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Maximization of Solar Radiation for Fixed and Tracking Surfaces in Antalya Province of Türkiye

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Abstract: Solar energy has gained increasing importance in today's world and become a viable primary energy source in the recent decade. Solar radiation obtained by the solar surface is highly affected by its orientation, azimuth, and tilt angles. Therefore, in this study, the performances of the fixed-axis system, one-axis, and two-axis solar tracking systems are investigated to enable maximal solar radiation in solar systems to be installed in Antalya by using climatic and latitude data provided by NASA. Furthermore, the optimal tilt angles are determined by examining the values of angles for which the total solar radiation falling on the tilted surface is maximal. The case study and measurement data investigations are conducted for the four districts of Antalya. The obtained radiation values throughout the year for one-axis and two-axis solar tracking systems are compared to an annual fixed system for evaluating the existing solar potential in Antalya province. Besides all these, solar system cost analyses including the average payback period for residential, commercial, and large-scale solar systems based on LCOE are investigated. The proposed methodology can be implemented for performance and cost analysis of the solar potential in a certain location of Türkiye and extended to any place in the world.

Keywords: cost analysis; fixed; optimal tilt; radiation; solar energy; tracking

1 INTRODUCTION

Nowadays, researchers are more concentrating on solar systems to meet the increasing energy demands of countries. Each region has its unique position in terms of solar radiation. Solar radiation data has a crucial role in solar systems for optimal design and size to be installed solar system in the region. Total solar radiation values for the region to be installed solar systems are the most crucial metric for determining energy generation. The efficiency of the solar surface extremely depends on its orientation, material characteristics, climatic conditions, seasonal variations, and geographical location as well as period of usage. The optimal tilt angle is dependent on latitude, solar declination, and the time and days in the year [1-3]. For this reason, the tilt angles of solar surfaces should be adjusted monthly, seasonal, or annual to obtain maximal solar radiation from solar surfaces.

This paper aims to investigate each optimal tilt angle for monthly, seasonal, and annual and to maximize total radiation falling on a tilted solar surface for the districts of Antalya which is located in the southern part of Türkiye. The regional calculation of the optimal tilt angles using the proposed model, obtaining the total solar radiation of one-axis and two-axis solar tracking systems, and comparison to a fixed system is one of the objectives of this study. It is also aimed to evaluate the results by calculating the optimal tilt angles to maximize the efficiency of fixed and tracking solar systems based on four districts of Antalya.

The outline of this study is as follows: The first section presents the introduction and objectives of this study. In the second section, a literature review and related works are presented. Materials and procedures are described in the third section such as the case study region, used data, theoretical analysis, description of the algorithm, and calculation model. In the fourth section, solar system cost analysis for residential, commercial, and large-scale solar systems based on *LCOE* are investigated and the average payback period is determined. In the fifth section, calculations, results, and discussions are presented specifically by focusing on optimal tilt angle values, solar radiation gains, performance analysis, and comparison of fixed systems and tracking systems carried out. The conclusions of the study are presented in the last section where also suggestions for improving the efficiency of solar systems are noted. This research is limited to the geographical region of Antalya province in the Mediterranean region of Türkiye.

2 LITERATURE REVIEWS AND RELATED WORKS

In Türkiye, several studies in the literature have been carried out by the researchers for different purposes and regions about optimization of tilt angle, the orientation of solar surfaces, and calculation of solar radiation values. Most of the studies to determine the solar radiation potential of a certain location were focused on the determination of total radiation falling on a horizontal surface using measured data [4-7]. Several solar radiation calculation models are performed in the literature by using Artificial Neural Networks [8, 9] and Machine Learning [10, 11]. The studies were carried out optimization of tilt angles and maximization of solar radiation falling on the tilted surface for the different locations are contributed to Türkiye in this field [12-16]. Besides, there are different studies in the literature to provide maximal radiation with solar tracking systems and compare radiation values with fixed systems for Türkiye [17-21].

It is well-known in the literature that the tilt angle is an important parameter to obtain maximal radiation efficiency. In literature, there exist some studies which focused on the calculation of the total solar radiation components to find the optimal tilt angle. Additionally, although there are a few studies to determine the optimal tilt angle and to calculate the solar radiation methods for Antalya province [22-24], the number of district-based studies is negligible. Therefore, it is believed that this study will contribute to the case study of the region just in case an installation of large-scale solar systems in the region.

Several studies have been focused on the calculation of the Levelized Cost of Energy (*LCOE*) of solar systems. It was seen that the financial parameters have the biggest impact on the *LCOE*, apart from the location [25], and it was shown that both device and field lifetimes are critical for achieving a low *LCOE* for a solar power station [26]. The energy gain and *LCOE* resulting from fixed, single, and dual-axis solar trackers had been compared [27]. The impact of the installation parameters of fixed-tilt and single-axis systems on the energy yield, the *LCOE*, and the bifacial gain had been investigated [28]. In the current study, *LCOE*-based solar installation and solar energy costs have been investigated and evaluated for approximate cost analysis of solar systems to be installed in Antalya province.

3 MATERIALS AND METHODS

Optimal tilt angle determination models are based on using various optimization techniques to reach maximum radiation fall on a tilted solar surface. The used model in this study provides a more advanced approach that includes other factors such as atmospheric scattering, the impact of air pollution, climatic conditions, as well as direct sunlight.

3.1 Basics of Solar Energy and Numerical Analysis

The monthly average daily solar radiation values falling on horizontal surfaces are required to measure the monthly average daily solar radiation collected by the tilted surfaces in solar systems. A basic method is presented by Liu and Jordan [29] to estimate the monthly average daily radiation falling on tilted south-facing solar surfaces. The declination angle is measured from the sun north or south of the earth's equator. The tilt angle of the surface is the angle between the earth of the solar surface and the horizon. In relation to the earth's orbit around the sun, the axis of the earth is inclined at 23.45 degrees. Solar declination is affected by the time of year and can be obtained by using Eq. (1) [30, 31].

$$\delta = 23.45 \cdot \sin\left(2\pi \frac{284+n}{365}\right), \tag{1}$$

where δ is the declination and n is the day of the year.

Solar time is a method of determining the passage of time based on the sun's position in the sky. Sunset has occurred when the cosine of the zenith angle is 0, this is when the sun is at the horizon and is obtained by using Eq. (2) [31].

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

where ω is the solar time.

Extraterrestrial radiation is the solar radiation that exists outside of the earth's atmosphere. Daily extraterrestrial radiation on a horizontal surface is given by Eq. (3) [29].

$$H_0 = \frac{24}{\pi} \cdot G_{sc} \left[1 + 0.033 \cdot \cos\left(\frac{360 \cdot n}{365}\right)\right] \cdot \left(\cos\phi \cdot \cos\delta \cdot \sin\omega + \frac{\pi \cdot \omega}{180} \cdot \sin\phi \cdot \sin\delta\right), \tag{3}$$

where H_0 is the daily extraterrestrial radiation falling on a horizontal surface, G_{sc} is the solar constant 1367 W/m^2, and ϕ is the latitude of the location.

Global solar radiation is broken down into two components: beam radiation emanates from the sun to the earth's surface without any scattering by the atmosphere, and diffuse radiation emanates from the rest of the sky and does not cast a shadow. The sum of the beam and diffuse radiation is expressed by Eq. (4).

$$H = H_b + H_d, \tag{4}$$

where H is the global solar radiation, H_d and H_b are diffuse and beam radiation components of the average daily solar radiation.

Monthly average daily diffuse radiation is calculated using correlation formula given in Eq. (5) [32] which gives the diffuse fraction as a function of the clearness index.

$$\frac{H_d}{H} = 1.391 - 3.560 \cdot K_t + 4.189 \cdot K_t^2 - 2.137 \cdot K_t^3, \tag{5}$$

where K_t is the clearness index, which is basically the ratio of surface radiation to extraterrestrial radiation.

The isotropic model is preferred to obtain monthly average daily solar radiation falling on a tilted surface and is expressed by Eq. (6) [26, 31].

$$H_t = H_b R_b + H_d \cdot \left(\frac{1+\cos\beta}{2}\right) + H \cdot \rho \cdot \left(\frac{1-\cos\beta}{2}\right), \tag{6}$$

where H_t is the calculation of hourly radiation in the plane of the solar surface, H_d and H_b are diffuse and beam radiation components of the average daily solar radiation, R_b is the beam radiation tilt factor, and β is the tilt angle.

The beam radiation tilt factor is affected by atmospheric transmittance which includes water vapor, cloudiness, and particulate concentration. It is expressed with its component by Eqs. (7) and (8) [29].

$$R_b = \frac{\cos(\phi-\beta) \cdot \cos\delta \cdot \sin\omega' + \left(\frac{\pi}{180}\right) \cdot \omega' \cdot \sin(\phi-\beta) \cdot \sin\delta}{\cos\phi \cdot \cos\delta \cdot \sin\omega + \left(\frac{\pi}{180}\right) \cdot \omega \cdot \sin\phi \cdot \sin\delta}, \tag{7}$$

$$\omega' = \min \begin{cases} \omega = \cos^{-1}(-\tan\phi \cdot \tan\delta) \cdot \\ \cdot \cos^{-1}\left[-\tan(\phi-\beta) \cdot \tan\delta\right] \end{cases} \tag{8}$$

where "min" expresses the smaller of the two items on the right side.

3.2 Case Study Region

The case study region is Antalya province with the scope of this study. Knowledge of total solar radiation distribution is needed for the correct structure and size of solar systems. The annual average global solar radiation distribution (between 2004 and 2018) provided by the Turkish State Meteorological Service [33] for the region is shown in Fig. 1. As depicted in the figure, Antalya has a high solar radiation potential. Also, the geographical locations of Antalya districts are presented in Tab. 1, the districts of research interest in this study are established at altitudes very close to sea level except for Manavgat.

Table 1 Geographical location of Antalya districts

Districts	Latitude (°N)	Longitude (°N)	Elevation (°)
Alanya	36.6	32	86
Kaş	36.2	29.6	17
Manavgat	36.8	31.5	272
Muratpaşa	36.9	30.7	45

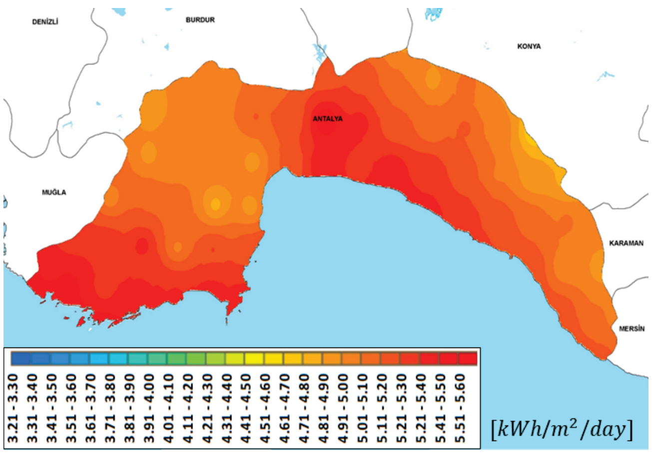

Figure 1 Annual average global solar radiation distribution of Antalya Province

3.3 Used Data and Proposed Calculation Model

Various estimation methods and simulation programs are used by researchers to determine the optimal tilt angle and obtain maximal benefit from solar radiation. In this way, it has become easier to make realistic analyses. RETScreen is a clean energy management and simulation software developed by the Minister of Natural Resources Canada that calculates using satellite and ground station interactive meteorological data provided by the National Aeronautics and Space Administration (NASA) [34]. It simulates the optimal hourly, daily, monthly, and annual solar radiation values in different options, depending on the desired geographical region and the clearness index [35]. So, within the scope of the study, the RETScreen model is preferred to compute the amount of radiation falling on the tilted surfaces and to find optimal angles of the tilted surfaces for fixed and solar tracking systems.

3.4 Description of the Calculation Algorithm

To measure radiation falling on a tilted solar surface, total radiation is initially measured falling on a horizontal surface, and collective data of the horizontal surface is used to calculate radiation falling on a tilted surface. Because the amount of radiation can be varied according to the region, the daily average values of solar radiation falling on a horizontal surface is the most important parameter to optimize the tilt angles of the solar surfaces.

The total solar radiation falling on a tilted surface is possible to calculate hourly and daily by using well-known equations [29, 31]. The RETScreen calculation model [36] is applied based on Duffie and Beckman's methods, and it is used an approach similar to the proposed algorithm by Klein and Theilacker [37]. On the other hand, the algorithm has been extended to solar tracking systems by using well-known solar geometry equations to investigate maximal solar radiation [38]. Solar geometry for fixed and tracking surfaces with oriented south are illustrated in Fig. 2. The fixed-axis solar surface, one-axis tracking solar surface, and two-axis tracking solar surface are illustrated in Fig. 2a, Fig. 2b, and Fig. 2c respectively.

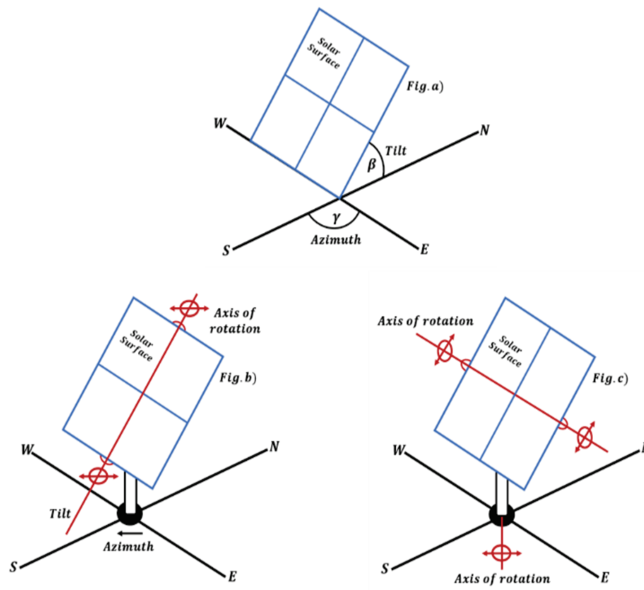

Figure 2 Solar geometry for fixed and tracking solar surfaces
a) Fixed-axis, b) One-axis tracking, c) Two-axis tracking.

The independent variables of the calculation algorithms are the latitude, longitude, and elevation of the analyzed geographic region. Total radiation values are obtained daily and hourly for fixed and tracking systems. The calculation is performed with one-hour step covering 365 days of the year. Calculations start with hourly total radiation falling on a horizontal surface. A mathematical method is then used to transpose these values onto a tilted surface. The optimal tilt angle is determined by looking for values at which the total radiation falling on the solar surface is maximum for a certain day or a certain period.

The calculation algorithm shown in Fig. 3 for the solar radiation collected by the tilted surfaces can be broken down into 3 simple phases. Phase 1 is the calculation of the hourly total radiation (beam and diffuse) falling on a horizontal surface for all hours of an "average day" as the monthly average. The concept of the suggested average days for months and declination values are presented in Tab. 2. Phase 2 is the calculation of the hourly values of total solar radiation falling on the fixed or tracking surfaces for all hours of the day. Phase 3 is the calculation of the hourly tilted values to find the average daily radiation falling on the surfaces.

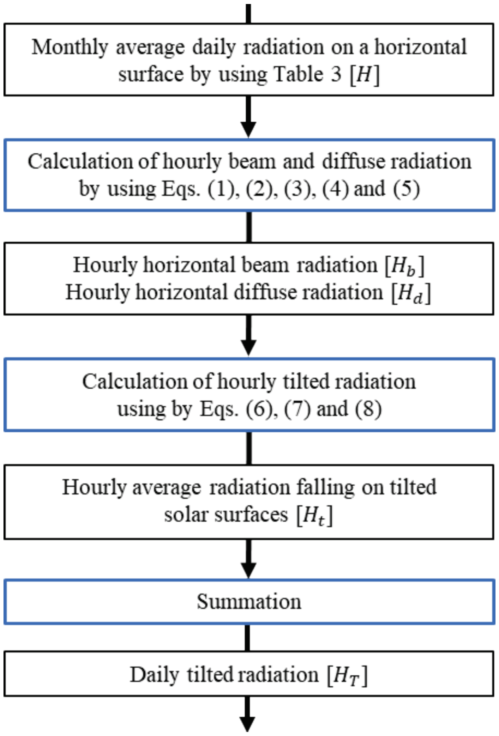

Figure 3 Flowchart of the calculation algorithm [kWh/m²]

Table 2 Suggested AVG days for months and values of n by months [24-26]

Month	Day of the Year	Date	Decl. δ
Jan	17	17 January	–20.9
Feb	47	16 February	–13.0
Mar	75	16 March	–2.4
Apr	105	15 April	9.4
May	135	15 May	18.8
Jun	162	11 June	23.1
Jul	198	17 July	21.2
Aug	228	16 August	13.5
Sep	258	15 September	2.2
Oct	288	15 October	–9.6
Nov	318	14 November	–18.9
Dec	334	10 December	–23.0

4 SOLAR SYSTEM COST ANALYSIS BASED ON LCOE

The cost of solar energy continues to decrease thanks to increased module efficiency as well as lowered hardware and inverter costs in recent years despite the impact of the global pandemic and the disruptions caused by the spread of the COVID-19 virus [39]. A significant portion of the cost declines over the past decade has been sourced from an 85% cost decline in solar module price [40]. *LCOE* [41] is a useful metric for detailed cost comparison, assessing economic potential including the payback period, and the most important criteria for the most large-scale solar systems. Solar engineers and investors aim to create solar systems to maximize financial returns by minimizing the *LCOE*.

4.1 Numerical Background of LCOE

The economic potential of solar systems is determined in this study via an *LCOE*, which describes how much it would cost to produce a unit of energy taking generalized assumptions about the costs of construction and operation of a typical solar system. It is expressed by Eq. (9) [42, 43].

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t \cdot F_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+d)^t}}, \tag{9}$$

where *LCOE* is the average lifetime levelized cost of electricity generation, I_t is investment expenditures in the year t, M_t is operations and maintenance expenditures in the year t, F_t is fuel expenditures in the year if any, E_t is energy generation in the year t, d is the discount rate, and n is the lifetime of the solar system in years.

4.2 Solar Energy Cost

LCOE is the product of all of the lifetime costs associated with the construction and operation of the solar system divided by the energy produced during this lifetime. The value is ranged globally from under $0.03/kWh to $0.12/kWh. The *LCOE* in Türkiye almost halved between 2016 and 2021, reaching to a value of $0.064/kWh [42]. For this reason, there is no doubt that the solar energy can be profitable in countries with high energy tariffs and high solar potential at the same time such as Türkiye.

4.3 Solar System Installation Cost

Multiple unique factors go into the cost of solar surfaces, and the cost varies depending on different regions of the world. According to Solar Energy Industries Association's (SEISA) average cost figures in 2021, utility-scale solar system installation costs are typically between $0.89 to $1.01/Wdc [44]. It is assumed that the land is already owned to build the solar system on. Based on the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) [45], on average, complete solar system costs are $2.65/Wdc for 7.2 kW residential, $1.56/Wdc for 200kW commercial, $1.03/Wdc for 10 MV fixed-tilt large-scale, and $1.13/Wdc for 10 MV one-axis-tracking large-scale. These values represent the *LCOE* which is the average revenue per unit of energy generated that would be required to recover the costs of the solar systems over their life expectancy. The average cost of a solar system for the last 5-years is presented in Fig. 4, and the solar system cost for a complete installation is shown in Tab. 3 provided by the NREL [45].

Compared to single-axis trackers, the initial cost of dual-axis trackers is higher, and both trackers require extra space to avoid shadowing effects from one solar surface to the next, thus, space may not be utilized as effectively as with fixed panels. Oftentimes, solar trackers also require more maintenance. So, most solar engineers recommend buying additional solar surfaces instead of installing trackers. On the other hand, seasonal variations significantly affect the total energy provided by the solar surface. For a 1 kWp PV system, the additional energy produced from the single-axis and double-axis tracking systems was found to be 33% and 37 %

higher in comparison to the static systems [46]. Also, one-axis tracking systems are the best option in all countries, reducing *LCOE* by more than 20% when compared to two-axis tracking systems [47].

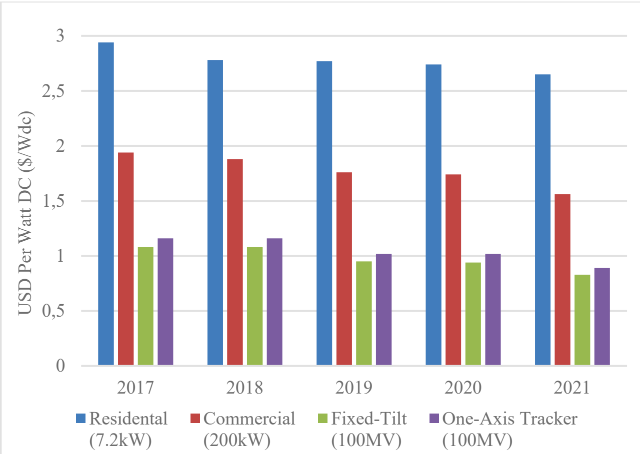

Figure 4 The average cost of a solar system for the last 5-years ($/Wdc)

Table 3 The average cost of a solar system for the year 2021 ($/Wdc)

Type	Capacity	Cost ($)	Type	Capacity	Cost ($)
Residential	7.5 kWdc	2.65	Fixed Tilt	10 MV	1.03
	9 kWdc	2.34		50 MW	0.91
	11 kWdc	2.14		100 MV	0.83
Commercial	200 kW	1.56	1-Axis Tracker	10 MV	1.13
	500 kW	1.46		50 MW	0.98
	1 MW	1.43		100 MV	0.89

4.4 Solar System Installation Cost Factors

The cost of solar system installation depends on location, energy needs, type of solar surfaces, inverter and equipment options, permits, inspection, tax credits, labor costs, etc. The cost factors are shown in Fig. 5 as percentage values. Balance of System (BOS) includes structural, electrical, and installation components. Through the BOS components, cost control, efficiency, and modernization of systems are realized. Operational costs include supply chain, general overheads, tax, maintenance requirements, etc.

4.5 Payback Period (Recovery of Investment)

A solar system's cost recovery period can vary depending on the used technology, system type, region, and the cost of electricity. Payback periods could vary depending on different countries, and different regions even within one country. This period compares with the average solar system lifetime of around 25-30 years [48]. The average solar system payback period is 7 to 12 years globally and most solar systems start generating a return on investment after 8-years [49-52]. Economic analysis and payback period (recovery of investment) calculation studies have been conducted for various regions of Türkiye. It is found that the average solar system payback period can vary depending on the region of the Türkiye [53-56]. The new incentives and tax breaks in Türkiye reduce average payback periods to under 7-years today and 2-years in 2030 [57, 58] for residential systems.

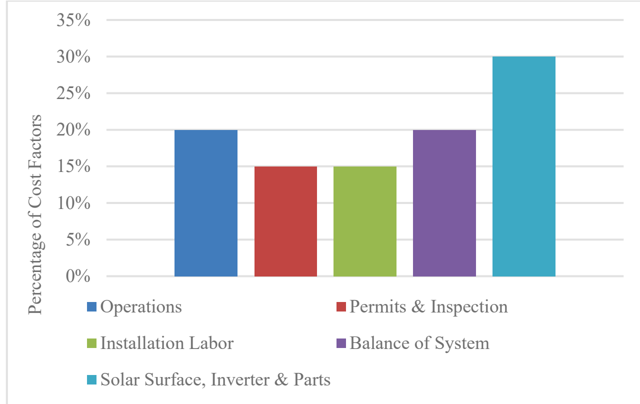

Figure 5 The average cost of a solar system for the last 5-years ($/Wdc)

5 CALCULATIONS AND RESULTS

In this section, first the proposed calculation model is applied to the Antalya province. Later, the discussions on *LCOE* and payback, and the discussions for applying the calculation model to large scope are presented respectively.

By using monthly average daily radiation values falling on a horizontal surface, climatic, and latitude data obtained from NASA for the districts of Antalya province, optimal tilt angles of the solar surfaces, and maximal solar radiation gain have been calculated for a specific period. Results are presented in tabular and graphical forms. By using the calculation method, the tilt angle value where the measured maximum radiation is determined as the optimum tilt angle. The surface azimuth angle is fixed to 0° for directly facing the equator. It can be used to calculate average solar radiation at any time of year for solar surfaces.

5.1 Solar Radiation Falling on Horizontal Surfaces

The monthly average daily radiation values falling on a horizontal surface for the Antalya districts are presented in Tab. 4. It is seen that from Tab.3, the Manavgat district has the best radiation efficiency considering the monthly and annual values. The second-best productive district is Kaş. The elevation of Manavgat is higher than the others. Since the most important solar parameter is horizontal radiation value, Manavgat has advantageous productivity compared to other districts.

5.2 Optimal Tilt Angle Results

Optimal tilt angles of the districts of Antalya province are calculated for solar systems, and the comparison of monthly optimal tilt angle values of the districts is shown in Fig. 4. Monthly optimal tilt angle values depending on the months are shown in the extreme points of the curves which represent the maximum values. It is understood from Fig. 4 that there is an optimal tilt angle for each month of the year when solar radiation is at its highest. Taking the calculated tilt angle values into account, solar radiation can be utilized to the maximum level.

Table 4 Monthly average daily radiation on horizontal surface (kWh/m²/d) [26]

Month	Alanya	Kaş	Manavgat	Muratpaşa
Jan	2.16	2.50	2.48	2.09
Feb	2.88	3.32	3.38	2.88
Mar	4.00	4.63	4.75	4.12
Apr	5.04	5.70	5.78	5.12
May	6.36	6.96	7.03	6.13
Jun	7.45	8.06	8.06	7.17
Jul	7.44	7.93	7.98	7.18
Aug	6.61	7.08	7.19	6.32
Sep	5.42	5.90	6.00	5.30
Oct	3.86	4.20	4.23	3.79
Nov	2.50	2.77	2.78	2.58
Dec	1.87	2.11	2.11	1.85
Annual	4.64	5.11	5.16	4.55

To find the optimal tilt angles of surfaces and total solar radiation collected by the tilted solar surface monthly, calculations are done for all tilt angles between 0° and 90°. For the districts of Antalya province, the monthly, seasonal, and annual optimal tilt angles and the monthly average daily solar radiation gain at these tilt angles are presented in Tab. 5. The differences in the amount of radiation gain as a result of the effect of the tilt angle can be seen in Tab. 4. It is seen that the optimal tilt angle values are determined between 0° (Jun) and 61° (Dec) throughout the year. The annual optimal tilt angle is determined to be between 28° and 30° for a solar surface that faces south throughout the year.

It is determined that the lowest optimal tilt angle is between 0° (Jun) and 2° (Jul), and the highest monthly average daily radiation values are observed during the same months. The optimal tilt angle then rises during the winter months and reaches 61° in December. The optimal tilt angles are determined for the winter season between 55°-57°, and the lowest monthly average daily radiation values are observed in December and January. The optimal tilt angles determined for the summer season are between 4°-5°.

As seen from the monthly tilt angles graph (see Fig. 6), the tilt angles reach their highest value in the winter season and go down to their lowest value in the summer season. While the highest optimal tilt angles of all districts are seen in December, the lowest optimal tilt angle value for all districts is in June. This is because Türkiye is located in the northern hemisphere, the sun rays in the summer are steep compared to the winter months. The optimal tilt angle values for Antalya districts decrease from January to June and increase again from June to December. The biggest reason for this decrease and increase in the optimal tilt angles during the year is that the declination angle (δ) increases until June and decreases after June. As the declination angle increases, the optimal tilt angle decreases or vice versa. The orientation (azimuth and tilt angles) of the solar surfaces can be adjusted when the supporting structure is designed accordingly.

In solar surfaces that do not have a solar tracking system, the tilt angles can be varied seasonal to benefit from solar radiation more efficiently. However, when the tilt angles of the surfaces are not possible to set monthly or seasonally, the tilt angles of the solar surfaces can be set annually.

Table 5 Opt. tilt angles (°) and monthly average daily radiation gains (kWh/m²/d)

Alanya District of Antalya Province						
Month	Monthly-Fixed		Seasonally-Fixed		Annually-Fixed	
	Tilt	Rad. Gain	Tilt	Rad. Gain	Tilt	Rad. Gain
Dec	59	3.05	55	3.04	28	2.70
Jan	57	3.41		3.41		3.06
Feb	48	3.84		3.81		3.67
Mar	34	4.60	19	4.47		4.57
Apr	19	5.26		5.26		5.22
May	6	6.39		6.30		6.12
Jun	0	7.45	5	7.44		6.89
Jul	2	7.45		7.45		7.00
Aug	15	6.79		6.7		6.68
Sep	31	6.10	43	6.0		6.09
Oct	46	5.10		5.1		4.90
Nov	56	3.87		3.79		3.51
Kaş District of Antalya Province						
Month	Monthly-Fixed		Seasonally-Fixed		Annually-Fixed	
	Tilt	Rad. Gain	Tilt	Rad. Gain	Tilt	Rad. Gain
Dec	60	3.59	56	3.59	29	3.17
Jan	59	4.15		4.15		3.70
Feb	49	4.58		4.55		4.36
Mar	36	5.43	21	5.28		5.40
Apr	20	5.98		5.98		5.93
May	5	6.99		6.85		6.65
Jun	0	8.06	4	8.05		7.37
Jul	2	7.94		7.94		7.39
Aug	16	7.28		7.14		7.14
Sep	32	6.70	44	6.59		6.69
Oct	47	5.65		5.64		5.43
Nov	57	4.41		4.31		3.99
Manavgat District of Antalya Province						
Month	Monthly-Fixed		Seasonally-Fixed		Annually-Fixed	
	Tilt	Rad. Gain	Tilt	Rad. Gain	Tilt	Rad. Gain
Dec	61	3.70	57	3.69	30	3.25
Jan	60	4.20		4.20		3.75
Feb	50	4.76		4.73		4.52
Mar	37	5.64	21	5.46		5.60
Apr	21	6.08		6.08		6.03
May	6	7.07		6.93		6.71
Jun	1	8.06	5	8.05		7.35
Jul	2	7.98		7.99		7.42
Aug	16	7.41		7.30		7.26
Sep	32	6.87	45	6.74		6.86
Oct	48	5.78		5.77		5.55
Nov	58	4.53		4.44		4.10
Muratpaşa District of Antalya Province						
Month	Monthly-Fixed		Seasonally-Fixed		Annually-Fixed	
	Tilt	Rad. Gain	Tilt	Rad. Gain	Tilt	Rad. Gain
Dec	59	3.04	55	3.03	29	2.71
Jan	57	3.29		3.29		2.98
Feb	48	3.86		3.84		3.7
Mar	35	4.77	20	4.65		4.75
Apr	20	5.36		5.36		5.31
May	6	6.16		6.06		5.88
Jun	0	7.17	5	7.16		6.62
Jul	2	7.19		7.19		6.73
Aug	15	6.49		6.41		6.37
Sep	31	5.97	44	5.86		5.96
Oct	46	5.02		5.01		4.83
Nov	57	4.09		4.01		3.71

5.3 Analyzing Optimal Tilts and Optimal Average Tilts

A comparison of the annual optimal tilt angle and the annual average optimal tilt angle is presented in Tab. 6. As can be seen in Tab. 6, by taking the average of the monthly and seasonally determined optimal tilt angles, the annual average optimal tilt angle values have been found. There are 2°-2.5° deviations between the annual average optimal tilt angle values and the annual optimal tilt angle values of the districts of Antalya province.

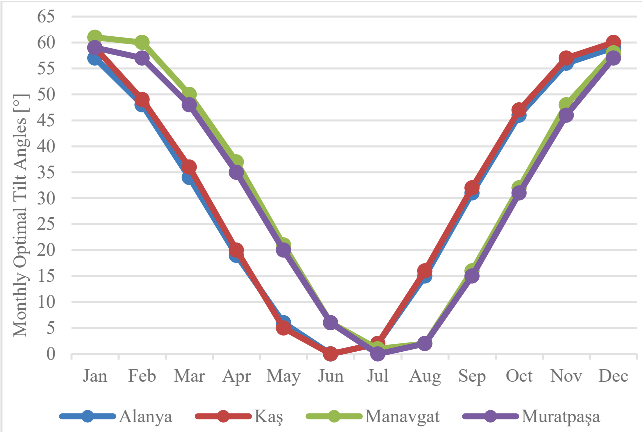

Figure 6 Monthly optimal tilt angle values obtained for districts of Antalya

This deviation is expected to increase further as move from the equator to the poles (especially at great latitudes) because the variations in the angle of incidence of the sun are greater or more frequent. This means the annual average optimal tilt angles do not represent the annual optimal tilt angles which is a separate concept. Optimal tilt degrees are reached when it is done over the maximum amount of radiation falling on the tilted surface, using the mathematical model that takes into account the solar climate conditions. So, calculations made with this model show that monthly and seasonal average tilt angles are not an optimal tilt angle determination, it is an approximate estimation of tilt angles. It has been determined that average angles deviate from optimal angles.

Table 6 Comparison of the annual opt. Tilt, and annual average opt. tilt (°)

Annual Optimal Tilts	Alanya	Kaş	Manavgat	Muratpaşa
Monthly AVG Opt. Tilt	31.08	31.92	32.67	31.33
Seasonally AVG Opt. Tilt	30.50	31.25	32	31
Fixed Annual Opt. Tilt	28	29	30	29

5.4 Solar Radiation Collected by the Fixed-Axis Surfaces

When the monthly average daily radiation values collected by solar surfaces with different tilt angles presented in Tab. 5 are analyzed comparatively. The monthly average daily radiation values are measured between 2.70 kWh/m^2 (Dec) and 7.42 kWh/m^2 (Jul) in case the solar radiation reaches the solar surface with the annual optimal angles range. In the winter season (Dec-Jan-Feb), the optimal tilt angle values are determined between 55° and 58°, the monthly average daily radiation values are measured between 3.04 kWh/m^2 and 4.76 kWh/m^2. In the spring season (Mar-Apr-May), the optimal tilt angle values are determined between 19° and 21°, the monthly average daily radiation values are measured between 4.60 kWh/m^2 and 7.07 kWh/m^2. In the summer season (Jun-Jul-Aug), the optimal tilt angle values are determined between 4° and 5°, the monthly average daily radiation values are measured between 6.49 kWh/m^2 and 8.06 kWh/m^2. In the autumn season (Sept-Oct-Nov), the optimal tilt angle values are determined between 43° and 45°, the monthly average daily radiation values are measured between 3.87 kWh/m^2 and 7.87 kWh/m^2.

5.5 Analysis of Solar Radiation Maximization Results

The monthly total solar radiation gain collected by the solar surfaces in case of using monthly, seasonal, and annual optimal tilt angles for Antalya districts are listed in Tab. 7. Calculations have been performed to maximize solar radiation falling on the solar surfaces regarding each combination of a tilt and azimuth angle. The results are presented for all months of the year, it returns the best combination of both geometry parameters for calculated periods in terms of finding optimal tilt angle and maximizing solar radiation accordingly. Also, it can be observed that the increase or decrease of the collected radiation for any values of azimuth and tilt of solar surface in the chosen period. So, one of the important outcomes in this study is the graphs and tables displaying the change in tilt angle in terms of increase or decrease and the amount of collected radiation. It is seen that from Tab. 6, the total monthly average radiation values are measured between 83.70 kWh/m^2 in December, and 230.02 kWh/m^2 in Jul in case of radiation reaches the solar surface with the optimal annual tilt angle. The conclusion to be drawn from the data in Tab. 6 is that solar radiation can be captured as a maximal level if the optimal tilt angle is set for each month. As a result, surfaces should be tilted at certain angles to maximize the benefits of solar radiation.

The annual total solar radiation collected by the solar surfaces for the Antalya districts is presented in Tab. 8. Manavgat district has the best radiation efficiency considering the annual fixed values in Tab 7. The maximal total annual average radiation values are measured in Manavgat as 2,194.66 kWh/m^2 for monthly, 2,173.28 kWh/m^2 for seasonal, 2,082.50 kWh/m^2 for annual respectively with applying the optimal tilt angles provided in this study. The high radiation rates of districts are contributed significantly to the gain of more radiation on fixed surfaces. It seems that the reason why Antalya province is preferred especially for the establishment of large-capacity solar systems is that it can be made a serious difference in energy generation.

5.6 Analyzing Radiation Gain for Tracking Systems

Solar tracking systems are effective tools to be used in solar systems where higher solar radiation efficiency is required. The average monthly total radiation on south-facing solar surfaces along the tilt angle gradient of 0° to 90° is calculated and presented in Tab. 9 for one-axis, and two-axis tracking surfaces of four districts of Antalya. It is understood that from Tab. 9, Manavgat and Kaş are the best productive districts for the radiation efficiency of the solar surfaces in case using tracking systems. The maximal total monthly radiation values are measured in Manavgat as 326.12

kWh/m² for one-axis, and 340.69 kWh/m² for two-axis respectively. In cases where it is not applicable to set the tilt angles of the surfaces, or if there is no solar tracking system, the monthly optimal tilt values presented in Fig. 4 can be used for districts of Antalya province.

Table 7 Total monthly radiation gain [kWh/m²/d] in case of using opt. tilt angles (°)

Alanya District of Antalya Province			
Month	Monthly	Seasonally	Annually
Jan	105.71	105.71	94.86
Feb	107.52	106.68	102.76
Mar	142.60	138.57	141.67
Apr	157.80	157.80	156.60
May	198.09	195.30	189.72
Jun	223.50	223.20	206.70
Jul	230.95	230.95	217.00
Aug	210.49	207.70	207.08
Sep	183.00	180.00	182.70
Oct	158.10	158.10	151.90
Nov	116.10	113.70	105.30
Dec	94.55	94.24	83.70
Kaş District of Antalya Province			
Month	Monthly	Seasonally	Annually
Jan	128.65	128.65	114.70
Feb	128.24	127.40	122.08
Mar	168.33	163.68	167.40
Apr	179.40	179.40	177.90
May	216.69	212.35	206.15
Jun	241.80	241.50	221.10
Jul	246.14	246.14	229.09
Aug	225.68	221.34	221.34
Sep	201.00	197.70	200.70
Oct	175.15	174.84	168.33
Nov	132.30	129.30	119.70
Dec	111.29	111.29	98.27
Manavgat District of Antalya Province			
Month	Monthly	Seasonally	Annually
Jan	130.20	130.20	116.25
Feb	133.28	132.44	126.56
Mar	174.84	169.26	173.60
Apr	182.40	182.40	180.90
May	219.17	214.83	208.01
Jun	241.80	241.50	220.50
Jul	247.38	247.69	230.02
Aug	229.71	226.30	225.06
Sep	206.10	202.20	205.80
Oct	179.18	178.87	172.05
Nov	135.90	133.20	123.00
Dec	114.70	114.39	100.75
Muratpaşa District of Antalya Province			
Month	Monthly	Seasonally	Annually
Jan	101.99	101.99	92.38
Feb	108.08	107.52	103.60
Mar	147.87	144.15	147.25
Apr	160.80	160.80	159.30
May	190.96	187.86	182.28
Jun	215.10	214.80	198.60
Jul	222.89	222.89	208.63
Aug	201.19	198.71	197.47
Sep	179.10	175.80	178.80
Oct	155.62	155.31	149.73
Nov	122.70	120.30	111.30
Dec	94.24	93.93	84.01

Maximal radiation gains for fixed systems and tracking systems are presented in Tab. 10. It is calculated that optimally angled surfaces achieve between 8.23% (Alanya) and 10.63% (Manavgat) more solar radiation annually compared to surfaces that are not angled at all for the fixed surface. It is also calculated that one-axis tracking systems harvest between 28.72% (Muratpaşa) and 33.17% (Manavgat) higher solar radiation, and two-axis tracking systems harvest between 32.19% (Kaş) and 37.49% (Manavgat) higher solar radiation than the fixed-axis systems in districts of Antalya. Considering an expected 25-year lifetime for the solar systems, optimal tilting of the surfaces should be taken seriously in solar systems. It is highly advised to utilize a one-axis tracking system in solar systems. However, solar tracking systems are high-cost to operate and maintain and are not always feasible because of the lack of free space. If changing the tilt angles of the solar surface is not possible, the annual fixed optimal tilt angle values can be used for solar energy systems during the installation. In the light of the obtained results, it is calculated that if the tilt angle is changed every month in the Antalya districts, an increase in the radiation values falling on the solar surfaces can be achieved between 4.87% (Kaş) and 5.28% (Manavgat) compared to annual fixed tilt angle. It is also calculated that if seasonally setting it between 3.80% (Alanya) and 4.32% (Manavgat) radiation gain compared to an annual fixed system. Especially for large-scale solar systems, this difference will have a significant impact.

Table 8 Total annual radiation gains (kWh/m²/d) in case of using opt. tilt angles (°)

Districts	Monthly	Seasonally	Annually
Alanya	1,928.41	1,911.95	1,839.99
Kaş	2,154.67	2,133.59	2,046.76
Manavgat	2,194.66	2,173.28	2,082.50
Muratpaşa	1,900.54	1,884.06	1,813.35

Table 9 Total avg. monthly radiation gain (kWh/m²/d) for solar tracking systems

Month	Alanya		Kaş	
	One-Axis	Two-Axis	One-Axis	Two-Axis
Jan	114.70	122.14	141.05	150.97
Feb	122.36	125.44	148.68	152.60
Mar	175.15	175.15	214.21	214.52
Apr	191.10	192.30	223.80	225.30
May	249.86	257.61	280.55	290.16
Jun	281.10	294.90	310.80	327.30
Jul	298.22	310.31	323.64	340.38
Aug	285.51	289.54	313.10	317.75
Sep	237.90	237.90	266.40	266.40
Oct	197.16	200.88	222.27	225.99
Nov	128.40	135.90	147.90	156.60
Dec	100.44	107.88	119.66	128.96
Month	Manavgat		Muratpaşa	
	One-Axis	Two-Axis	One-Axis	Two-Axis
Jan	143.22	153.14	110.98	117.49
Feb	154.84	159.04	123.76	126.56
Mar	224.44	224.75	183.83	183.83
Apr	228.90	230.70	195.60	196.80
May	284.58	294.50	237.77	245.83
Jun	310.50	327.30	267.00	280.80
Jul	326.12	340.69	284.27	296.05
Aug	320.85	325.81	268.77	272.80
Sep	275.10	275.10	231.60	231.60
Oct	228.16	232.19	194.06	197.16
Nov	152.40	161.10	136.50	144.60
Dec	123.38	132.99	100.75	107.88

Tab. 11 presents the annual average solar radiation gain in the four investigated districts in case using the solar tracking systems. Manavgat district is the best productive district for the radiation efficiency of the solar surfaces. Total annual average radiation values are measured 2,772.49 kWh/m^2 for one-axis, 2,857.31 kWh/m^2 for two-axis respectively. It is also revealed that the second-best productive district is Kaş in terms of radiation efficiency. Compared annually, a considerable increase in radiation values is observed in the Antalya districts. For this reason, it is recommended to investors that Manavgat and Kaş districts can be preferred in the Antalya province.

Table 10 Radiation gains of fixed systems and tracking systems (%)

Districts of Antalya	Annual Fixed-Axis (%)	On-Axis Tracking (%)	Two-Axis Tracking (%)
Alanya	8.23	29.34	33.15
Kaş	9.62	32.19	36.09
Manavgat	10.63	33.17	37.49
Muratpaşa	9.03	28.72	32.59

Especially for large-capacity solar systems, a two-axis tracking system can be created a considerable impact and can contribute greatly to the business economy. However, two-axis systems are quite costly. In this context, to utilize a two-axis tracking system, cost and benefit analysis should be done first. It is strongly advised to utilize a one-axis tracking system in solar systems.

Table 11 Total avg. annual radiation gain (kWh/m^2/d) for solar tracking systems

District	Solar Tracker Type	Radiation Gain
Alanya	One-Axis	2,381.90
	Two-Axis	2,449.95
Kaş	One-Axis	2,712.06
	Two-Axis	2,796.93
Manavgat	One-Axis	2,772.49
	Two-Axis	2,857.31
Muratpaşa	One-Axis	2,334.89
	Two-Axis	2,401.40

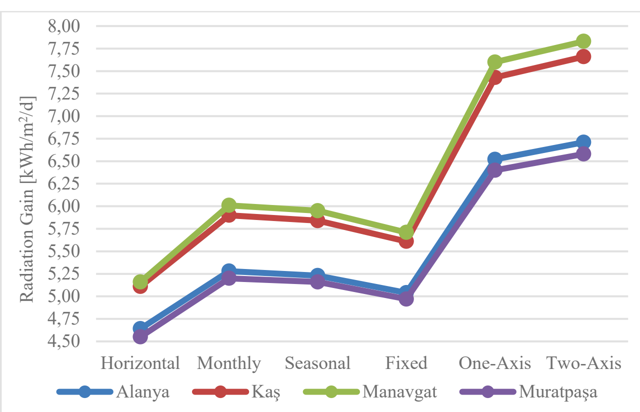

Figure 7 Annual average daily radiation falling on horizontal and tilted surfaces

Fig. 7 shows a comparison of solar radiation falling on fixed and tracking systems in the districts. The annual average daily radiation values are calculated by changing the tilt of the south-oriented surfaces with steps between 0°-90°, curve graphs are drawn depending on radiation gain from the fixed and tracking systems. It can be seen once again in Fig. 5 that tracking systems make a serious contribution to energy efficiency. So, to maximize radiation efficiency, solar surfaces need to be structured so that the tilt angle can be set effortlessly to use monthly or seasonal optimal tilt. At a minimum, surfaces should be set with an annual optimal tilt if the tracking system setup is not affordable financially.

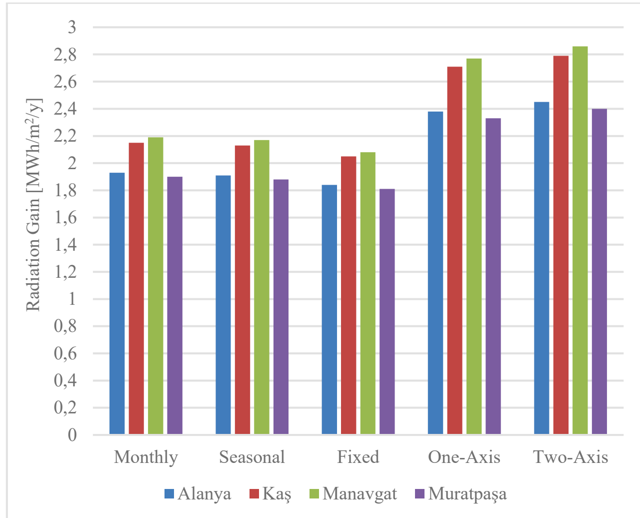

Figure 8 Total annual radiation for the districts of the Antalya province

Fig. 8 presents the annual radiation values of tracking systems and fixed systems for evaluating the existence of solar potential in Antalya districts. It is understood that from Fig. 8, the variation of collected solar radiation values from the tracking systems and fixed systems are the most essential parameter to the design and size of the large-capacity solar systems. It is also seen that tracking systems may significantly increase the collecting the radiation. Because of this, it is extremely important to use solar tracking systems to get high radiation efficiency.

5.7 Discussions on the Cost Analysis and Payback Period

As depicted Fig. 4, the cost of solar energy continues to decrease thanks to improved module efficiency as well as low hardware equipment costs in recent years. It is understood Tab. 3, large-scale solar systems are much cheaper to install and operate compared to residential and commercial solar systems. In other words, as the capacity of the solar system grows, the system installation costs decrease or change the type of solar system. Also, the cost increase in installing one-axis tracker structures in large-scale solar systems is less than expected. It is therefore highly suggested to install a one-axis tracker in such solar systems in terms of cost and economic efficiency. Fig. 4 shows that between the last 2 years, there were 3.28% ($0.09/Wdc), 10.34% ($0.18/Wdc), 10.83% ($0.11/Wdc), and 12.74% ($0.13/Wdc) globally reductions in the residential, commercial, large-scale fixed tilt and one-axis solar system cost respectively. The latest statistical data show that the solar energy in Türkiye cost is almost halved last 5-years. Hence, there is no doubt solar energy to support the economy in countries with high energy tariffs and at the same time high solar potential such as Türkiye. It is also seen that the average solar system payback period is 7 to 12 years globally and most solar systems start generating a return on investment after 8-years comparing the 25 years lifespan of the system. The new incentives and tax breaks in Türkiye are reduced average payback periods to under 7-years. Due to the decrease in setup costs in the future, it is anticipated that the payback period will be lot less than today's payback periods.

5.8 Discussions on the Proposed Calculation Model

Because tilting and tracking are significant effects to increase incident solar radiation at all latitudes, the proposed model can be implemented in any location of interest to obtain specific estimates with a low computational cost. The proposed model can be used for evaluating the solar potential of a certain location before establishing a solar system and can be also easily applied by researchers and technicians in the field to avoid energy yield losses and unnecessarily high *LCOE*. In addition, different desired periods can be obtained such as daily, weekly, monthly, seasonally, and yearly optimal tilt values or radiation values for solar systems by using the data set for each location of interest in Türkiye or the world. The model can be extended to other rural regions in developing countries.

6 CONCLUSIONS

This study contributes in-depth to determining the optimal tilt angle of the solar surfaces and measuring total solar radiation falling on the tilted surface monthly, seasonal, and annually in Antalya districts within the proposed calculation model. The study also highly contributes to the estimation of radiation values collected by the surfaces in case using solar tracking systems for evaluating the existence of solar potential in Antalya districts.

The average daily radiation values are calculated using the proposed model by changing the tilt of the south-oriented surface with steps between 0° and 90°. It is observed that the optimal tilt angles during the year are varied between 0° and 61°. The annual optimal tilt angle is determined to be between 28° and 30° for a south-facing solar surface throughout the year. So, it has been determined that there is a ±1 or ±2 tilt angle difference between the four districts.

The monthly average daily radiation values are measured between 2.70 kWh/m^2 and 7.42 kWh/m^2 in case of radiation reaches the solar surface with the optimal annual tilt angle in the districts. The maximal total annual average radiation values are measured 2,194.66 kWh/m^2 for monthly, 2,173.28 kWh/m^2 for seasonal, 2,082.50 kWh/m^2 for annual respectively with applying the optimal tilt angles. The maximal total monthly radiation values are measured 326.12 kWh/m^2 for the one-axis, and 340.69 kWh/m^2 for the two-axis respectively. It is calculated that optimally angled surfaces achieve between 8.23% and 10.63% more solar radiation annually compared to surfaces that are not angled at all for the fixed surface. It is also calculated that one-axis tracking systems harvest between 28.72% and 33.17% higher solar radiation, two-axis tracking systems harvest between 32.19% and 37.49% higher solar radiation than the fixed-axis systems in districts of Antalya.

For the districts of Antalya, it is calculated that the monthly optimal tilt setting contributes between 4.87 and 5.28% radiation gain compared to an annual fixed system. It is also calculated that a seasonally setting contributes between 3.80 and 4.32% radiation gain compared to an annual fixed system.

These results demonstrate that monthly, seasonally, and annual positioning of the solar surfaces at the optimal tilt angles provides significant radiation efficiency. It is found that, under the same conditions, the tracking systems harvest great radiation efficiency compared to the fixed systems.

It is understood that the period, latitude, climatic characteristics, and geographical location are the most important parameters affecting the optimal tilt angle and radiation efficiency. It is also seen that Antalya has a perfect location for the installation of solar systems. The proposed calculation method can be applied to specific locations in Turkiye where the importance of solar systems is constantly increasing. It is thought that this study can help solar engineers and designers to improve the efficiency of solar surfaces, properly set optimal tilt angles, and choose the right methodology for installing solar systems in the districts of Antalya province.

When the findings of this study are compared to those of other studies in the literature, it is discovered that as consistent with the findings of similar studies. This study shows the importance of accurate tilt angle and orientation. It is thought that the study can contribute to the solar data literature of Antalya province. The proposed calculation model can be implemented any location in Türkiye and the world.

Recent research studies show that the solar energy cost and solar system installation cost continued to decrease thanks to increased panel efficiency and decreased hardware costs in globally. It is believed that *LCOE* based analysis presented in this study can guide engineers and investors to create solar systems and maximize financial returns by minimizing the costs in Antalya province. It is expected that solar energy will support the economy in countries with high energy tariffs and at the same time, high solar potential such as Türkiye since the solar energy cost is almost halved last 5-years. Because of the global reduction in large-scale one-axis solar system costs for the last 2-years 12.74%, it is highly recommended to install one-axis tracker systems in terms of not only economic potential but also energy efficiency.

It is also shown that in Türkiye, most solar systems start generating a return on investment after 8-years comparing the 25 years lifespan, the new incentives, tax breaks, existing solar potential, and continued declines in installation costs reduced average payback periods to under 7-years today.

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