**Journal of Tekirdag Agricultural Faculty**
Tekirdağ Ziraat Fakültesi Dergisi

Eylül/September 2023, 20(3)
**Başvuru/Received:** 21/03/23
**Kabul/Accepted:** 10/06/23
**DOI:** 10.33462/jotaf.1268745

http://dergipark.gov.tr/jotaf
http://jotaf.nku.edu.tr/

**ARAŞTIRMA MAKALESİ** **RESEARCH ARTICLE**

# Estimation of Monthly, Seasonal and Annual Total Solar Radiation on the Tilted Surface at Optimum Tilt Angles in Two Provinces, Turkiye

Türkiye'de İki İlde Optimum Eğim Açılarında Eğimli Yüzeyde Aylık, Mevsimsel, Yıllık Toplam Güneş Işınımının Tahmini

**Eray ÖNLER[1]*, Birol KAYİŞOĞLU[2]**

## Abstract

In solar energy systems that use solar panels, it's important to know the best tilt angle to optimize solar energy production. Monthly, seasonal, and annual optimum tilt angles were determined in this study using meteorological insolation data from many years in the provinces of Tekirdag and Konya, which are located in different regions of Turkey. At optimum tilt angles, monthly, seasonal, and annual total radiation on the tilted surface were 1516.7 kWh $m^{-2}$ $year^{-1}$, 1504.1 kWh $m^{-2}$ $year^{-1}$ and 1448.1 kWh $m^{-2}$ $year^{-1}$ in Tekirdag, respectively. In Konya, these values were 1851.4 kWh $m^{-2}$ $year^{-1}$, 1833.51 kWh $m^{-2}$ $year^{-1}$ and kWh $m^{-2}$ $year^{-1}$, respectively. In the seasonal and annual optimum tilt angles, there was an approximately 1% and 5% loss in the total radiation values on the tilted surface, respectively, according to the monthly optimum tilt angle. In addition, the coefficients of the relationship between the monthly mean daily radiation on the tilted surface and the tilt angles were determined for each month using the cubic regression model in both provinces. The Cubic regression model coefficients are computed for each month in the provinces of Tekirdag and Konya. All months in both provinces had $R^2$ (Coefficient of determination) values of 0.999 for the Cubic model. To determine whether there is a difference between the total amounts of radiation reaching the tilted surface for each month at the best tilt angles obtained by the two methods, the t-test was used. The monthly average daily radiation values on the tilted surface obtained by the two methods at the best tilt angles in both provinces have not been found to differ statistically ($p>0.05$; $t=0.001$).

**Keywords:** Solar radiation, Extraterrestrial radiation, Tilted surface, Optimum tilt angle, Cubic regression model

[1]***Sorumlu Yazar/Corresponding Author:** Eray Önler, Tekirdag Namik Kemal University, Tekirdag, Turkiye. E-mail: erayonler@nku.edu.tr OrcID: 0000-0001-7700-3742.

[2] Birol Kayişoğlu, Tekirdag Namik Kemal University, Tekirdag, Turkiye. E-mail: bkayisoglu@nku.edu.tr OrcID: 0000-0002-2885-3174.

**Atıf/Citation Yazar** Önler, E., Kayişoğlu, B. Estimation of monthly, seasonal and annual total solar radiation on the tilted surface at optimum tilt angles in two provinces, Turkiye. *Journal of Tekirdag Agricultural Faculty*, 20(3): 712-722.

# Öz

Güneş panelleri kullanılan güneş enerjisi sistemlerinde, güneş enerjisi üretimini optimize etmek için panellerin konumlandırılacağı yerde monte edilirken kullanılacak, en iyi eğim açısını bilmek önemlidir. Bu çalışmada Türkiye'nin coğrafi olarak farklı bölgelerinde yer alan Tekirdağ ve Konya illerinde uzun yıllara ait meteorolojik güneşlenme verileri kullanılarak aylık, mevsimsel ve yıllık optimum güneş paneli eğim açıları belirlenmiştir. Tekirdağ ili için hesaplanan optimum eğim açılarında, eğimli yüzeydeki aylık, mevsimsel ve yıllık toplam güneş ışınımı sırasıyla 1516.7 $m^{-2}$ $yıl^{-1}$, 1504.1 kWh $m^{-2}$ $yıl^{-1}$ ve 1448.1 $m^{-2}$ $yıl^{-1}$ olmuştur. Konya ili için yapılan hesaplamalarda ise bu değerler sırasıyla 1851.4 $m^{-2}$ $yıl^{-1}$, 1833.51 $m^{-2}$ $yıl^{-1}$ ve 1754.7 $m^{-2}$ $yıl^{-1}$ olarak bulunmuştur. Mevsimsel ve yıllık optimum eğim açılarında, eğimli yüzeyde elde edilen toplam güneş ışınımı değerlerinde aylık optimum eğim açısına göre sırasıyla yaklaşık %1 ve %5 oranında kayıp olduğu görülmüştür. Ayrıca eğimli yüzeydeki aylık ortalama günlük ışınım ile panel eğim açıları arasındaki ilişkinin katsayıları her ay için kübik regresyon modeli kullanılarak belirlenmiştir. Kübik regresyon modeli katsayıları Tekirdağ ve Konya illerinde her ay için ayrı ayrı hesaplanmıştır. Kübik regresyon modeli için her iki ilde de tüm ayların $R^2$ (Determinasyon Katsayısı) değeri 0,999'dur. Yüksek $R^2$ değeri seçilen modelin bağımsız değişkeni olan panel eğim açılarındaki varyansın, bağımlı değişken olan eğimli yüzeydeki aylık ortalama günlük ışınımın sahip olduğu varyansın 99.9%' unu açıklayabildiğini göstermektedir. İki yöntemle elde edilen en iyi eğim açılarında eğimli yüzeye aylara göre ulaşan toplam güneş ışınımı miktarları arasında fark olup olmadığını belirlemek için t-testi kullanılarak karşılaştırma yapılmıştır. Her iki ilde en iyi eğim açılarında iki yöntemle elde edilen eğimli yüzeydeki aylık ortalama günlük güneş ışınımı değerleri istatistiksel olarak farklılık göstermemiştir ($p>0,05$; $t=0,001$).

**Anahtar Kelimeler:** Güneş Işınımı, Uzay Işınımı, Eğik Yüzey, Optimum Eğim Açısı, Kübik Regresyon Modeli

## 1. Introduction

Determining the optimum tilt angle of the solar panel in a region where a solar energy system will be installed is an important parameter in terms of energy efficiency (Altan et al., 2021; Diken and Kayisoglu, 2022). The technical staffs who install the system generally ignore the optimum tilt angle and determine it according to the criteria, which are not based on scientific basis. The most efficient way to benefit from solar energy in solar panels is to use solar tracking systems. In a study, it was stated that when solar tracking systems are used, there is a 43.87% more daily total energy gain than fixed systems (Abdallah, 2004). Tomson (2008) stated that seasonal energy yield increased 10–20% of collectors which are used the two-positional tracking system. However, solar tracking systems are fairly costly and are more cost-effective when utilized in solar power plants where solar energy is utilized extensively (Despotovic and Nedic, 2015). Thus, they are not advised for use in smaller solar panel installations (Mousazadeh et al., 2009). Determining the annual, seasonal or monthly optimum tilt angles in relatively small panel systems where solar tracking systems are not economical gains importance in terms of increasing the amount of energy collected on the tilted surface of collector. For this purpose, a lot of research has been done and numerous models have been used. Gong and Kulkarni (2005) stated in their research that the optimum tilt angle is close to site's latitude degree in conditions where the azimuth angle is zero, but it is lower in some cases. Using a mathematical model, the total solar radiation on the tilted PV (Photovoltaic) surface was estimated, and the optimal tilt angles for a PV panel installed in Sanliurfa, Turkey were determined. Researchers stated that the optimum tilt angle of PV panels for Sanliurfa is 14º (Kacira et al., 2004). In a study conducted in China, optimum tilt angles were determined for 30 cities by using the actual monthly global and diffuse radiation values on horizontal surface of 152 settlements (Tang and Wu, 2004). In a study investigating the performance of PV systems placed at different angles in Brisbane, Australia, it was stated that the theoretical optimal tilt angle was approximately 26º facing true North (Yan et al., 2013). Using annual optimal tilt angles as opposed to monthly optimum tilt angles resulted in projected energy losses of 5.68 percent for Aligarh and 4.91 percent for New Delhi. Based on the study, it was suggested that the inclined surface be tilted at the optimal monthly or seasonal tilt angle for optimal solar energy generation (Jamil et al., 2016). Vieira et al. (2016) in their experimental study, they stated that there is a low average energy gain in panels using solar tracking system compared to fixed panels.

There are numerous models for estimating the total radiation incident on the tilted surface with the help of global radiation incident on the horizontal surface. In most of these models, direct, diffuse and reflected radiation predictions are made (Muzathik et al., 2011). There are also many empirical models developed using available meteorological data in order to calculate total radiation on the tilted surface (Psiloglou and Kambezidis, 2007). Using the data obtained from the Turkish State Meteorological Service, Bakirci (2009) used 7 models to estimate the monthly average daily amount of global radiation in many provinces, Turkey, and compared them.

In this study, it was aimed to determine the monthly, seasonal and annual optimum tilt angles by using monthly average daily radiation data obtained from the Turkish State Meteorological Service in Tekirdağ and Konya provinces, Turkey. Tekirdag is in the Thrace region in the northwest of Turkey. Konya is in the Central Anatolian region. Intensive industrial and agricultural activities are carried out in both provinces and there is a large amount of energy consumption. In addition, the relationship between the angle of tilt and the monthly average daily total radiation on the tilted surface was also investigated for each month.

## 2. Materials and Methods

Latitudes, longitudes and altitudes of provinces where this research was conducted are given in *Table 1*. Tekirdag is on the west and coast of the Marmara Sea. Konya is quite far from the sea and is located in the Central Anatolian region.

***Table 1. Laritudes, longitudes and altitudes of provinces***

| City | Latitude (º) | Longitude (º) | Altitude (m) |
|---|---|---|---|
| Tekirdag | 40.98 | 27.52 | 37 |
| Konya | 37.87 | 32.48 | 1023 |

The daily extraterrestrial radiation on horizontal surface on northern hemisphere has been calculated by the equation given below (Eq. 1) (Duffie and Beckman, 1991; Türk Togrul and Onat, 1999);

$$H_o = \frac{24 G_{sc} k}{\pi} * \left(\cos\delta \cos\phi \sin\omega_s + \frac{\pi\omega_s}{180}\sin\delta \sin\phi\right) \quad \text{(Eq.1).}$$

Where, $H_o$ is the Daily extraterrestrial radiation on horizontal surface (kWh m$^{-2}$ day$^{-1}$), $G_{sc}$ is the solar constant (1367 W m$^{-2}$), $k$ is the eccentricity correction factor and calculated the equation (Eq. 2) given below;

$$k = \left(1 + 0.033\cos\frac{360n}{365}\right) \quad \text{(Eq.2).}$$

Where, $n$ is the number of the day of the year starting from the first of January.

Sunset hour angle is calculated by the following equation (Eq. 3) (Cooper, 1969; Yorukoglu and Celik, 2006);

$$\omega_s = \cos^{-1}(-\tan\delta \tan\phi) \quad \text{(Eq.3).}$$

Where; $\omega_s$ is the sunset hour angle (º), $\delta$ is the declination angle (º) and $\phi$ is the latitude of site (º).

The declination angle is calculated with the following equation (Eq. 4) in the northern hemisphere according to certain days of the year (Cooper, 1969; Ertekin and Yaldiz, 1999);

$$\delta = 23.45 * \sin\left(360\frac{(284-n)}{365}\right) \quad \text{(Eq.4).}$$

The calculated average declination and hour angles for days specified in *Table* 2 have been used to calculate the monthly average daily radiation on the tilted surfaces (Mehleri et al., 2010; Bakirci, 2012).

***Table 2. Recommended average declination and hour angles for each month in the northern hemisphere***

| **Month** | **Day** | $n$ | $\delta$ (°) | $\omega_s$ (°) |
|---|---|---|---|---|
| January | 17 | 17 | -20.92 | 70.6 |
| February | 16 | 47 | -13.00 | 78.4 |
| March | 16 | 75 | -2.40 | 87.9 |
| April | 15 | 105 | 9.40 | 98.3 |
| May | 15 | 135 | 18.80 | 107.2 |
| June | 11 | 162 | 23.10 | 111.8 |
| July | 17 | 198 | 21.20 | 109.7 |
| August | 16 | 228 | 13.50 | 102.0 |
| September | 15 | 258 | 2.20 | 91.9 |
| October | 15 | 288 | -9.60 | 81.5 |
| November | 14 | 318 | -18.90 | 72.7 |
| December | 10 | 344 | -23.00 | 68.3 |

Many models have been developed to determine the amount of diffuse radiation using the monthly daily global solar radiation. In this study, the model developed by Erbs et al. (1982) was used. In this model, after calculating the monthly daily average clearness index using monthly average values, cubic relations between diffuse radiation and global radiation reaching the earth are developed. The average clearness index has been calculated for each month as below (Eq. 5) (Duffie and Beckman, 1991);

$$\bar{K}_T = \frac{\bar{H}_g}{\bar{H}_0} \quad \text{(Eq.5).}$$

Where; $\bar{H}_g$ is the montly daily average global radiation on horizontal surface (kWh/m$^2$.day), $\bar{H}_0$ is the monthly daily average extraterrestrial radiation (kWh m$^{-2}$ day$^{-1}$).

The monthly daily average global radiation values on the horizontal surface obtained from the Turkish State Meteorological Service for the period between 1991 and 2020 have been used in this research. The monthly average daily global radiation data on the horizontal surface of Tekirdag and Konya provinces are given in *Figure 1*. Maximum monthly average daily radiation values on the horizontal surface in Tekirdag and Konya provinces are 5.97 kWh m$^{-2}$ day$^{-1}$ in June and 6.81 kWh m$^{-2}$ day$^{-1}$ in July, respectively.

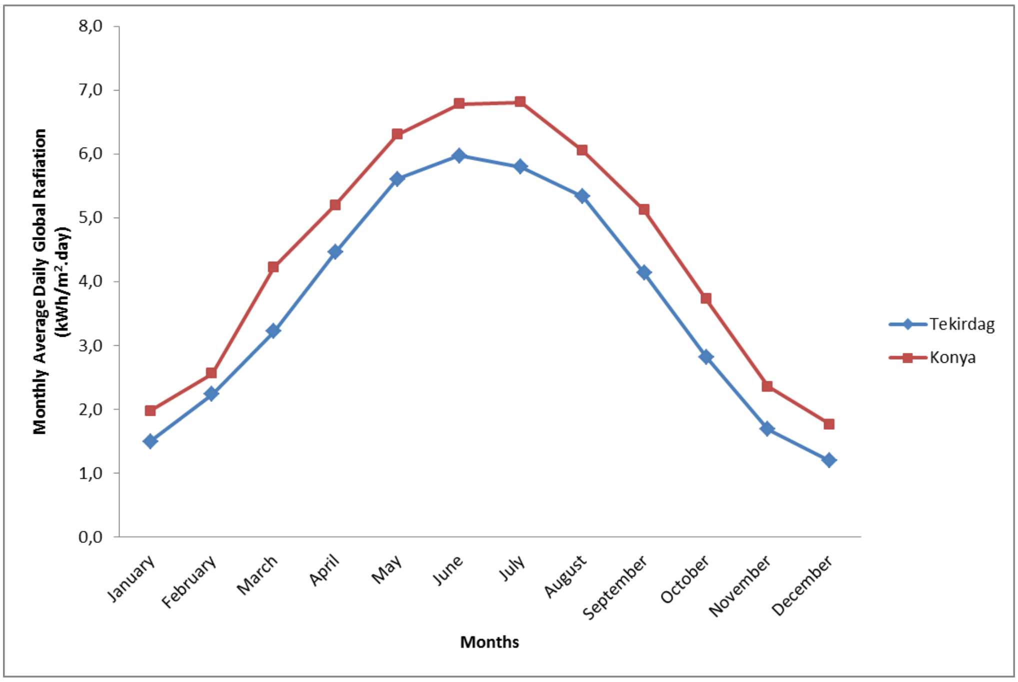



***Figure-1. The monthly average daily global radiation values on the horizontal surface***

In the model used in this study, two different equations (Eq. 6-7) have been developed depending on limit values of the sunset hour angle with clearness index.

At the boundary conditions $\omega_s \leq 81.4^o$ and $0.3 \leq \bar{K}_T \leq 0.8$;

$$\frac{\bar{H}_d}{\bar{H}_g} = 1.392 - 3.560\bar{K}_T + 4{,}189\bar{K}_T{}^2 - 2.137\bar{K}_T{}^3 \quad \text{(Eq.6).}$$

At the boundary conditions $\omega_s > 81.4^o$ and $0.3 \leq \bar{K}_T \leq 0.8$;

$$\frac{\bar{H}_d}{\bar{H}_g} = 1.311 - 3.022\bar{K}_T + 3.427\bar{K}_T{}^2 - 1.821\bar{K}_T{}^3 \quad \text{(Eq.7).}$$

In Eq6 and Eq7, $\bar{H}_d$ is the monthly daily average diffuse radiation on the horizontal surface (kWh m$^{-2}$ day$^{-1}$).

The average monthly daily beam radiation on horizontal surfaces has been computed as follows (Eq. 8);

$$\bar{H}_b = \bar{H}_g - \bar{H}_d \quad \text{(Eq.8).}$$

Where; $\bar{H}_b$ is the monthly daily average beam radiation on the horizontal surface (kWh m$^{-2}$ day$^{-1}$).

The total amount of radiation coming to the tilted surface has been calculated using following equation (Eq. 9) (Liu and Jordan, 1960; Liu and Jordan, 1963);

$$\bar{H}_C = \bar{H}_b\bar{R}_b + \bar{H}_d\left(\frac{1+\cos\beta}{2}\right) + \bar{H}_g\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad \text{(Eq.9).}$$

Where; $\bar{H}_C$ is the monthly daily average total radiation on tilted surface (kWh m$^{-2}$ day$^{-1}$), $\bar{R}_b$ is the geometric angle factor, $\beta$ is the collector tilt angle and $\rho_g$ is the surface reflection rate. Assuming that the tilted surface is on the ground, the reflection ratio ($\rho_g$) is taken as 0.14.

$\bar{R}_b$ for surfaces sloped towards the southern in the northern hemisphere is calculated by following equation (Eq. 10) (Yakup and Malik, 2001);

$$\bar{R}_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_s' + \left(\frac{\pi}{180}\right)\omega_s'\sin(\phi-\beta)\sin\delta}{\cos\omega_s\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s\sin\phi\sin\delta} \quad \text{(Eq.10).}$$

Where; $\omega_s'$ is the monthly averaged daily mean sunset hour angle for the tilted surface and calculated as follows (Eq. 11);

$$\omega_s' = min\{\omega_s | \cos^{-1}(-\tan(\phi-\beta)\tan\delta)\} \quad \text{(Eq.11).}$$

In the above equation, whichever of the values to the left and right of the separator is smaller is taken as $\omega_s'$.

For each month, the monthly average daily total radiation values coming to the tilted surface between 5 and 85 degrees with 5-degree intervals were calculated. With the help of the calculated monthly average daily radiation values, the monthly, seasonal and annual total radiation values on the tilted surface were calculated for each tilt angle. The tilt angles with the highest total radiation value on the tilted surface were accepted as the optimum tilt angle.

In addition, the regression relations between the monthly average daily total radiation values on the tilted surface ($\bar{H}_C$) and the angle of tilt (β) investigated. Among the models examined, the most appropriate one was the cubic regression model. In this model, it has been observed that there is a very close relationship between the total radiation on the tilted surface and the tilt angle ($R^2$=~1).

The Cubic regression equation (Eq. 12) is given below;

$$\bar{H}_C = a + b_1\beta + b_2\beta^2 + b_3\beta^3 \quad \text{(Eq.12).}$$

The coefficients in the Cubic regression model were calculated with the SPSS ver.18 package program.

Optimum monthly slope angles obtained by the derivative of the cubic regression model (Eq.12) were compared with the monthly optimum slope angles obtained from meteorological data (Eq. 13) (Jamil et al., 2016);

$$\frac{d}{d\beta}(\bar{H}_C) = 0 \quad \text{(Eq.13).}$$

### 3. Results and Discussion

The monthly daily average extraterrestrial radiation, beam and diffuse radiation values on horizontal surface and clearness indexes of two cities have been given in *Table 3*. It was observed that the clearness index was higher in Konya than Tekirdag in all months. While the clearness index was higher in the summer months in both provinces, it was lower in the winter months.

***Table 3. The monthly daily average extraterrestrial, beam, diffuse radiation values (kWh/m$^2$.day) and clearness indexes***

| Month | Tekirdag | | | | Konya | | | |
|---|---|---|---|---|---|---|---|---|
| | $\bar{H}_o$ | $\bar{H}_b$ | $\bar{H}_d$ | $\bar{K}_T$ | $\bar{H}_o$ | $\bar{H}_b$ | $\bar{H}_d$ | $\bar{K}_T$ |
| January | 4.06 | 0.689 | 0.811 | 0.37 | 4.59 | 1.060 | 0.920 | 0.43 |
| February | 5.54 | 1.128 | 1.112 | 0.40 | 6.04 | 1.350 | 1.210 | 0.42 |
| March | 7.50 | 1.606 | 1.614 | 0.43 | 7.89 | 2.557 | 1.673 | 0.54 |
| April | 9.55 | 2.402 | 2.058 | 0.47 | 9.77 | 3.125 | 2.075 | 0.53 |
| May | 11.01 | 3.254 | 2.356 | 0.51 | 11.07 | 3.997 | 2.303 | 0.57 |
| June | 11.61 | 3.489 | 2.481 | 0.51 | 11.59 | 4.398 | 2.382 | 0.59 |
| July | 11.29 | 3.386 | 2.414 | 0.51 | 11.31 | 4.519 | 2.291 | 0.60 |
| August | 10.11 | 3.180 | 2.150 | 0.53 | 10.27 | 3.948 | 2.102 | 0.59 |
| September | 8.23 | 2.376 | 1.764 | 0.50 | 8.56 | 3.381 | 1.739 | 0.60 |
| October | 6.12 | 1.501 | 1.319 | 0.46 | 6.58 | 2.361 | 1.369 | 0.57 |
| November | 4.41 | 0.807 | 0.883 | 0.38 | 4.93 | 1.385 | 0.975 | 0.48 |
| December | 3.67 | 0.479 | 0.721 | 0.33 | 4.20 | 0.928 | 0.842 | 0.42 |

Monthly average geometric angle factors according to tilt angles in all months have been seen in *Figure 1*. Geometric angle factors were higher in summer than winter months. While the geometric angle factors decreased as the tilt angle increased in winter months, they increased up to 65-70 degrees tilt angle in summer months and started to decrease after.

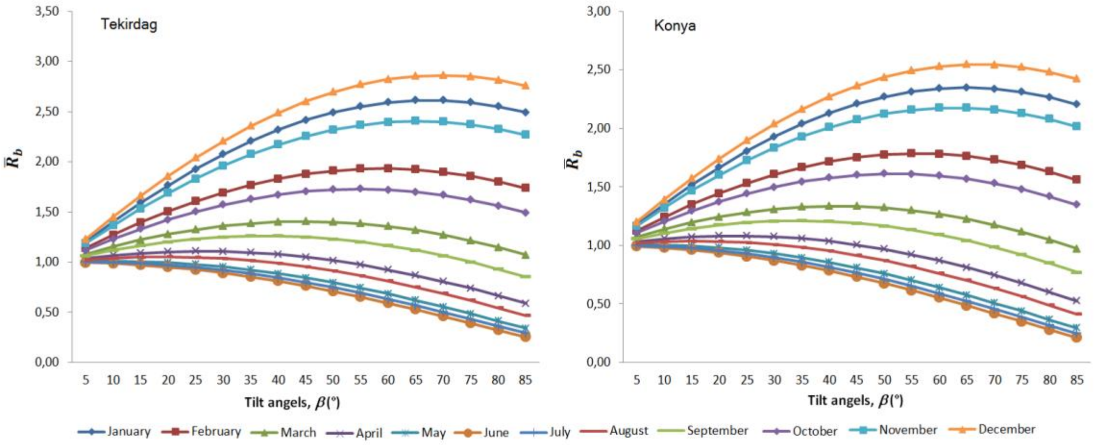



***Figure 2. Monthly average geometric angle factors ($\bar{R}_b$)***

Depending on the optimum tilt angles, the total radiation values coming to the tilted surface for each month are calculated and given in *Table 4*. Optimum tilt angles in all months were the same in both provinces. In Tekirdağ and Konya, the maximum monthly total radiation values on the tilted surface were 179.9 kWh m$^{-2}$ month$^{-1}$ and 210.7 kWh m$^{-2}$ month$^{-1}$, respectively, in July. Monthly total radiation values on tilted surface were higher in Konya province in all months.

***Table 4. Monthly total radiation on tilted surface (kWh m$^{-2}$ month$^{-1}$) and optimum tilt angles (º)***

| Months | Tekirdag | | Konya | |
|---|---|---|---|---|
| | $H_{C,m}$ | $\beta_{ort}$ | $H_{C,m}$ | $\beta_{ort}$ |
| January | 75.8 | 60 | 100.4 | 60 |
| February | 87.5 | 50 | 96.7 | 50 |
| March | 115.8 | 35 | 154.1 | 35 |
| April | 139.9 | 20 | 162.4 | 20 |
| May | 174.6 | 5 | 195.8 | 5 |
| June | 178.6 | 5 | 202.4 | 5 |
| July | 179.9 | 5 | 210.7 | 5 |
| August | 169.5 | 15 | 191.4 | 15 |
| September | 139.6 | 30 | 172.7 | 30 |
| October | 116.0 | 45 | 155.8 | 45 |
| November | 79.6 | 55 | 114.8 | 55 |
| December | 60.0 | 60 | 94.3 | 60 |
| **Total (kWh/m$^2$.year)** | **1516.7** | | **1851.4** | |

Annual and seasonal total radiation on tilted surface at optimum tilts angles have been given *Table 5*. While the annual optimum tilt angles were different in the two provinces, the seasonal optimum tilt angles were the same. In Tekirdag province, the total radiation on tilted surface at annual and seasonal tilt angles decreased 4.5% and 0.8% according to monthly tilt angle, respectively. This decrease was 5.2% and 1.0%, respectively, in Konya province (*Figure 2*).

***Table 5. Annual and seasonal total radiation on tilted surface (kWh m⁻²) and optimum tilts angles (º)***

| City | Annual | | Seasonal | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Spring | | Summer | | Autumn | | Winter | | Total |
| | $H_{C,an}$ | $\beta_{ort}$ | $H_{C,sp}$ | $\beta_{ort}$ | $H_{C,sm}$ | $\beta_{ort}$ | $H_{C,au}$ | $\beta_{ort}$ | $H_{C,wn}$ | $\beta_{ort}$ | $H_{C,sea}$ |
| Tekirdag | 1448.4 | 25 | 424.4 | 20 | 526.0 | 5 | 331.0 | 45 | 222.8 | 55 | 1504.1 |
| Konya | 1754.7 | 30 | 503.1 | 20 | 603.0 | 5 | 436.9 | 45 | 290.5 | 55 | 1833.5 |

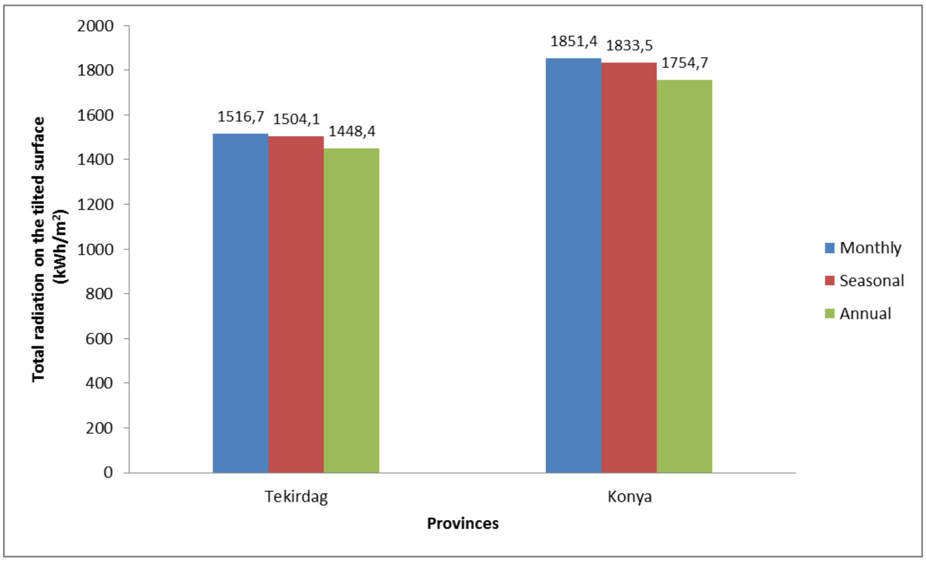


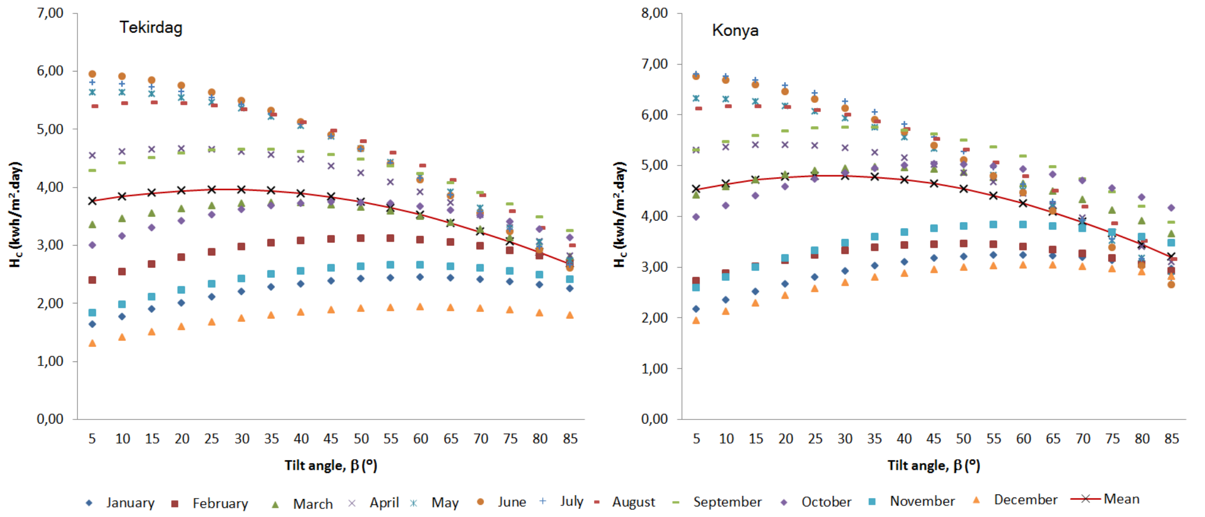

***Figure 3. Monthly, seasonal and annual total radiation values on the tilted surface at optimum tilt angles.***

In Tekirdag and Konya province, the Cubic regression model coefficients calculated for each month are given in *Table 6*. $R^2$ values of Cubic model were 0.999 in all months in both provinces. The distribution of the monthly daily average total radiation values on tilted surface according to the months depending on the tilt angles have been calculated by the Cubic regression model and given in the *Figure 3*.

***Table 6. Coefficients of the Cubic regression model in Tekirdag and Konya***

| Month | Tekirdag | | | | Konya | | | |
|---|---|---|---|---|---|---|---|---|
| | a constant | $b_1$ | $b_2$ (x10⁻⁴) | $b_3$ (x10⁻⁷) | a constant | $b_1$ | $b_2$ (x10⁻⁴) | $b_3$ (x10⁻⁷) |
| January | 1.491 | 0.0306 | -2.19 | -4.11 | 1.968 | 0.0414 | -3.04 | -5.34 |
| February | 2.229 | 0.0345 | -3.23 | -2.07 | 2.547 | 0.0371 | -3.73 | -1.32 |
| March | 3.207 | 0.0300 | -4.41 | 3.73 | 4.212 | 0.0428 | -6.24 | 5.08 |
| April | 4.444 | 0.0225 | -5.90 | 17.60 | 5.180 | 0.0256 | -7.20 | 15.20 |
| May | 5.588 | 0.0114 | -7.01 | 20.30 | 6.274 | 0.0107 | -8.22 | 25.60 |
| June | 5.944 | 0.0039 | -7.11 | 23.90 | 6.749 | 0.0017 | -8.52 | 31.00 |
| July | 5.776 | 0.0073 | -7.07 | 22.30 | 6.779 | 0.0063 | -8.83 | 30.10 |
| August | 5.309 | 0.0212 | -7.11 | 16.70 | 6.026 | 0.0223 | -8.39 | 21.00 |
| September | 4.122 | 0.0348 | -5.92 | 7.10 | 5.099 | 0.0441 | -7.70 | 9.48 |
| October | 2.807 | 0.0393 | -4.09 | -1.05 | 3.711 | 0.0555 | -5.81 | -1.17 |
| November | 1.681 | 0.0324 | -2.46 | -3.97 | 2.345 | 0.0493 | -3.75 | -5.89 |
| December | 1.193 | 0.0236 | -1.67 | -3.29 | 1.759 | 0.0399 | -2.74 | -5.76 |
| **Mean** | **3.649** | **0.0243** | **-4.86** | **7.65** | **4.387** | **0.0314** | **-6.19** | **9.87** |

Optimum tilt angles calculated for each month with the meteorological solar radiation data and the cubic regression model are given in *Table 7*. The t-test was applied to investigate whether there is a difference between the total amounts of radiations coming to the tilted surface for each month at the optimum tilt angles obtained by the two methods. It has been observed that there is no statistically significant difference between the monthly




average daily radiation values on the tilted surface obtained by the two methods at optimum tilt angles in both provinces (p>0.05; t=0.001).

***Figure 4. The monthly average daily total radiation values on tilted surface according to the months depending on the tilt angles***

***Table 7. Optimum tilt angles calculated with solar radiation data ($\beta_{opt,md}$) and the cubic regression model ($\beta_{opt,cm}$).***

| Months | Tekirdag | | Konya | |
|---|---|---|---|---|
| | $\beta_{ort,md}$ | $\beta_{ort,cm}$ | $\beta_{ort,md}$ | $\beta_{ort,cm}$ |
| January | 60 | 59.8 | 60 | 58.9 |
| February | 50 | 50.9 | 50 | 48.5 |
| March | 35 | 35.6 | 35 | 35.9 |
| April | 20 | 21.1 | 20 | 18.9 |
| May | 5 | 8.4 | 5 | 6.7 |
| June | 5 | 2.8 | 5 | 1.0 |
| July | 5 | 5.3 | 5 | 3.6 |
| August | 15 | 15.8 | 15 | 14.0 |
| September | 30 | 31.1 | 30 | 30.3 |
| October | 45 | 47.2 | 45 | 47.1 |
| November | 55 | 57.8 | 55 | 57.8 |
| December | 60 | 60.0 | 60 | 61.1 |
| **Annual** | **25** | **26.7** | **30** | **27.1** |

## 4. Conclusions

In this study, monthly, seasonal and annual optimum tilt angles and total radiation values on the tilted surface were determined by using meteorological data in the provinces of Tekirdag and Konya. In both provinces, it was observed that there was no significant difference in the total radiation values coming to the tilted surface in monthly and seasonal optimum tilt angles (~1%). At the annual optimum tilt angle, a decrease of approximately 5% was observed in the total amount of radiation coming to the tilted surface compared to the monthly optimum tilt angle. If solar energy systems with too many panels are taken into account, since the cost of adjusting the panels to the optimum tilt angle every month will be quite high, it will be more economical to adjust the tilt angles seasonal if possible. However, it is obvious that the cost of radiation losses on the tilted surface at the annual optimum tilt angles will be less than the monthly cost of adjusting to the optimum tilt angles. For this reason, it can be recommended to adjust the panel tilt angles to the annual optimum tilt angle in both provinces.

Depending on the tilt angles of the existing panel systems, the monthly average daily total radiation coming to the tilted surface can be estimated with the cubic model coefficients which are calculated in this study in both provinces. It is also possible to use these coefficients in software to be developed to estimate the total radiation amounts in panel systems in these provinces.

## References

Abdallah, S. (2004). The effect of using sun tracking systems on the voltage – current characteristics and power generation of flat plate photovoltaics. *Energy Conversion and Management,* 45: 1671–1679.

Altan Duman, A., Diken, B. and Kayişoğlu, B. (2021). Prediction of photovoltaic panel power outputs using time series and artificial neural network methods. *Journal of Tekirdag Agricultural Faculty,* 18(3): 457-469.

Bakirci, K. (2009). Correlations for estimation of daily global solar radiation with hours of bright sunshine in Turkey. *Energy,* 34: 485–501.

Bakirci, K. (2012). General models for optimum tilt angles of solar panels: Turkey case study. *Renewable and Sustainable Energy Reviews,* 16: 6149–6159.

Cooper, P. I. (1969). The absorption of solar radiation in solar stills. *Solar Energy,* 12: 313–331.

Despotovic, M. and Nedic, V. (2015). Comparison of optimum tilt angles of solar collectors determined at yearly , seasonal and monthly levels. *Energy Conversion and Management*, 97: 121–131.

Diken, B. and Kayişoğlu, B. (2022). Feasibility study of photovoltaic system that can be applied to Tekirdag Namik Kemal University Ziraatbiyotek Building using RetScreen Program. *Journal of Tekirdag Agricultural Faculty*, 19(3): 656-667.

Duffie, J. A. and Beckman, W.A. (1991). Solar Engineering of Thermal Processes, 2nd ed., Wiley, New York, USA, 1991.

Erbs, D. G., Klein, S. A. and Duffie, J. A. (1982). Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy,* 28: 293–302.

Ertekin, C. and Yaldiz, O. (1999). Estimation of monthly average daily global radiation on horizontal surface for Antalya (Turkey). *Renewable Energy,* 17: 95–102.

Gong, X. and Kulkarni, M. (2005). Design optimization of a large scale rooftop photovoltaic system. *Solar Energy,* 78: 362–374.

Jamil, B., Siddiqui, A. T. and Akhtar, N. (2016). Estimation of solar radiation and optimum tilt angles for south-facing surfaces in Humid Subtropical Climatic Region of India. *Engineering Science Technology, an International Journal,* 19: 1826–1835.

Kacira, M., Simsek, M. and Babur, Y. (2004). Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey. *Renewable Energy,* 29: 1265–1275.

Liu, B. Y. H. and Jordan, R. C. (1960). The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar Energy,* 4: 1–19.

Liu, B. Y. H. and Jordan, R. C. (1963). The Long-Term Average Performance of Flat-Plate Solar Energy Collectors: With Design Data for the U.S.. *Solar Energy*, 7 (1963): 53–74.

Mehleri, E. D., Zervas, P. L., Sarimveis, H., Palyvos, J. A. and Markatos, N. C. (2010). Determination of the optimal tilt angle and orientation for solar photovoltaic arrays. *Renewable Energy,* 35: 2468–2475.

Mousazadeh, H., Keyhani, A., Javadi, A., Mobli, H., Abrinia, K. and Sharifi, A. (2009). A review of principle and sun-tracking methods for maximizing solar systems output. *Renewable and Sustainable Energy Reviews,* 13: 1800–1818.

Muzathik, A. M., Ibrahim, M. Z0., Samo, K. B. and Wan Nik, W. B. (2011). Estimation of global solar irradiation on horizontal and inclined surfaces based on the horizontal measurements. *Energy,* 36: 812–818.

Psiloglou, H. D. and Kambezidis, B. E. (2007). Performance of the meteorological radiation model during the solar eclipse of 29 March 2006. *Atmospheric Chemistry and Physics,* 7: 6047–6059.

Tang, R. and Wu, T. (2004). Optimal tilt-angles for solar collectors used in China. *Applied Energy,* 79: 239–248.

Tomson, T. (2008). Discrete two-positional tracking of solar collectors. *Renewable Energy,* 33: 400–405.

Türk Togrul, I. and Onat, E. (1999). Study for estimating solar radiation in Elazig using geographical and meteorological data. *Energy Conversion and Management,* 40: 1577–1584.

Vieira, R. G., Guerra, F. K. O. M. V., Vale, M. R. B. G. and Araújo, M. M. (2016). Comparative performance analysis between static solar panels and single-axis tracking system on a hot climate region near to the equator. *Renewable and Sustainable Energy Reviews,* 64: 672–681.

Yakup, M. H. M. and Malik, A. Q. (2001). Optimum tilt angle and orientation for solar collector in Brunei Darussalam. *Renewable Energy*, 24 (2001): 223–234.

Yan, R., Kumar, T., Meredith, P. and Goodwin, S. (2013). Analysis of yearlong performance of differently tilted photovoltaic systems in Brisbane, Australia. *Energy Conversion and Management,* 74: 102–108.

Yorukoglu, M. and Celik, A. N. (2006). A critical review on the estimation of daily global solar radiation from sunshine duration. *Energy Conversion and Management*, 47: 2441–2450.