Gümüşhane University Journal of Science

GUFBD / *GUJS* (2025) 15(1): 93-104 doi: 10.17714/gumusfenbil.1509643 Research Article

Determination of optimum tilt angle for solar panels: case study for Eastern Anatolia Region of Turkey

Güneş panelleri için optimum eğim açısının belirlenmesi: Türkiye'nin Doğu Anadolu Bölgesi örneği

Rahim Aytug OZER*[1], Merve DEMIRCI[2]

[1]*Erzurum Technical University, Faculty of Engineering and Architecture, Department of Aerospace Engineering, 25050, Erzurum*
[2]*Kafkas University, Faculty of Engineering and Architecture, Department of Electrical and Electronics Engineering, 36100, Kars*

• Received: 03.07.2024 • Accepted: 17.01.2025

Abstract
The increase in energy demand has led to an increase in the tendency towards alternative sources to fossil fuels. Solar energy stands out as an alternative energy source. This study was conducted to increase the energy production efficiency in solar energy system investments to be made in the Eastern Anatolia region. For this purpose, Erzurum, Kars, Iğdır, Ağrı and Muş provinces were taken into consideration. The effects of monthly, seasonal, six month and annual changes in panel tilt angle on panel performance were investigated. When determining the monthly optimum tilt angle, PVGIS and HW methods were first used. For other cases, the PVGIS method was used. As a result of the calculations, it was seen that the maximum angle difference between the PVGIS method and the HW method was seen in the summer months and its maximum value was 13.45° in June in Ağrı province. The minimum angle difference was calculated as 0.01° for September in Kars province. In addition, compared to the tilt angle being 0°, an increase of 17.16%, 16.32%, 16.03% and 12.26% in energy production was achieved when the optimum tilt angle was changed monthly, seasonally, six month and annually, respectively. As a result of this study, it was determined that maximum energy production was achieved by changing the panel angle monthly, and it was concluded that the most efficient angle change period in solar panel installation is monthly.

Keywords: Energy production, PV system, Renewable Enegy, Solar irradiation, Tilt angle

Öz
Enerji talebindeki artış beraberinde fosil yakıtlara alternatif olabilecek kaynaklara yönelimin artmasına neden olmuştur. Güneş enerjisi, alternatif enerji kaynağı olarak ön plana çıkmaktadır. Bu çalışmada, Doğu Anadolu bölgesinde yapılacak güneş enerjisi sistem yatırımlarında enerji üretim verimini artırmak amacıyla yapılmıştır. Bu amaçla Erzurum, Kars, Iğdır, Ağrı ve Muş illeri değerlendirmeye alınmıştır. Panel tilt açısının aylık, mevsimlik, altı aylık ve yıllık değişimlerinin panel performansı üzerindeki etkisi araştırılmıştır. Aylık optimum tilt açısını belirlerken ilk olarak PVGIS ve HW metodu kullanılmıştır. Diğer durumlar için ise PVGIS metodu kullanılmıştır. Hesaplamalar sonucunda, PVGIS metodu ile HW metodu arasındaki maksimum açı farkının yaz aylarında görüldüğü ve maksimum değerini Haziran ayında 13.45° olarak Ağrı ilinde aldığı görülmüştür. Minimum açı farkı ise, Kars ilinde 0.01° olarak Eylül ayı için hesaplanmıştır. Ayrıca, eğim açısının 0° olması durumuna göre, optimum tilt açısının aylık, mevsimlik, altı aylık ve yıllık değiştirilmesi durumlarında enerji üretiminde sırasıyla 17.16%, 16.32%, 16.03% ve 12.26% artış elde edilmiştir. Bu çalışma sonucunda, panel açısının aylık olarak değiştirilmesi ile maksimum enerji üretimi sağlandığı belirlenmiş, güneş paneli kurulumunda en verimli açı değişim periyodunun aylık olduğu sonucuna ulaşılmıştır.

Anahtar kelimeler: *Eğim açısı, Enerji üretimi, Güneş ışınımı, PV system, Yenilenebilir enerji*

*Rahim Aytug OZER, aytugozerr@gmail.com

1. Introduction

The increase in world population and technological advancements are leading to a gradual rise in energy consumption. In response to the increasing energy need, the limited availability of fossil energy resources on a global scale has increased the tendency towards renewable energy resources (Öztürk et al., 2023; Karagözoğlu & Duranay, 2023). In addition, the human and environmental friendliness of renewable energy sources compared to fossil-based energy sources provides versatile benefits in meeting energy needs and designing a healthy and clean environment. In this respect, renewable energy sources are an effective and efficient solution to achieve sustainable development.

In Solar photovoltaic (PV) systems, the energy source is solar irradiation. The amount of electrical energy produced on the surface of a PV system varies directly with the amount of solar irradiation. Therefore, the most important factors affecting the efficiency of PV systems are tilt angle and orientation. Due to the movement of the earth within the solar system, the sun's rays hit the earth at a constantly changing angle. Therefore, it is very important to determine the optimum tilt angle of PV panels with the horizontal in order to obtain maximum benefit from solar irradiation (Bakirci, 2012). For this reason, it is necessary to determine the monthly average amount of solar irradiation falling on the panel in different orientations.

In the literature, monthly averages of daily solar irradiation falling on horizontal and inclined surfaces are available for some locations. In the study by Attia et al. (2024), an experimental investigation was conducted on an energy plant consisting of two PV panels in Baghdad province, examining different tilt angles for the months of June, July, August, and November. According to the results obtained, they stated that system efficiency can be increased by 10% to 12% by changing the panel tilt angle. Lu and Qin (2024) conducted a tilt angle optimization study to obtain the maximum hourly solar irradiation gain for PV systems to be installed in China. Tilt angle values were determined to reach maximum total solar irradiation in different periods by applying long-term ERA5 hourly surface solar irradiation data and optimization procedure. They emphasized that at the optimized tilt angle, there will be an increase of 1.11 TWh/year in China's PV energy production in 2018.

Al-Sayyab et al. (2019) numerically and experimentally investigated the effect of the optimum tilt angle on the power produced from the PV panel for the city of Basra in Iraq. The optimum tilt angle was determined as 28^o, with the inclination angle varying between 0^o and 90^o. In another study, Jacobson and Jadhav (2018) conducted a comprehensive study in which they estimated the optimum tilt angle in all countries around the world with the help of the program they developed at the National Renewable Energy Laboratory. As a result of the study, they derived the optimum tilt angle as a function of the latitude angle.

According to the data prepared by the Ministry of Energy and Natural Resources of the Republic of Turkey (Enerji ve Tabi Kaynaklar Bakalnlığı, 2024), it is possible to say that the Solar Energy potential of our country is quite high, especially in the central and Anatolian regions. In order to evaluate this energy potential accurately and effectively, various studies have been carried out investigating the optimum tilt angle of PV panels. In the study conducted by Dal (2021) in Kayseri province in 2021, the optimum tilt angle was determined using the Photovoltaic Geographic Information System (PVGIS) and the Hottel & Woertz (HW) method and compared the prediction ability of both approaches. According to the results of the research, it is emphasized that by changing the tilt angle of the PV panel monthly, seasonally and six month, an increase in efficiency of approximately 2.99% to 4.11% can be achieved compared to positioning it with an annual tilt angle of 29.5^o. In another study conducted by Bakirci (2012), a correlation was derived to estimate the optimum tilt angle across Turkey with calculations made specifically for eight major cities in Turkey. In the study conducted by Çağlar (2018) the optimum tilt angle for Istanbul, Ankara, Erzurum and Adana provinces was calculated and compared theoretically and with the Hottel & Woertz (HW) method. It was stated that the average difference between the tilt angles calculated by two methods during the year for all cities participating in the calculation was 12.64%. Koçer et al. (2016) is emphasized that the efficiency of PV panel usage can be increased by changing the tilt angle at least twice a year or once a month for Ankara province and its districts. In the optimization study conducted for Şanlıurfa province, Yıldırım and Aktacir (2018) concluded that power efficiency can be increased by 11.5% if PV panels are placed at the optimum tilt angle compared to horizontal placement.

As can be seen from the literature summary, the determination of the optimum tilt angle involves either adaptation to the whole of Turkey based on regional (several different provinces) calculations or evaluations made on a city basis. Eastern Anatolia region, whose solar energy potential is above Türkiye's average, is one of the priority regions. However, while there are various studies in the literature for the central and southeastern regions of Turkey, there is no comprehensive study specifically for the Eastern Anatolia region. Within the scope of this study, the optimum panel tilt angle for Erzurum, Iğdır, Kars, Muş and Ardahan provinces in the Eastern Anatolia region was determined by calculating with PVGIS and Hottel & Woertz (HW) method. Thus, it is aimed to provide a comprehensive data set to the literature that will guide the design and optimization during the solar power plant installation phase. For this purpose, it can be used as a guiding guide in the aim of utilizing solar energy processes more effectively and efficiently.

2. Material and method

2.1. Selection of province

According to the data presented by the Ministry of Energy and Natural Resources, Turkey's average annual total radiation value is calculated as 1527.46 kWh/m^2 (Enerji ve Tabii Kaynaklar Bakanlığı, 2024). Monthly average global radiation distribution is given on a provincial basis in the Turkey Solar Energy Atlas (GEPA) and is presented in Figure 6. According to the GEPA map, many cities in Turkey's central Anatolia, eastern and southeastern Anatolia regions receive radiation above the average annual total radiation value. In addition, as of June 2022, installed power based on solar energy constitutes 8.35% of the total installed power (Enerji ve Tabii Kaynaklar Bakanlığı, 2024). Therefore, the expansion of solar power plant investments in cities in these regions will make a significant contribution to national development by allowing a rapid increase in the share of installed power based on solar energy.

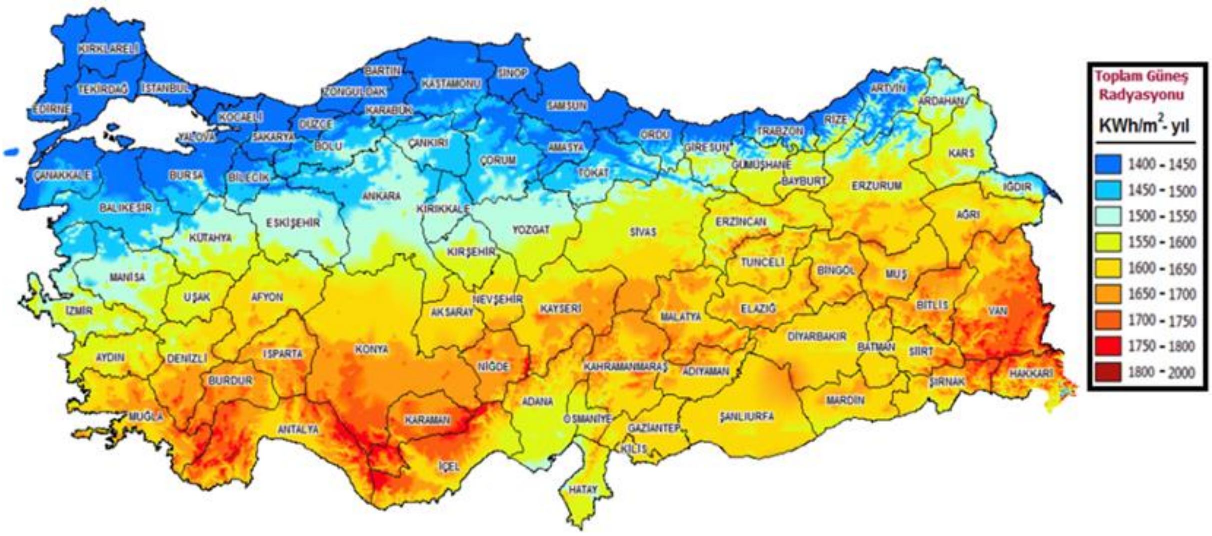

Figure 1. Average global irradiation distribution of Turkey (Enerji ve Tabii Kaynaklar Bakanlığı, 2024).

The cities included in the study were selected from regions with high energy potential, as the annual average total irradiation value is above the Turkish average. In this context, the cities of Erzurum, Iğdır, Ağrı, Kars and Muş are cities with high potential for solar energy investments and were deemed appropriate to be evaluated within the scope of this study.

2.2. Calculation metodology

PVGIS method is a simulation program developed by the European Commission using satellite interactive meteorological data. With this program, which is available to users free of charge, optimum solar radiation values can be simulated in daily, monthly and annual periods, depending on geographical location and panel angle (EU, 2024).

In the PVGIS module, Power P [W] is calculated by equation 1 as a function of solar irradiance and panel temperature (EU, 2024; Huld et al., 2011). Here, G_T', represents the normalized total solar irradiation value,

k_{1-6} represents the constants measured and determined by the European Solar Testing Installation (ESTI) dependhing on the PV panel type, and T' represents the panel temperature in degrees Celsius.

$$P(G'_T, T') = G'_T(P_{SCT}, m + k_1 \ln(G'_T) + k_2 \ln(G'_T)^2 + k_3T' + k_4T'(\ln(G'_T) + k_5T' \ln(G'_T)^2 + k_6T'^2) \quad (1)$$

The normalized total solar irradiation value is calculated with the help of equation 2. In this equation, G_T represents the total irradiation value reaching the inclined surface and G_{SCT}represents the maximum irradiation value in standard test conditions, and $G_{SCT} = 1000$ [W/m^2]. In the PVGIS interface, panel temperature (T'), is calculated by the difference between the module temperature T_{mod} and the panel temperature $T_{SCT} = 25$ [^{o}C] under SCT conditions (equation 3).

$$G'_T \equiv G_T/G_{SCT} \quad (2)$$

$$T' \equiv T_{mod}/T_{SCT} \quad (3)$$

Depending on the normalized total solar irradiation value G'_T and the panel temperature T', the panel efficiency η_{rel} is calculated with the help of Equation 4. In this equation, $P_{STC,m}$ is the equivalent of the maximum power value in Watts under standard test conditions (STC) (EU, 2024; Huld et al., 2011).

$$\eta_{rel}(G'_T, T') \equiv P(G'_T, T')/P_{SCT}, mG'_T \quad (4)$$

When calculating monthly energy production in the PVGIS simulation program, parameters such as PV technology, installed peak PV power, tilt angle (β_s [°]), azimut açısı (γ_s [°]) and system loss are taken as variable parameters.

In this study, for the locations of Erzurum (39.904', 41.262'), Iğdır (39.9518', 43.3836'), Ağrı (39.5292', 43.3836'), Kars (40.312', 43.249') and Muş (39.5999', 41.3503'), It was made with the assumption that the system loss is 14%, the installed peak power is 1kW, the azimuth angle (γ_s=0°) is zero and the system uses Crystalline Silicon PV type panel. For each location, the tilt angle was changed by 1^o and the total energy production and total irradiation values corresponding to the optimum tilt angle in the 0-90 tilt range were calculated.

With this method, when determining the optimum tilt angle, the angle at which global solar irradiation is maximum is taken as basis. Figure 2 shows the monthly tilt angle-solar irradiation (H) graph of Erzurum province. It can be seen in the monthly curves in Figure 2 that solar irradiation increases up to a certain angle value and then decreases. The solar irradiation value for December reached its maximum level of 74.9kWh/m^2 at 61° and 62°. Since the maximum value occurs at two angle values, the optimum tilt angle (OTA) was determined by taking the average of these two angle values.

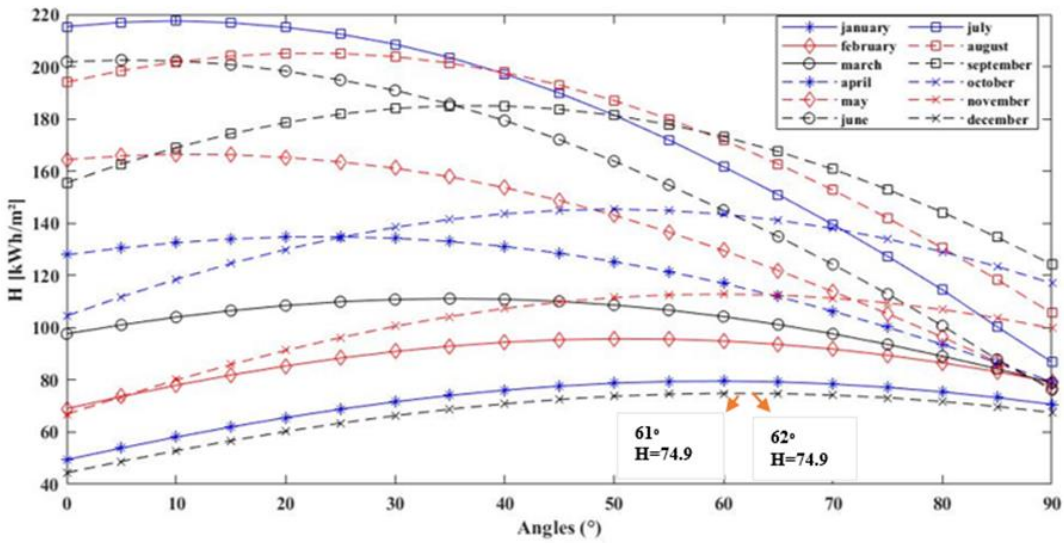

Figure 2. Tilt angle versus Global solar irradiation variation for Erzurum.

The HW method is widely used to determine the tilt angle when installing a solar power plant, as it is practical (Dal, 2021). In this method, the panel tilt angle (β) is calculated by taking the difference of the location latitude (φ [^{o}]) where the panel will be placed and the declination angle (δ [^{o}]) (equation 5). This method is used for ideal conditions assuming a cloudless sky with no obstacles or reflectors in the environment (Stanciu & Stanciu, 2014).

$$\beta = \varphi - \delta \qquad (5)$$

Declination angle is defined as the angle that the sun rays make with the equator plane during the rotation of the earth around itself and the sun, and is calculated with the help of equation 6 (Cooper, 1969).

$$\delta = 23.45 sin\left(360\,\frac{284+n}{365}\right) \qquad (6)$$

Here, n represents the number of days to be calculated and indicates the day of the calculation from the beginning of the year. For each city evaluated within the scope of the study, monthly, seasonal, six month and annual optimum slope angles were calculated and the methods were compared. In addition, in the PVGIS method, energy production and global solar irradiation values were compared for monthly, seasonal, six month and annual situations with the tilt angle being 0°.

3. Results and discussion

The changes in monthly optimum tilt angles for the cities of the Eastern Anatolia region, Erzurum, Iğdır, Ağrı, Kars and Muş, which were evaluated within the scope of the study, are presented in Figure 2. As can be seen, in all cities, the difference between the optimum tilt angle values obtained by the HW method and the PVGIS method started to increase in March, reached its maximum value in June, and then started to decrease as of September. The maximum tilt angle difference between the methods was calculated as 11.16° in May for Erzurum, and 9.88°, 11.45°, 9.24° and 8.53° in June for Iğdır, Ağrı, Kars and Muş, respectively. The minimum tilt angle difference between the methods was calculated as 0.57° in September for Erzurum, 0.44° in October for Iğdır, 1.2° in September for Ağrı, 0.01° in September for Kars and 0.56° in November for Muş.

In the HW method, considering that the environmental conditions are ideal and the tilt angle is calculated simply and quickly, the results obtained are less sensitive and are mostly used in preliminary analysis. In the HW method, the monthly optimum tilt angle is determined based only on latitude and declination angle, while in the PVGIS method, the solar irradiation value is calculated according to the total irradiation value coming to the inclined surface, the maximum irradiation value under standard test conditions, panel tilt angle and panel temperature. Maximum energy production (E_{max}) was determined for all angle values between 0°-90°, depending on the solar irradiation (H) and the calculated solar irradiation value. In Table 1, OTA values of the HW and PVGIS method and E_{max} and H values at the optimum tilt angle obtained from the PVGIS method are given for 5 cities. The difference between the OTA values obtained with the HW method and PVGIS is low in winter months, but high in summer months. This is due to the fact that environmental conditions such as solar radiation and air temperature are taken into account in the PVGIS method, while the analyses are performed under ideal conditions in the HW method. In addition, the PVGIS method allows the calculation of the maximum energy that can be produced from the panel with the instantaneous solar radiation data of the region being analyzed for the optimum tilt angle. Therefore, the optimum tilt angle for energy production corresponding to the same day of the year in the calculation made in the PVGIS method differs from the HW method. A similar situation is seen in the study conducted by Dal (2021) for the province of Kayseri.

After determining the monthly optimum tilt angle, seasonal optimum tilt angles were determined for 5 cities with the PVGIS method. Table 2 presents the optimum tilt angles, solar irradiation and maximum energy production values for 5 provinces. Seasonal optimum tilt angles for 5 cities vary between 51°-57° in winter, 21°-22° in spring, 10°-13° in summer and 43°-47° in autumn. The optimum tilt angles obtained decrease to a minimum in summer and reach maximum values in winter. Accordingly, maximum energy production reaches maximum values in summer and is at minimum values in winter.

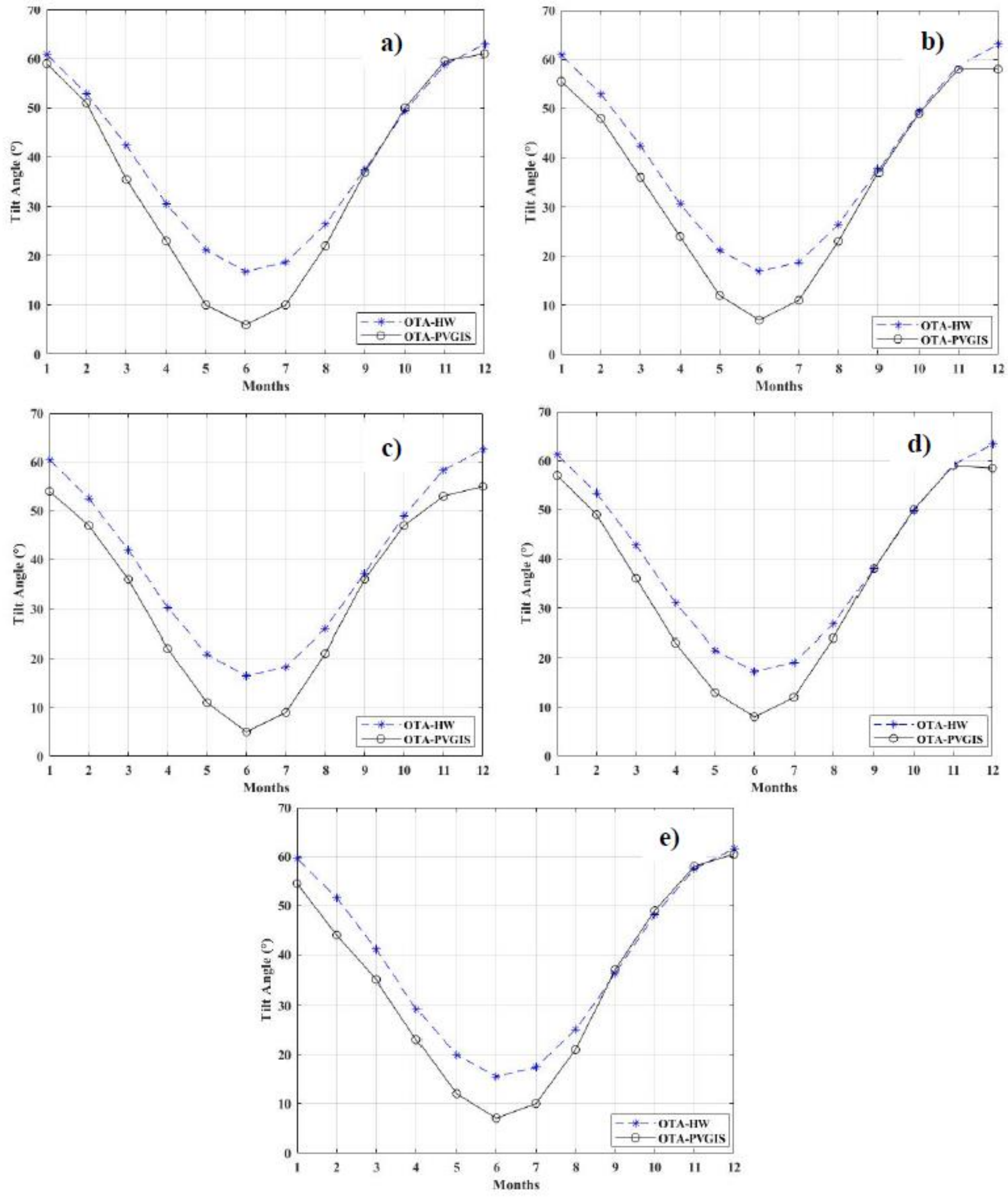

Figure 2. Monthly optimum tilt angle variaties for PVGIS and HW methods; (a) Erzurum, (b) Iğdır, (c) Ağrı, (d) Kars, (e) Muş.

Table 1. Montly optimum tilt angle for PVGIS and HW methods, maximum energy production and global solar irradiation.

		Erzurum	Iğdır	Ağrı	Kars	Muş
January	HW-OTA (°)	60.85	60.89	60.47	61.26	59.55
	PVGIS-OTA (°)	59	55.5	54	57	54.5
	E_{max} (kWh)	70.48	60.05	59.42	65.66	55.81
	H (kWh/m^2)	79.56	69.04	67.5	74.37	64.42
February	HW-OTA (°)	52.92	52.96	52.54	53.32	51.61
	PVGIS-OTA (°)	51	48	47	49	44
	E_{max} (kWh)	83.69	69.44	71.57	75.31	58.99
	H (kWh/m^2)	95.82	81.49	82.49	87.32	69.57
March	HW-OTA (°)	42.39	42.44	42.02	42.80	41.09
	PVGIS-OTA (°)	35.5	36	36	36	35
	E_{max} (kWh)	93.47	91.89	97.03	98.26	90.4
	H (kWh/m^2)	111.16	110.38	113.09	117.78	109.53
April	HW-OTA (°)	30.56	30.61	30.19	30.97	29.26
	PVGIS-OTA (°)	23	24	22	23	23
	E_{max} (kWh)	109.97	110.98	105.38	109.53	113.75
	H (kWh/m^2)	134.89	138.2	127.85	137.04	142.62
May	HW-OTA (°)	21.16	21.21	20.79	21.57	19.86
	PVGIS-OTA (°)	10	12	11	13	12
	E_{max} (kWh)	131.28	135.47	133.66	137.96	147.2
	H (kWh/m^2)	166.45	171.88	165.12	176.25	189.19
June	HW-OTA (°)	16.83	16.88	16.46	17.24	15.53
	PVGIS-OTA (°)	6	7	5	8	7
	E_{max} (kWh)	152.51	154.74	151.99	160.92	176.95
	H (kWh/m^2)	202.57	202.87	195.29	212.36	237.19
July	HW-OTA (°)	18.68	18.73	18.30	19.09	17.37
	PVGIS-OTA (°)	10	11	9	12	10
	E_{max} (kWh)	161.59	162.54	156.74	167.42	183.68
	H (kWh/m^2)	217.52	214.19	204.44	222.41	251.7
August	HW-OTA (°)	26.36	26.41	25.99	26.77	25.06
	PVGIS-OTA (°)	22	23	21	24	21
	E_{max} (kWh)	153.85	156.56	145.69	161.92	175.36
	H (kWh/m^2)	205.28	204.35	188.44	212.28	235.77
September	HW-OTA (°)	37.57	37.62	37.20	37.98	36.27
	PVGIS-OTA (°)	37	37	36	38	37
	E_{max} (kWh)	141.84	142.7	136.26	145.69	156.8
	H (kWh/m^2)	185.14	183.99	172.81	187.6	204.93
October	HW-OTA (°)	49.39	49.44	49.02	49.80	48.09
	PVGIS-OTA (°)	50	49	47	50	49
	E_{max} (kWh)	115.97	115.13	103.57	117.19	124.65
	H (kWh/m^2)	145.37	143.87	127.41	146.13	157.34
November	HW-OTA (°)	58.74	58.79	58.37	59.15	57.44
	PVGIS-OTA (°)	59.5	58	53	59	58
	E_{max} (kWh)	94.26	86.68	69.62	89.4	101.95
	H (kWh/m^2)	112.9	104.24	82.69	106.72	123.2
December	HW-OTA (°)	62.93	62.98	62.55	63.34	61.63
	PVGIS-OTA (°)	61.5	58	55	58.5	60.5
	E_{max} (kWh)	64.78	55.25	50.97	55.83	70.68
	H (kWh/m^2)	74.9	65.37	60.09	65.8	83.79

Table 2. Seasonal optimal tilt angle, maksimum energy production and global solar irradiation values for 5 provinces.

	Winter			Spring			Summer			Autumn		
	OTA	**E_{max}**	**H**	**OTA**	**E_{max}**	**H**	**OTA**	**E_{max}**	**H**	**OTA**	**E_{max}**	**H**
Erzurum	57	218.46	249.68	22	331.37	408.67	11	465.54	621.87	47	348.46	438.75
Iğdır	54	184.32	215.39	22	335.04	416.59	12	471.61	618.39	46	341.64	428.3
Ağrı	51	181.76	209.77	21	332.39	401.8	10	452.37	585.35	43	307.69	380.59
Kars	54	196.41	226.97	22	342.52	427.29	13	487.91	643.78	47	349.18	436.44
Muş	54	184.45	216.53	21	348.08	437.49	11	533.74	721.22	46	379.67	480.49

For the 5 selected cities, the optimum tilt angle for six-month periods was obtained with the PVGIS method. The optimum tilt angle, maximum energy production and maximum global solar irradiation values of these cities are presented in Table 3. The optimum tilt angle for the autumn-winter period varies between 46°-51°, while in the spring-summer period it is between 15°-16°. While the maximum global solar irradiation value of 695.9 kWh/m^2 was observed in Muş during the Autumn-Winter period, the minimum irradiation value was observed in Ağrı with 589.31 kWh/m^2. The maximum energy production was obtained in Erzurum with 565.57 kWh in the Autumn-Winter period, and the minimum energy production was obtained in Ağrı with 488.71 kWh. While the optimum tilt angle decreased in the Spring-Summer period, the global solar irradiation value increased for all cities and, accordingly, the maximum energy production increased. In the spring-summer period, the maximum solar irradiation value was obtained in Muş with 1156 kWh/m^2, and the minimum irradiation value was obtained in Ağrı with 984.75 kWh/m^2. The maximum energy production was observed in Muş with 879.84 kWh in the spring-summer period, and the minimum energy production was observed in Ağrı with 782.28 kWh.

Table 3. Optimal tilt angle, maksimum energy production and global solar irradiation values for six month periods

	Autumn-Winter			Spring-Summer		
	OTA (°)	**E_{max} (kWh)**	**H (kWh/m^2)**	**OTA (°)**	**E_{max} (kWh)**	**H (kWh/m^2)**
Erzurum	51	565.57	686.6	15	794.82	1028.52
Iğdır	49	525.31	642.75	16	804.73	1033.05
Ağrı	46	488.71	589.31	15	782.28	984.75
Kars	49	544.81	662.37	16	828.66	1069.19
Muş	49	563.37	695.9	15	879.84	1156.92

In Table 4, annual optimum tilt angle, global solar irradiation and maximum energy production values of 5 cities obtained with PVGIS are presented. The optimum slope angle for the 5 selected provinces varies between 28°-32° annually. The annual maximum global solar irradiation was observed in Muş with 1798.67 kWh/m^2 at an inclination angle of 29°. The minimum solar irradiation was observed in Ağrı with 1536.48 kWh/m^2 at an inclination angle of 28°. While the maximum energy production was 1398.94 kWh in Muş, which has the maximum annual solar irradiation, the minimum annual energy production was observed as 1240.14 kWh in Ağrı, which has the minimum solar irradiation.

Table 4. Optimal tilt angle, maksimum energy production and global solar irradiation values for annual.

	Annual		
	OTA (°)	**E_{max} (kWh)**	**H (kWh/m^2)**
Erzurum	32	1316.24	1661.74
Iğdır	30	1293.94	1631.21
Ağrı	28	1240.14	1536.48
Kars	32	1334.95	1684.35
Muş	29	1398.94	1798.67

The monthly, seasonal, semi-annual and annual variation range of optimum tilt angle, total solar irradiation and total produced energy amounts for the 5 selected cities are presented in Table 5. Additionally, total global solar irradiation and total energy production data for the case when the tilt angle of the panel is 0° are included in Table 5. When Table 5 is examined, it is observed that the lowest solar irradiation for all cities occurs when the panel is placed parallel to the ground and does not have any slope, with the angle of inclination being 0°. Additionally, it has been observed that when the inclination angle is 0°, minimum energy production occurs compared to other situations. In the process of changing the panel angle periodically, it was observed that the total global solar irradiation value for the 5 selected cities was maximum when the tilt angle was changed monthly compared to other situations. Accordingly, it was observed that the total energy production was maximum.

Table 5. Total solar irradiation and total energy production of selected cities

		Tilt angle= 0°	Monthly	Seasonally	Six month	Annual
Erzurum	**Σ E_{max} (kWh)**	1172.45	1373.7	1363.83	1360.39	1316.24
	ΣH (kWh/m²)	1491.09	1731.52	1718.97	1715.12	1661.74
Iğdır	**Σ E_{max} (kWh)**	1168.25	1341.44	1332.61	1330.04	1293.94
	ΣH (kWh/m²)	1477.2	1689.84	1678.67	1675.8	1631.21
Ağrı	**Σ E_{max} (kWh)**	1139.91	1282.07	1274.21	1270.99	1240.14
	H (kWh/m²)	1415.26	1587.02	1577.51	1574.06	1536.48
Kars	**Σ E_{max} (kWh)**	1197.71	1385.08	1376.02	1373.47	1334.95
	H (kWh/m²)	1518.03	1746.06	1734.48	1731.56	1684.35
Muş	**Σ E_{max} (kWh)**	1268.86	1456.12	1445.94	1443.21	1398.94
	H (kWh/m²)	1635.02	1869.25	1855.73	1852.82	1798.67

When the solar panel is placed parallel to the surface and the tilt angle is 0°, compared to other situations (monthly, seasonal, six month and annual) where the tilt angle of the panel is changed, it is observed that total irradiation and total energy production increase in cases where the tilt angle is changed. In Figure 3, the increase in total solar irradiation obtained by changing the tilt angle in monthly, seasonal, six month and annual periods for the selected cities compared to the situation where the tilt angle is 0° is presented as a percentage. While the maximum increase of 17.16% was obtained in Erzurum when the monthly angle change was made, an increase of 14.82% was achieved in Iğdır, 12.47% in Ağrı, 15.64% in Kars and 14.76% in Muş.

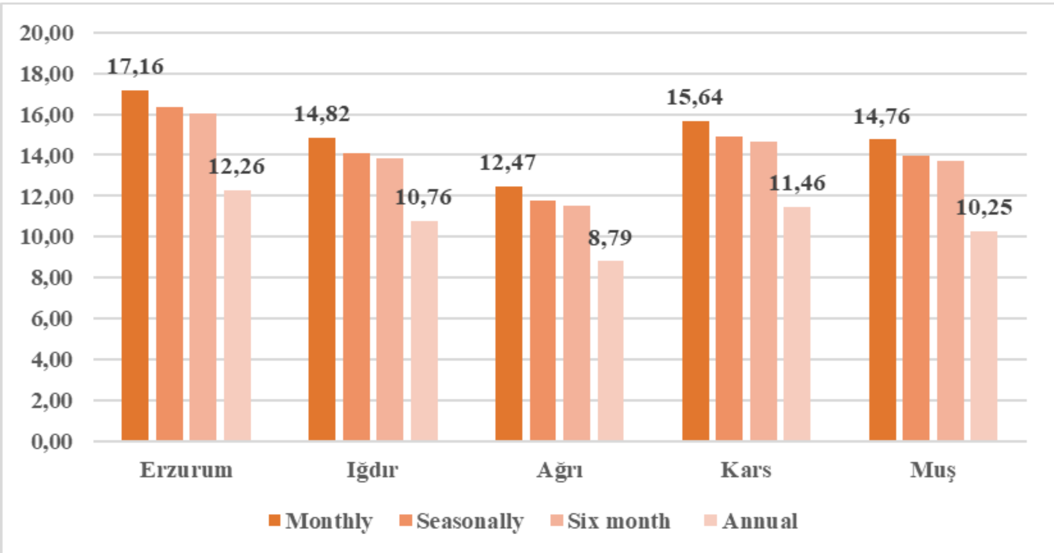

Figure 3. Percentage increase of global solar irradiation compared to tilt angle = 0° for selected cities

In Figure 4, the change in total energy production obtained by changing the tilt angle in monthly, seasonal, six month and annual periods for the selected cities compared to the situation where the tilt angle is 0° is presented as a percentage. While the maximum increase of 16.12% was obtained in Erzurum when the monthly angle change was made, an increase of 14.39% was obtained in Iğdır, 12.14% in Ağrı, 15.02% in Kars and 14.33% in Muş.

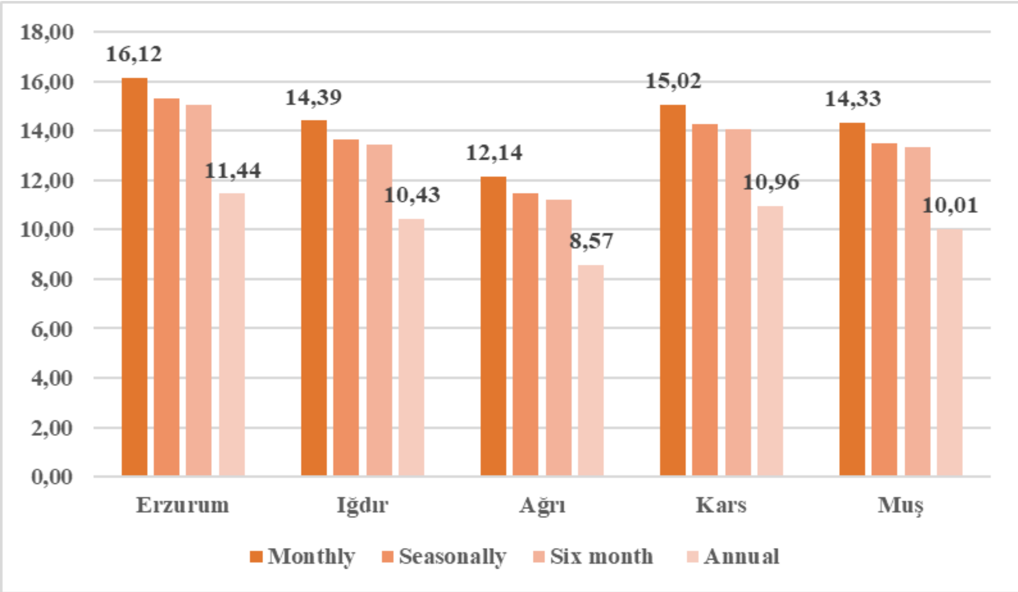

Figure 4. Percentage increase of energy production compared to tilt angle = 0° for selected cities

4. Conclusions

In this study, optimum tilt angle values were calculated to ensure maximum benefit from solar energy in 5 provinces selected from the Eastern Anatolia Region, whose solar energy potential is above the Turkey average. First, optimum tilt angles were compared using Hottel-Woertz and PVGIS methods for calculation. Then, if the optimum tilt angle was changed at monthly, seasonal, semi-annual and annual periods, the energy production efficiency was compared both with the tilt angle being 0° and changing it at the specified periods. The results obtained as a result of the study are listed below.

The monthly optimum tilt angle was determined by the HW method and the PVGIS method, and it was observed in the results obtained that the difference between the two methods increased in the summer months and decreased in the winter months. The fact that the HW method calculates only according to the declination angle and latitude shows that it is appropriate to use it in case of preliminary work for panel installation, as this method accepts the environmental conditions as ideal (cloudless weather, absence of hills, absence of any reflectors, etc.). In the PVGIS method, higher accuracy results can be produced since solar irradiation and energy production can be calculated in detail according to different angle values of the selected location.

With the PVGIS method, when the optimum tilt angle was changed in monthly, seasonal, six month and annual periods, the maximum global solar irradiation and maximum energy production were obtained when the angle was changed in monthly periods. When the tilt angle is determined annually, total energy production increased by 12.26% in Erzurum, 10.76% in Iğdır, 8.79% in Ağrı, 11.46% in Kars and 10.25% in Muş compared to the case when the tilt angle was 0°. In the case where the tilt angle is determined in six-month periods, total energy production increased by 16.03% in Erzurum, 13.85% in Iğdır, 11.50% in Ağrı, 14.67% in Kars and 13.74% in Muş, compared to the tilt angle 0°. In the case where the tilt angle is determined by seasonal periods, total energy production increased by 16.32% in Erzurum, 14.07% in Iğdır, 11.78% in Ağrı, 14.89% in Kars and 13.96% in Muş, compared to the case when the tilt angle was 0°. In the case where the tilt angle is determined in monthly periods, total energy production increased by 17.16% in Erzurum, 14.82% in Iğdır, 12.47% in Ağrı, 15.64% in Kars and 14.76% in Muş compared to the tilt angle 0° situation. The maximum increase was obtained when the tilt angle was changed monthly.

As a result of this study, it was determined that maximum energy production was achieved by changing the panel angle monthly, and it was concluded that the most efficient angle change period in solar panel installation is monthly. However, since performing this process will increase the labor cost, it is recommended to change the angle in seasonal or six month periods.

Acknowledgment

The authors sincerely thank the editor and anonymous reviewers for their contributions during the review and evaluation of the manuscript

Author contribution

Rahim Aytug Ozer and Merve Demirci contributed equally to the data collection, literature research, analysis and writing of the research.

Declaration of ethical code

The authors of this article declare that the materials and methods used in this study do not require ethical committee approval and/or legal-specific permission.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

Al-Sayyab, A. K. S., Al Tmari, Z. Y., & Taher, M. K. (2019). Theoretical and experimental investigation of photovoltaic cell performance, with optimum tilted angle: Basra city case study. *Case Studies in Thermal Engineering*, *14*, 100421. https://doi.org/10.1016/J.CSITE.2019.100421

Attia, O. H., Mousa, N. A., Mahmood, H. A., & Adam, N. M. (2024). Experimental evaluation the effect of tilt angle on solar panel performance in Baghdad. *In AIP Conference Proceedings*, *3002*(1). https://doi.org/10.1063/5.0205993

Bakirci, K. (2012). General models for optimum tilt angles of solar panels: Turkey case study. *Renewable and Sustainable Energy Reviews*, *16*(8), 6149-6159. https://doi.org/10.1016/J.RSER.2012.07.009

Cooper, P. I. (1969). The absorption of radiation in solar stills. *Solar energy*, *12*(3), 333-346. https://doi.org/10.1016/0038-092X(69)90047-4

Çağlar, A. (2018). Farklı derece-gün bölgelerindeki şehirler için optimum eğim açısının belirlenmesi. *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, *22*(2), 849-854. https://doi.org/10.19113/SDUFBED.94899

Dal, A. R. (2021). Güneş enerji panellerindeki optimum eğim açısının verime etkisinin incelenmesi. *Bilecik Şeyh Edebali Üniversitesi Fen Bilimleri Dergisi*, *8*(1), 241-250. https://doi.org/10.35193/BSEUFBD.878795

Enerji ve Tabi Kaynaklar Bakanlığı: Enerji ve Tabi Kaynaklar Bakanlığı. (2024, July 1) https://enerji.gov.tr/bilgi-merkezi-enerji-gunes

European Commission (EU): Photovoltaic Geographical Information System (PVGIS). (2024, June 20). https://joint-research-centre.ec.europa.eu/photovoltaic-geographical-information-system-pvgis_en

Huld, T., Friesen, G., Skoczek, A., Kenny, R. P., Sample, T., Field, M., & Dunlop, E. D. (2011). A power-rating model for crystalline silicon PV modules. *Solar Energy Materials and Solar Cells*, *95*(12), 3359-3369. https://doi.org/10.1016/J.SOLMAT.2011.07.026

Jacobson, M. Z., & Jadhav, V. (2018). World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. *Solar energy*, *169*, 55-66. https://doi.org/10.1016/J.SOLENER.2018.04.030

Karagözoğlu, L., & Duranay, Z. B. (2023). Yapay sinir ağları kullanılarak fotovoltaik sistemin maksimum güç noktası takibi. *Gümüşhane Üniversitesi Fen Bilimleri Dergisi*, *13*(3), 733-749. https://doi.org/10.17714/gumusfenbil.1217821

Koçer, A., Şevik, S., & Güngör, A. (2016). Ankara ve ilçeleri için güneş kolektörü optimum eğim açisinin belirlenmesi. *Uludağ Üniversitesi Mühendislik Fakültesi Dergisi*, *21*(1), 63-78. https://doi.org/10.17482/UUJFE.80088

Lu, N., & Qin, J. (2024). Optimization of tilt angle for PV in China with long-term hourly surface solar radiation. *Renewable Energy*, 120741. https://doi.org/10.1016/J.RENENE.2024.120741

Öztürk, Ö., Akyazı, Ö., & Çavdar, B. (2023). Fotovoltaik sistemlerde gri kurt optimizasyon (gko) algoritması ve artımlı iletkenlik (ai) yönteminin maksimumum güç noktası takibi (mgnt) için karşılaştırılması. *Gümüşhane Üniversitesi Fen Bilimleri Dergisi*, *13*(4), 962-978. https://doi.org/10.17714/gumusfenbil.1220816

Stanciu, C., & Stanciu, D. (2014). Optimum tilt angle for flat plate collectors all over the World–A declination dependence formula and comparisons of three solar radiation models. *Energy Conversion and Management*, *81*, 133-143. https://doi.org/10.1016/J.ENCONMAN.2014.02.016

Yıldırım, E., & Aktacir, M. A. (2018). Binaya entegre fotovoltaik sistemlerde azimut ve eğim açısı etkilerinin incelenmesi. *Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi*, *34*(2), 609-620. https://doi.org/10.17341/GAZIMMFD.416413