be directed according to these months. The second important factor is the intended use of the system. If a system is installed for a seasonal job that needs to work with maximum efficiency in the spring or autumn seasons, calculating the inclination angle accordingly will make a serious economic contribution with productivity increase.

Also, it is not easy to precisely determine the best model out of all as all equations provide similar R^2 values in Table 3, which means all the models have nearly the same output, efficiency-wise. As a result of this, it can be said that since all models work with very low error, the parameters used in the models have been chosen sufficiently.

The models developed specifically for the city of Adana are simple and usable, as well as provide strong statistical data. Thus, when needed, appropriate equations can be used for the optimum panel angle independent of meteorological data. Additional methods can also be applicable, such as symbolic regression, evolutional algorithms etc., which might provide competitive results. These approaches are left to future studies. We plan to use such algorithms in future studies.

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