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ESTIMATING THE SOLAR EXERGY POTENTIAL OF SURFACES WITH DIFFERENT TILT ANGLES

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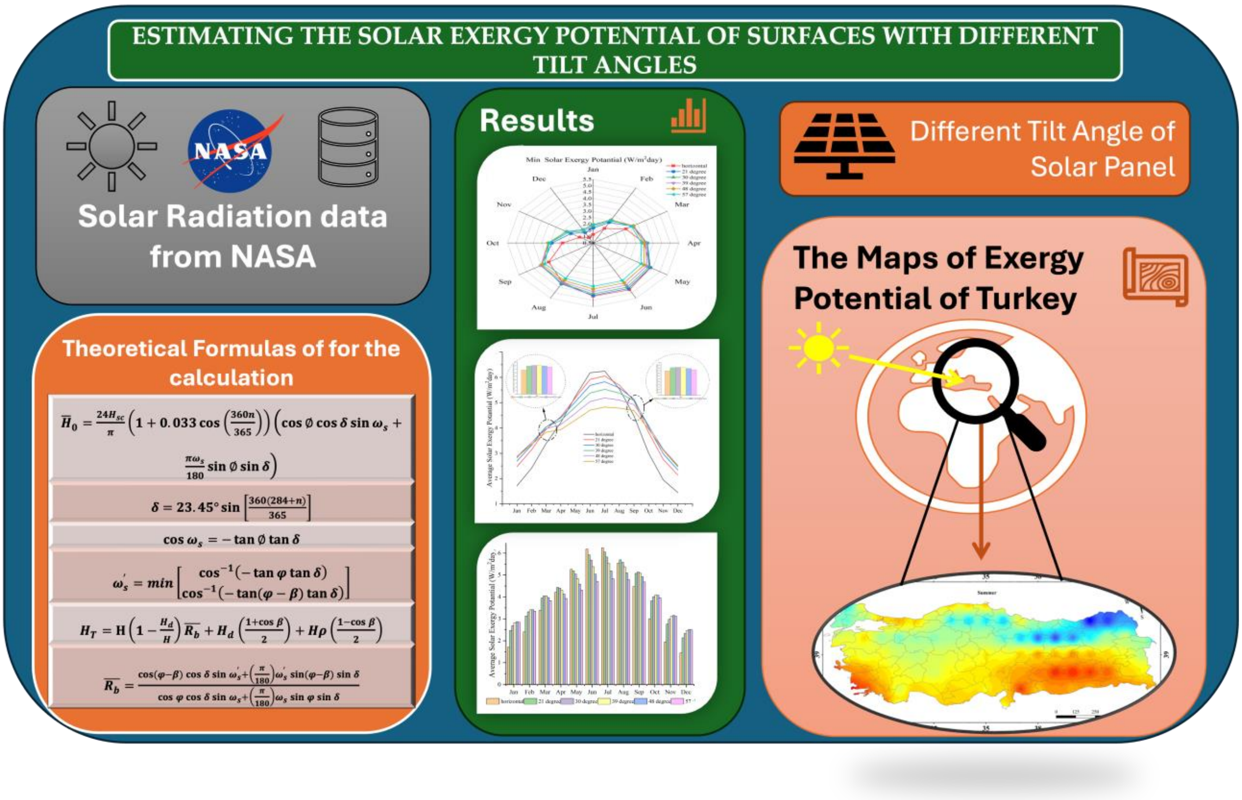
Highlights

- The importance of utilizing Turkey's solar energy potential
- The effect of different tilt angles on solar energy potential
- Determination of the exergy potaintial of solar energy at different tilt angles
- Solar exergy maps of Turkey at the optimum tilt angle

Graphical Abstract



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ABSTRACT: Solar energy, which is a clean, unlimited, and environmentally friendly energy source, has critical importance in sustainable energy management. The usable potential of energy is expressed in terms of exergy, and the determination of the exergy potential of solar energy ensures the correct utilization of this potential. Turkey has a very high solar energy potential, and this potential should be utilized in the most efficient way possible to achieve sustainable energy targets. The tilt angle of solar panels has a significant effect on efficiency. Efficient operation of solar panels can be achieved by determining the optimum tilt angle. In this study, Turkey's solar exergy potential was calculated for the horizontal plane and five different tilt angles (21°, 30°, 39°, 48°, and 57°). Thus, it was tried to determine the appropriate panel angle to get the highest efficiency from solar panels that can be used in different regions of Turkey. The calculations are based on 22-year average solar energy potential data obtained from NASA. The exergy potential was determined for the coordinates where Turkey is located, and the potential for the regions between the coordinates was determined by the interpolation method. With the interpolation method used, an approximate estimation for the areas where there is no measurement is also provided, and it is aimed at saving the time and cost required for long-term measurements. Among the tilt angles analyzed, the optimum angle for the whole year was determined to be 30 degrees. The exergy potential for 30° inclined surfaces in all coordinates of Turkey is given as a seasonal map. With the use of the maps, it is thought that the optimum angle and exergy potential for different regions and seasons of Turkey will be predicted, and thus it will be easier for new investors to determine the high-potential regions of Turkey.

Keywords: *Exergy Potential, Optimum Tilt Angle, Solar Energy, Solar Exergy Potential Maps*

1. INTRODUCTION

Energy is essential for sustaining human existence, providing comfort, and meeting needs. The sustainable management of energy is necessary to meet all these demands, keep the economy and industry running, and preserve a habitable environment [1], [2]. Conventional energy sources, especially fossil fuels, provide much of the energy needed by the modern world. However, the exploitation of these resources causes pollution, such as greenhouse gas emissions, which accelerate climate change and damage ecosystems. The use of renewable energy sources might help to lessen these detrimental impacts on the environment. Renewable energy sources are essential for a sustainable future, and solar energy is particularly notable among them [3], [4]. Solar energy is essential to meeting our energy demands since it is a clean, endless, and environmentally friendly energy source. Determining solar energy's potential is crucial to its efficient utilization. Utilizing Turkey's abundant solar energy resources is essential to achieving sustainable energy targets and expanding the country's energy portfolio [5]. Several studies have explored Turkey's solar energy potential, focusing on various regions and employing different methodologies to evaluate and optimize solar energy applications.

Turkey's solar energy potential has been the subject of several studies. Research conducted in the province of Karabük aimed to evaluate local solar energy applications and examine the benefits and drawbacks of this energy source [6]. An efficiency map was made using the Analytical Hierarchy Process

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(AHP) technique to evaluate the solar energy potential of Gaziantep province [7]. In the province of Kars, potential sites for solar power plant projects were identified by the application of AHP methodologies and CSB investigations [8]. An attempt was made to determine which of the three accessible alternative provinces—Istanbul, Nevşehir, and Bilecik—is the best location for a solar power plant (SPP) to be established in Turkey using the Multi-Criteria Decision Making (MCDM) approach [9]. Several studies have been conducted to evaluate Turkey's energy situation, renewable energy resources, and solar energy [10], [11], [12], [13].

A fundamental concept in thermodynamic analysis and performance evaluation of energy systems is the determination of energy potential. Exergy is a unit of measurement for energy quality that describes an energy form's capacity for work. In addition to energy analysis, energy analysis provides a more accurate and efficient means of evaluating energy conversion or distribution processes and systems. Energy is wasted during recycling in real processes, whereas it is saved during ideal processes. Consequently, exercise can be employed to calculate the thermal losses and inefficiencies of each energy system unit, as well as a useful indicator of possible environmental effects. Researchers have carried out studies on the exergy of Turkey's solar energy potential. The exergy of global solar radiation was investigated using measurement data for Erzurum province [14]. In another study, horizontal-plane solar radiation data were taken from 8 measurement stations in Turkey, and energy and exercise research were carried out for these regions [15]. The researchers analyzed Turkey's solar radiation exergy and the environmental-economic analysis of solar radiation incidents on the horizontal plane [16].

The tilt angle of solar panels with respect to the surface can have a substantial impact on their efficiency. By ensuring that the sun's rays reach the panels at their highest level, the optimal tilt angle increases the amount of energy produced. According to studies, altering the tilt angles can have a significant impact on the amount of energy that solar panels can capture annually [17], [18], [19], and [20]. For instance, a study conducted in Kayseri revealed that positioning solar panels with an optimal monthly tilt angle yielded 4.11% more energy than a constant annual tilt angle. Additionally, it was demonstrated that adjusting seasonal and semi-annual tilt angles could enhance energy efficiency, although this increase was less pronounced than that observed with monthly adjustments [21].

The Photovoltaic Geographic Information System (PVGIS) [22] and the Hottel & Woertz (HW) methods are two of the techniques used to calculate the tilt angles. The optimal tilt angles for the panels are determined using these techniques, considering the region and climate data currently available. The PVGIS approach employs satellite-interactive meteorological data to simulate the ideal hourly, daily, monthly, and annual solar radiation levels based on the desired geographic location and panel tilt angle.

A study conducted in Ardahan province demonstrated that surfaces with the optimal tilt angle for each day exhibited an increase of up to 17% in annual total solar radiation values when compared to horizontal surfaces. The minimum increase was 3.4% on surfaces with a $\beta=\phi+15°$ tilt angle [23]. A comprehensive evaluation of solar collectors at various tilt angles has been conducted for the province of Erzincan, with particular focus on energy and exercise considerations [24]. These studies demonstrate the importance of solar collector tilt and orientation in optimizing solar radiation energy harvesting. Identifying the optimal tilt angles is crucial for enhancing the efficiency of solar energy systems and reducing energy costs. Furthermore, these studies present a scientific approach for planning and arranging solar collectors, enabling a more effective utilization of renewable energy sources.

Despite these efforts, a gap remains in understanding the exergy potential of solar energy in Turkey, particularly concerning the optimal tilt angles for solar panels. This study addresses this gap by calculating the solar energy potential for different tilt angles and providing detailed seasonal maps. The primary contributions of this study are the identification of the optimum tilt angle for maximizing solar energy potential and the presentation of energy potential maps that can guide future solar energy investments in Turkey.

In this study, the exergy potential of surfaces with varying tilt degrees can be quantified, providing valuable insights for solar collector design and optimization. This knowledge can be used to inform the design of solar energy collectors, enabling more effective use of solar energy. The data set utilized for this study comprised the 22-year average total average daily irradiation to the horizontal plane, diffuse average daily irradiation to the horizontal plane, and outdoor temperatures at 10 m height. These data were obtained from NASA for 140 coordinate points located between 26° and 45° east. As a general approach, it is recommended to position the solar panels so that the latitude angle of the panels is 15 degrees below the latitude angle in summer and 15 degrees above the latitude angle in winter. Therefore, considering Turkey's smallest latitude angle of 36 degrees and the largest latitude angle of 42 degrees, angles that will cover 15 degrees more (57 degrees) and 15 degrees less (21 degrees) were studied. The calculations of Turkey's solar energy potential were made for both horizontal and five different inclination angles (21°, 30°, 39°, 48°, and 57°), covering a latitude range of 36°–42° north parallel.

The long-term NASA data and IDW interpolation method used in this study allow us to make accurate forecasts even in missing data regions. This is one of the innovative aspects of our study. In addition, the detailed examination of the performance of specific tilt angles in different seasons provides a more comprehensive analysis compared to other studies in this field.

The organization of this paper is as follows: Section 2 describes the materials and methods used in this study, including the exercise analysis and the determination of solar potential. Section 3 presents the results and discussion, including seasonal exercise potential maps and an analysis of different tilt angles. Finally, Section 4 concludes the study and suggests directions for future research.

2. MATERIAL AND METHODS

To optimize the utilization of solar radiation in solar energy system design, it is of paramount importance to accurately calculate the tilt angles of the solar collectors. By ensuring that the sun's rays are perpendicular to the collector surface, these angles enhance the efficiency of energy collection. The optimal tilt angle of the collectors is significantly influenced by variations in solar incidence angles due to seasonal variations and geographic locations.

The following equations are employed to determine the inclination angles of 21°, 30°, 39°, 48°, and 57° on a horizontal plane, with the objective of illustrating the impacts of these angles on the exergy potential of solar energy. To determine the solar exergy potential, the diffuse average daily irradiance to the horizontal plane, the 22-year average total average daily irradiance to the horizontal plane, and the outdoor temperatures at a height of 10 meters were taken into consideration for 140 coordinate points between the 26°–45° east latitudes and the 36°–42° north parallels in Turkey.

2.1. Exergy Analysis

Exergy is the portion of the thermodynamic potential that can be transformed into the greatest amount of work. It is a key concept in determining the amount of work that thermodynamic systems can produce. It is frequently used to evaluate the energy quality of thermodynamic systems and to identify potential flaws or issues. When a system moves from its current thermodynamic equilibrium to one of reversible processes and reaches equilibrium with its external environment, that state is referred to as exertion. When there is no exchange of matter or energy between a thermodynamic system and its environment, or in the case of reversible processes, the maximum amount of work that can be produced from the system is measured. In this case, the external work of the system is maximized, but its internal energy and entropy are constant. Exergy is the name given to this maximum theoretical work [25], [26].

In Equation 1, the ratio of the maximum work (W) that can be achieved using radiation to the energy "E" of the solar source can be used to mathematically describe the conversion efficiency of thermal radiation into real work [27].

$$\eta = \frac{W}{E} \tag{1}$$

This useful work from radiation will be maximized for a reversible process. The highest formula efficiency is given in Equation 2 below.

$$\eta_{c,max} = \frac{W_{max}}{E} \quad 2$$

The exergy of the system is the maximum amount of work that can be extracted, and the exergy efficiency is the maximum system efficiency. Exergy efficiency can be expressed as in Equation 3:

$$\psi = \frac{\underline{H}_{g,ex}}{\underline{H}} \quad 3$$

The exergy efficiency "ψ" in Equation 3 replaces $\eta_{c,max}$ in Equation 2. Similarly, $\underline{H}_{g,ex}$ represents the solar radiation exergy W_{max} term, while $\underline{H}$ (incoming solar radiation) is used instead of the energy input E. According to Petela, ψ represents the highest percentage of solar radiation that can be converted into work (Petela, 2003). Petela developed the concept of exergy of solar radiation to assess the efficiency and reversibility of all energetic processes involving heat radiation. To estimate the exergy of heat radiation, formulas have been proposed that consider the ratio of exergy to radiation energy.

The exergy of solar energy is determined by the model given by Petela, [28] as follows (Equation 4).

$$\psi_i = 1 + \frac{1}{3}\left(\frac{T_0}{T_s}\right)^4 - \frac{4}{3}\frac{T_0}{T_s} \quad 4$$

Here, ψ_i represents the relative potential of the maximum output from solar radiation, T_s is the solar temperature and its value is 1459.5 K for diffuse solar radiation and T_s 5760 K for beam (or direct) solar radiation. T_0 is the monthly average air temperature (in Kelvin) for the considered location. The Petela model gives similar results to the Jeter and Spanner model, so the choice of the Petela model is reasonable and leads to acceptable results.

As the outside temperature increases, the efficiency of both radiant and diffuse solar energy decreases. This implies that less work can be produced from incoming radiation when the ambient temperature rises. Equations 5 and 6 can be used to determine the exergy values of the highest relative energy availability potential ψ, diffuse $\underline{H}_{d,ex}$ and direct $\underline{H}_{b,ex}$ solar radiation [29], [30].

$$\underline{H}_{d,ex} = \psi_d \underline{H}_d \quad 5$$

$$\underline{H}_{b,ex} = \psi_b \underline{H}_b = \psi_b(\underline{H}_g - \underline{H}_d) \quad 6$$

The exergy of global solar radiation is calculated using Equation 7 or Equation 8. Global solar energy efficiency can be calculated using Equation 9 or Equation 10 [29].

$$\underline{H}_{g,ex} = \underline{H}_{b,ex} + \underline{H}_{d,ex} \quad 7$$

$$\underline{H}_{g,ex} = \psi_g \underline{H}_g \quad 8$$

$$\psi_g = \frac{\underline{H}_{g,ex}}{\underline{H}_g} = \frac{\psi_b \underline{H}_b + \psi_d \underline{H}_d}{\underline{H}_g} \quad 9$$

$$\psi_g = \psi_b\left(1 - \frac{\underline{H}_d}{\underline{H}_g}\right) + \psi_d\left(\frac{\underline{H}_d}{\underline{H}_g}\right) \quad 10$$

2.2. Determination of Solar Potential

To optimize the of use solar energy, it is necessary to ascertain the capacity of the sun for solar energy. Solar radiation intensity at a specific location is defined as the quantity of solar energy received per unit area. This is influenced by the angle at which sunlight strikes an item, the atmospheric condition, and obstructions such as clouds or buildings. A region with a higher solar radiation intensity also has a larger solar energy potential. Several factors must be considered when calculating solar energy potential, including the quantity and duration of solar radiation, the environment, and the location. The potential for solar energy is also affected by the length of time exposed to sunshine. Regions with longer daylight hours or generally more sunny days may have greater solar energy potential. Seasonal fluctuations in daylight length should also be considered when assessing solar energy potential.

Geographical location is one of the most crucial elements in determining solar energy potential. Areas situated closer to the equator receive a greater quantity of direct sunlight throughout the year than those situated at a greater distance from the equator. This phenomenon enhances the potential for solar energy generation in these regions. The angle and orientation of solar panels with respect to the sun are also influenced by latitude, and this has an impact on the effectiveness of energy capture. Equation 11 provides the formula for calculating solar radiation from extraterrestrial sources [29], [31].

$$\underline{H}_0 = \frac{24H_{sc}}{\pi}\left(1 + 0.033\ cos\ cos\ \left(\frac{360n}{365}\right)\right)\left(cos\ cos\ \emptyset\ \ cos\ cos\ \delta\ \ sin\ sin\ \omega_s\ + \frac{\pi\omega_s}{180}\ sin\ sin\ \emptyset\ \ sin\ sin\ \delta\ \right) \quad 11$$

Here $\emptyset$ is the degree of latitude (north (+), south (+), -90<$\emptyset$<90), δ is the solar declination angle, ω_s is the solar hour angle and H_{sc} is the solar constant (1367 W/m²). The solar declination angle δ and the solar hour angle ω_s are calculated using Equation 12 and Equation 13, respectively [29], [31]

$$\delta = 23.45°\ sin\ sin\ \left[\frac{360(284+n)}{365}\right] \quad 12$$

$$cos\ cos\ \omega_s\ = -\ tan\ tan\ \emptyset\ \ tan\ tan\ \delta \quad 13$$

2.3. Monthly Average Solar Radiation Incident on A Given Area in The Horizontal Plane

(Klein, 1977) simplified the calculation of $\underline{H}_0$ in Equation 11 by defining for each month a typical day when the daily extraterrestrial solar radiation value is extremely close to the monthly average value. The monthly average solar radiation (H) incident on a given area on a horizontal plane can be determined by Equation 14.

$$\frac{H}{H_0} = \left(a + b\,\frac{n}{N}\right) \quad 14$$

Here, a and b are region-dependent constants, and $\frac{n}{N}$ is the relative insolation time (insolation time/day length). The region-dependent constants a and b in Equation 14 are given in Equation 15 and Equation 16 below for Turkey, depending on the latitude angle (υ), declination angle (δ) and location height (Z) in meters above sea level ([31], [32]).

$$a = 0.103 + 0.000017Z + 0.198\ cos\ cos\ (\varphi - \delta) \quad 15$$

$$(\varphi - \delta) \quad 16$$

Conditions associated with climate, like humidity, cloud cover, and air pollution, have an impact on the amount of solar energy that is accessible. In locations with poor sky conditions, solar energy potential may be lower than in areas with clear skies. It is therefore necessary to comprehend local climate trends in order to make an appropriate assessment of solar energy potential. Based on the clarity index (CT), Equation 17 can be used to calculate the ratio of daily horizontal plane diffuse radiation to total radiation [31], [32].

$$\frac{H_d}{H} = 0.173 - 0.414K_T - 0.428{K_T}^2 \quad 17$$

Based on the relative insolation time and clarity index of Equation 18, the equation calculates the monthly average daily solar radiation to the horizontal unit plane on Earth.

$$K_T = \frac{H}{H_0} \quad 18$$

Several variables, such as solar radiation intensity, sunlight duration, geographic location, climate, and technical infrastructure, should be considered when estimating solar energy potential. By carefully weighing these variables, stakeholders may identify the best sites for solar projects and maximize the efficient use of this renewable resource.

2.4. Average Daily Total Radiation Falling on The Sloping Surface

On the inclined plane, there is a difference between the dawn angle of the incident radiation and the first-hour angle of first fall (ω_s) Equation 19 yields the-first hour angle of first fall (ω_s) The equation's usage of the word "min" designates that the smaller of these two integers will be chosen [29], [32].

$$\omega_s' = min[(- tan\, tan\, \varphi \;\; tan\, tan\, \delta\,) \;\; (- tan\, tan\, (\varphi - \beta) \;\; tan\, tan\, \delta\,) \;] \quad 19$$

The average daily total radiation falling on the sloped surface is found using equation 20. Rb is defined as the ratio of daily direct radiation (H_b) falling on the horizontal surface to daily direct radiation (H_{bT}) falling on the inclined surface. Equation 21 establishes it for the northern hemisphere's south-facing surface (γ=0°) [31], [32].

$$H_T = H\left(1 - \frac{H_d}{H}\right)\underline{R_b} + H_d\left(\frac{1+coscos\,\beta}{2}\right) + H\rho\left(\frac{1-coscos\,\beta}{2}\right) \quad 20$$

$$\underline{R_b} = \frac{coscos\,(\varphi-\beta)\; coscos\,\delta\; sinsin\,\omega_s' + \left(\frac{\pi}{180}\right)\omega_s' sinsin\,(\varphi-\beta)\; sinsin\,\delta}{coscos\,\varphi\; coscos\,\delta\; sinsin\,\omega_s + \left(\frac{\pi}{180}\right)\omega_s sinsin\,\varphi\; sinsin\,\delta} \quad 21$$

2.5. Study Area and Data

Turkey was selected as the research site for this study to evaluate the potential for solar energy. Turkey is located between the 26°–45° east meridians and the 36°–42° north parallels. For each coordinate between the 26°–45° east meridians and the 36°–42° north parallel, NASA has supplied solar energy data. For each coordinate, the exergy potential of solar energy was calculated using the formulas presented in the initial section of this website. The resulting exergy potential was then visualized using IDW (inverse distance weighting) interpolation.

2.6. IDW Interpolation Method

The fields of geographic information systems (GIS) and geology are two contexts in which IDW is applied. It is commonly used to depict point data on a regular surface or to fill in missing data. The interpolation of point data to create a map is a typical use case for IDW. Using this method, a point's value is determined by weighing it based on the separation between known points. IDW's fundamental principle is that a point's estimated value is calculated by inversely weighting its distances to known points. This means that points that are closer together weigh more than points that are further away. The value of a point should ideally be determined by weights proportional to the distances to that location. The mathematical model of IDW interpolation is given in Equation 22 [33],[34].

$$Z(x,y) = \frac{\sum_{i=1}^{n} \frac{Z_i}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \tag{22}$$

Here, $Z(x,y)$, is the value of the point with the estimated value, Z_i is the value of one of the known points, and d_i is the distance of the known points to the target point p is the weighting factor (usually taken as 2 or 3).

Among the benefits of IDW are the following:

- It is fast and easy.
- Non-linear relationships are modeled by it.
- Since it is based on point data, it can work with irregular or incomplete data.

However, IDW has several disadvantages.

- It requires a homogeneous distribution of known points to work properly.
- When data from close points is weighted too heavily compared to data from other points, it can lead to the problem of overscoring.
- If the weighting factor is not chosen correctly, the results can be negatively affected.

3. RESULTS AND DISCUSSION

This study calculates the solar exergy potential of Turkey for both the horizontal plane and five specific tilt angles (21°, 30°, 39°, 48°, and 57°). These angles were selected to cover a broad range of possible panel orientations, reflecting both practical and theoretical considerations for optimizing solar energy capture. Previous studies have indicated varying efficiency gains at different tilt angles, and the study aims to identify the most effective angle for maximizing exergy potential. Calculations were made using 22-year average solar energy potential data obtained from NASA, ensuring a robust and comprehensive analysis.

The exergy potentials of Turkey in the horizontal plane and five different tilt angles (21, 30, 39, 48, and 57) were calculated, and seasonal maps were created. For Turkey, the winter season is considered December, January, and February; the spring season is March, April, and May; the summer season is June, July, and August; and the autumn season is September, October, and November, respectively.

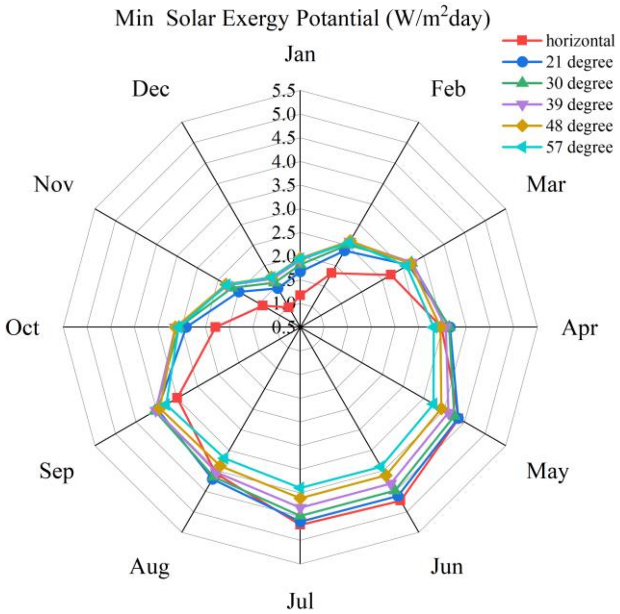

Figure 1. Minimum solar exergy potential of different tilt angles for each month

Figure 1 shows the variation of the average lowest solar exergy potential for different inclination angles according to the months. In Figure 1, it is seen that the lowest solar exergy potential in the winter months is seen on the horizontal plane with 1.324 W/m²day and the highest with 2.094 W/m²day on the surface inclined at 48°. In the spring months, the lowest solar exergy potential is 3.381 W/m²day with a 57° inclined plane, and the highest solar exergy potential is 3.711 W/m²day with a 21° inclined surface. In summer, the lowest solar exergy potential was 3.383 W/m²day at a 57° inclined plane, and the highest solar exergy potential was 4.490 W/m²day at a horizontal surface. In autumn, the lowest solar exergy potential was 2.400 W/m²day on the horizontal plane, and the highest solar exergy potential was 3.141 W/m²day on the surface inclined at 39°.

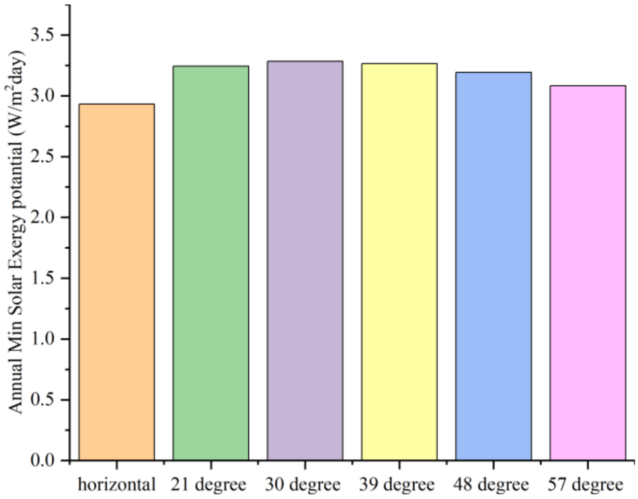

Figure 2. Average minimum annual solar energy potential of different tilt angles

Figure 2 shows the annual average minimum solar exergy potential for different tilt angles. Although the highest and lowest exergy potentials are observed at different inclination angles (Figure 1), when the annual average solar exergy potential is considered (Figure 2), it is determined that the highest potential is on 30° inclined surfaces (3.283 W/m²day) and the lowest potential is on horizontal planes (2.932 W/m²day).

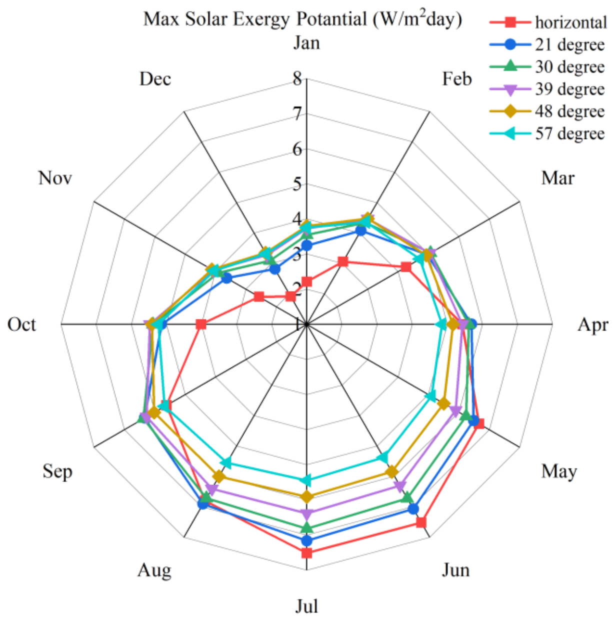

Figure 3. Maximum solar exergy potential of different tilt angles for each month

The average maximum solar energy potential fluctuation per month for various inclinations is displayed in Figure 3. Figure 3 shows that the solar energy potential is highest on the surface inclined at 48°, with 3.871 W/m²day, and lowest on the horizontal plane, at 2.396 W/m²day. During the spring season, the solar energy potential ranged from 4.888 W/m²day on a 57° inclined plane to 5.713 W/m²day on a 21° inclined surface. During summer, the solar energy potential ranged from 5.460 W/m²day at a 57° inclined plane to 7.281 W/m²day at a flat surface. Autumn solar exergy potentials were as low as 4.064 W/m²day on the horizontal plane and as high as 5.272 W/m²day on the 39-° inclined surface.

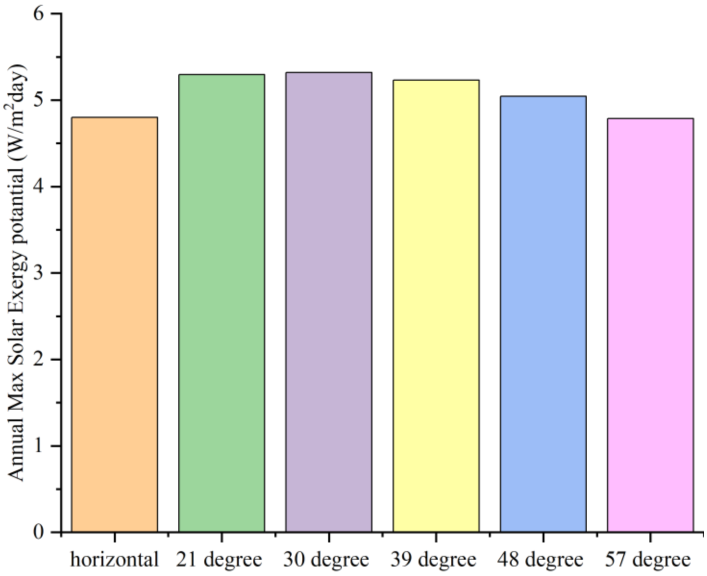

Figure 4. Average maximum annual solar energy potential of different tilt angles

The yearly average maximum solar energy potential for various tilt degrees is displayed in Figure 4. The annual average solar exergy potential (Figure 4) shows that, despite the highest and lowest exergy potentials being observed at different inclination angles (Figure 3), the highest potential is at 30° inclined surfaces (5.319 W/m²day) and the lowest potential is at 57° inclined planes (4.785 W/m²day).

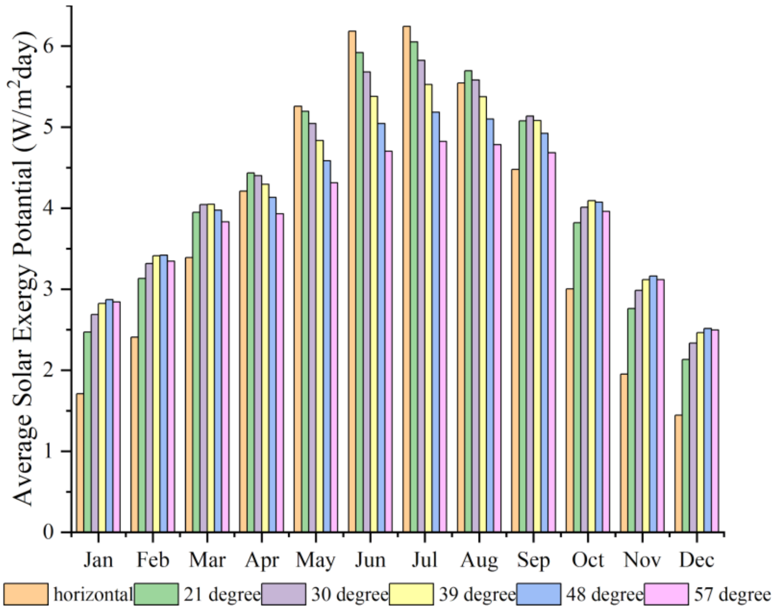

Figure 5. Average solar exergy potential of different tilt angles for each month

The average solar energy potential variation according to month for various inclination degrees is depicted in Figure 5. Figure 5 shows that during the winter, the solar energy potential is lowest on the horizontal plane (1.855 W/m²day) and maximum on the surface inclined at 48° (2.936 W/m²day). During the spring season, the solar energy potential ranged from 4.026 W/m²day on a 57° inclined plane to 4.527 W/m²day on a 21° inclined surface. During the summer, the solar energy potential ranged from 4.771 W/m²day at a 57° inclined plane to 5.990 W/m²day at a horizontal surface. During the fall season, the solar exergy potential reached its maximum on an inclined surface at 39° and its lowest on a level plane at 3.145 W/m²day.

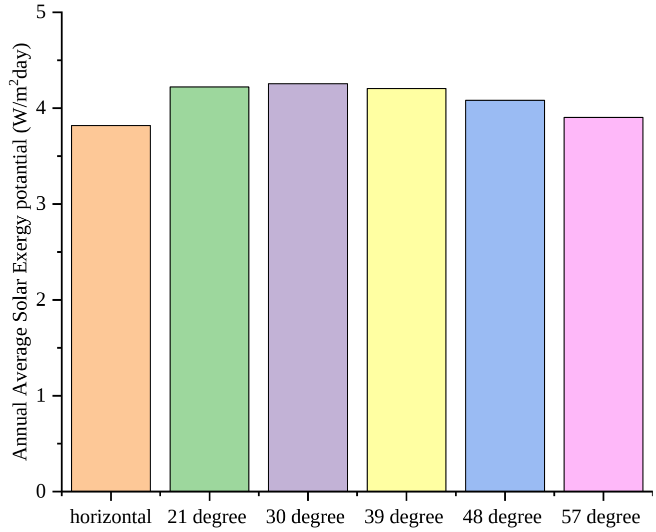

Figure 6. Average annual solar energy potential of different tilt angles

Figure 6 shows the annual average solar exergy potential for different tilt angles. Although the highest and lowest exergy potentials are observed at different inclination angles (Figure 5), when the annual average solar exergy potential is considered (Figure 6), it is determined that the highest potential is on 30° inclined surfaces (4.255 W/m²day) and the lowest potential is on horizontal planes (3.819 W/m²day).

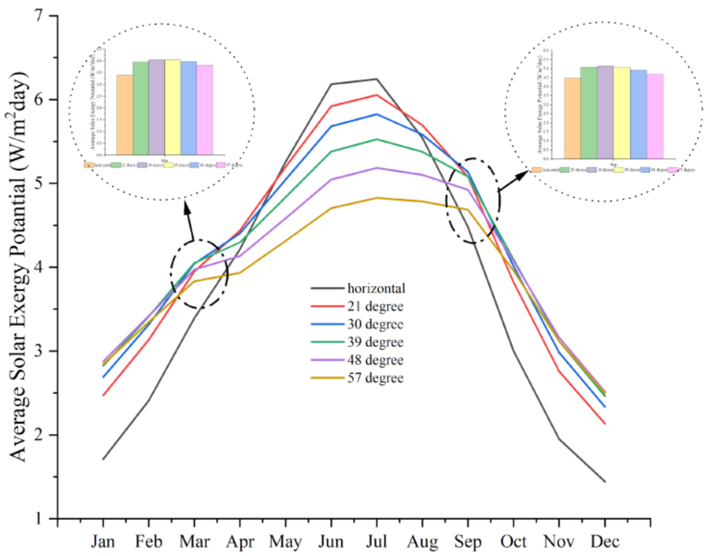

Figure 7. Detailed representation of the average solar energy potential of different tilt angles for the equinox

The equinoxes are two special days when the angle between the plane of the Earth's ecliptic and the plane of the equator is zero. Due to the Earth's axis tilt, the angle of its orbit around the sun changes according to the seasons. On the days of the equinoxes, the Earth's obliquity to the sun is at its minimum, and the sun's rays come at a right angle to the equator. On these days, the duration of day and night is approximately equal. The equinox periods are called the vernal equinox (in March) and the autumnal equinox (in September). At these times, the angle at which the sun's rays fall changes depending on the position of the Earth in its orbit around the sun. Equinox days are the times when this change is most pronounced. Figure 7 shows the average solar energy potential of different inclination angles for the equinox in detail. Considering the equinox days, it is observed that the solar exergy potential decreases approximately with the increase in the inclination angle after March, which includes the spring equinox, while the solar exergy potential increases approximately with the increase in the inclination angle after September, which includes the autumn equinox. It was found that the effect of tilt angle on solar exergy potential in the equinox months is less compared to other months.

Between Figures 8 and 11, the four-season solar exergy potential of the 30° sloping surfaces that provide the highest solar exergy potential is given in the form of a map. The color scales in the figures are arranged separately for each season to reveal the differences according to the regions more clearly. In the maps, the change of the exergy potential from low to high is colored from blue to red.

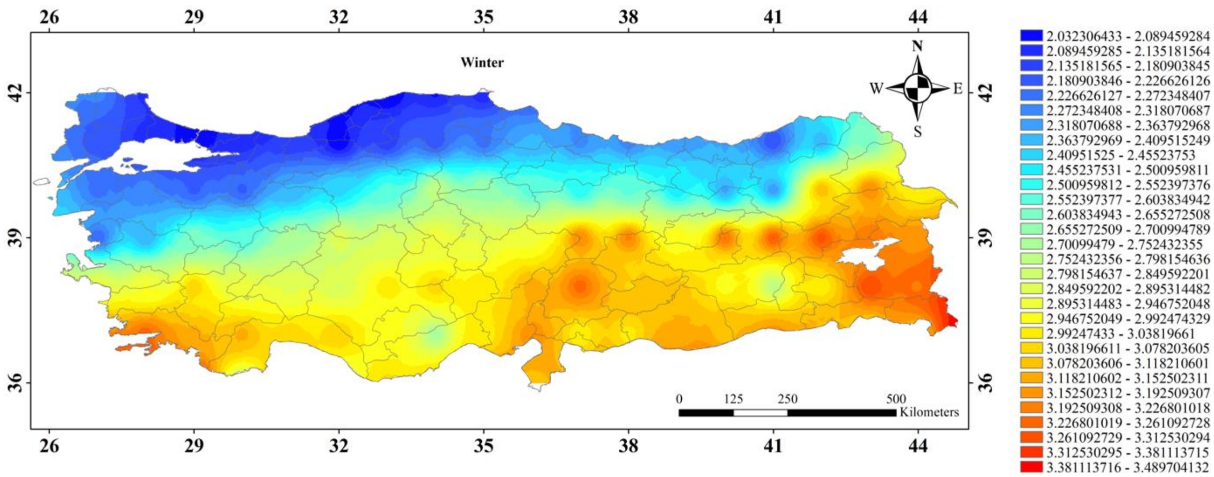

Figure 8. Solar exergy potential in winter for 30° inclined surfaces

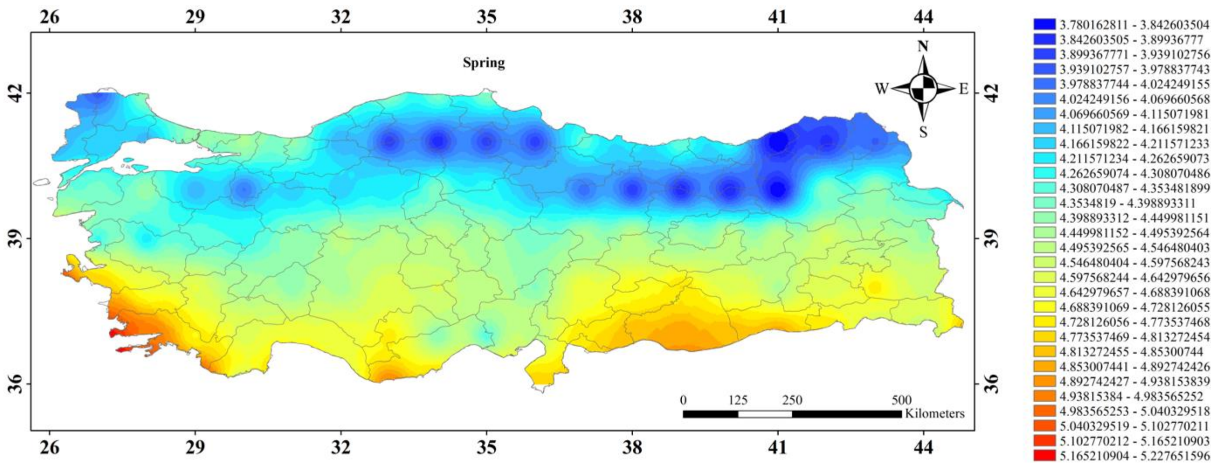

Figure 9. Solar exergy potential in spring for 30° inclined surfaces

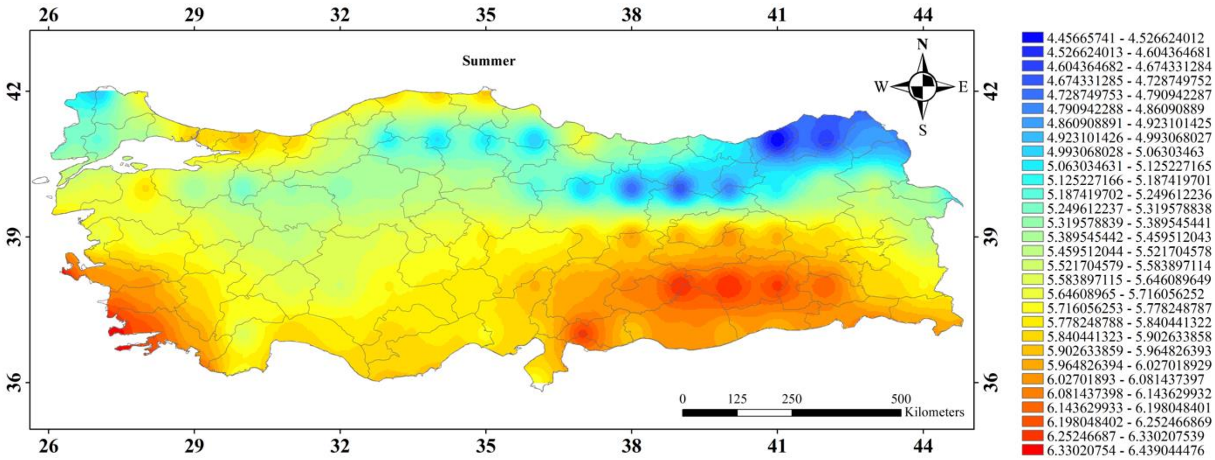

Figure 10. Solar exergy potential in summer for 30° inclined surfaces

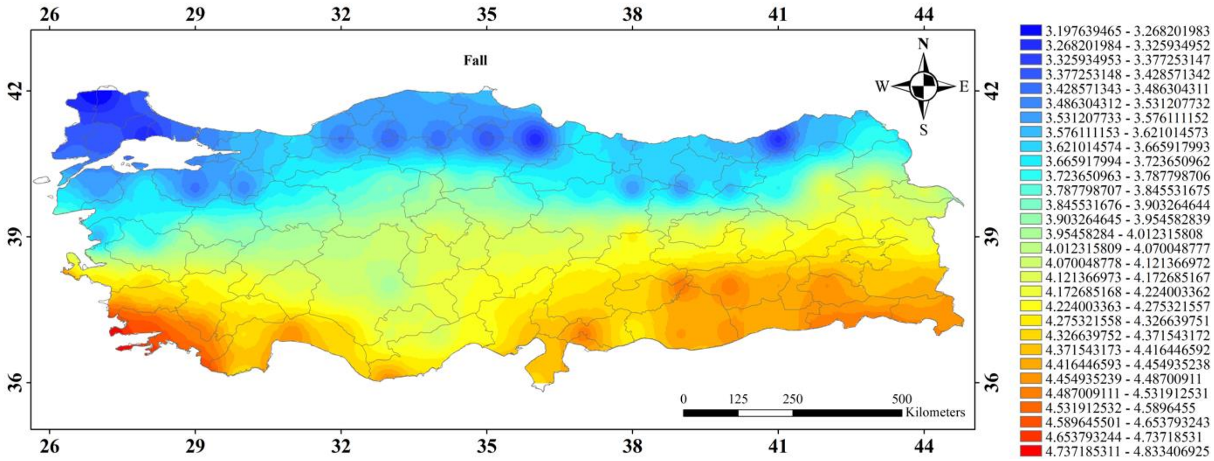

Figure 11. Solar exergy potential in autumn for 30° inclined surfaces

The findings of the study showed that the 30° slope angle provided the highest value for the annual average exergy potential (4.255 W/m²/day). This value is 10% higher than the potential of horizontal surfaces. Furthermore, the seasonal performance of the different tilt angles was also analyzed. For example, it was found that the 48° slope angle provided the highest exergy potential in winter (2.936 W/m²/day), while in summer, the horizontal surfaces provided the highest potential (5.990 W/m²/day).

The study was compared with previous studies in terms of data source, methodology, results and innovative approaches, and common and different aspects were revealed. In the comparisons, firstly the studies conducted for the cities of Turkey and then similar studies conducted for different countries and cities were taken into consideration. A comparison chart is given in Table 1.

Table 1. Comparison with previous studies

Name of the Study	Bibliography	Working area	Tilt Angles	Data Source	Methodology of the Study	Results of the Study	Innovative Approaches of the Study
Solar Energy Potential Assessment for Karabük, Turkey	[6]	Karabük	Various (e.g., optimal monthly, seasonal)	Solar energy potential data from local meteorological stations	AHP, GIS-based analysis	Identification of optimal locations for solar energy plants	Use of AHP and GIS for optimal site selection, focus on local conditions
Solar Energy Potential Evaluation in Gaziantep, Turkey	[7]	Gaziantep	Various (monthly, seasonal)	Solar energy data from local sources, NASA data	AHP analysis	Evaluation of solar energy potential using AHP methodology	AHP methodology to evaluate regional solar potential
Solar Energy Potential in Kars, Turkey	[8]	Kars	Various (seasonal)	Local solar radiation data and GIS analysis tools	AHP, GIS-based analysis	Identification of potential areas for solar power plants	Combining AHP and GIS for detailed spatial analysis
Solar Energy Potential and Optimal Tilt Angles in Istanbul, Turkey	[21]	Istanbul	Monthly, seasonal, annual	Solar irradiance data from local meteorological stations, NASA data	Experimental analysis, tilt angle optimization	Optimal monthly and seasonal tilt angles identified	Focus on experimental validation of tilt angle optimization
Solar Energy Potential and Optimal Site Selection in Nevşehir, Turkey	[9]	Nevşehir	Various (annual)	Solar energy potential data from local sources and meteorological stations	AHP-VIKOR hybrid method	Identification of optimal sites for solar power plants using AHP-VIKOR	Use of hybrid AHP-VIKOR method for comprehensive site selection analysis
Estimating the Optimum Tilt Angles for South-Facing Surfaces in Palestine	[35]	Palestine	Various (e.g., optimal monthly, seasonal, semi-annual, annual)	PVGIS, PVWatts, mathematical models	Mathematical models, software tools (PVGIS, PVWatts)	Monthly adjustments yield 17% more energy, yearly optimal tilt angle around 29°	Use of PVGIS and PVWatts tools, focus on efficiency gains from tilt adjustments
Solar irradiance estimation models and optimum tilt angles	[36]	General studies	Various	Mathematical models	Mathematical models	Optimal tilt angles identified for various conditions	Use of various mathematical models for irradiance estimation
Assessment of potential solar energy with the models for optimum tilt angles	[37]	General studies	Various	Mathematical models	Mathematical models	Potential energy gains with optimal tilt angles	Comprehensive model-based analysis of solar potential
Estimation of ideal tilt angle for solar-PV panel surfaces facing south	[38]	General studies	Various	Mathematical models	Mathematical models	Ideal tilt angles significantly improve energy capture	Focus on ideal tilt angles for maximum energy capture

In this study, the whole of Turkey was selected as the study area and the optimum tilt angle was tried to be determined by Interpolation method (IDW) and exergy analysis methods considering NASA 22-year average solar energy data for horizontal, 21°, 30°, 39°, 48°, 57° angles. Detailed seasonal exergy potential maps were created and IDW interpolation was used for missing data regions. The findings of our study show the reliability and accuracy of our method and the data used when compared with similar studies conducted in provinces such as Karabük, Gaziantep and Kars. For example, studies conducted in Karabük evaluated the benefits and challenges of local solar energy applications [6]. In another study conducted in Gaziantep, solar energy potential was evaluated using the Analytic Hierarchy Process (AHP) method [7]. Similarly, potential areas for solar power plants in Kars province were identified using AHP methodology and GIS analyses [8]. This comparison shows that our study is compatible with other studies and the methodology used gives reliable results. While the Karabük study focussed on the evaluation of local applications, the Gaziantep study made a potential assessment with the AHP method. The Kars study identified potential areas with AHP and GIS analyses. In this study, NASA's long-term data and IDW interpolation method provide a comprehensive analysis across Turkey by making accurate predictions even in missing data regions.

In this study, NASA's 22-year average solar energy data were used. Other studies used data obtained from PVGIS, PVWatts, local meteorological stations and various meteorological sources. While IDW interpolation method and exergy analysis were used in this study, other studies used mathematical models, optimisation techniques and efficiency analyses. In this study, it is stated that the optimum tilt angle is 30° throughout the year and seasonal maps are provided. Other studies have presented results on how seasonal and annual adjustments can improve energy efficiency. This study presented detailed seasonal exergy potential maps using the IDW interpolation method to make accurate predictions in missing data regions. Other studies have utilised tools such as PVGIS and PVWatts, and have presented detailed seasonal exergy potential maps based on climatic conditions.

These findings are an important guide for solar energy investments in Turkey and will contribute to increasing energy efficiency and reducing energy costs by determining optimal tilt angles for the design and layout of solar collectors.

4. CONCLUSIONS

The aim of this study is to determine the solar energy exergy potential for different tilt angles in different regions of Turkey and to determine the most suitable panel tilt angles. In this context, NASA's 22 years of solar energy data were used to accurately determine the solar energy potential of Turkey. The IDW interpolation method is preferred for estimating the exergy potential in regions with data deficiency, which provides advantages in terms of cost and time. In this study, to utilize solar energy more, the exergy potential incident on the horizontal surface was calculated, and the effect of the panel tilt angle on the exergy potential was investigated. The average solar exergy potential varies according to months and seasons at different tilt angles. The results obtained in the study are as follows:

- Considering the annual average solar exergy potential, it was determined that the highest potential for the horizontal, 21° inclination, 30° inclination, 39° inclination, 48° inclination, and 57° inclined surfaces was found to be on the 30° inclined surface.
- Solar exergy potential was found to be less in January, February, March, October, November, and December and more in April, May, June, July, August, and September compared to the year average.
- In January, February, November, and December, as the slope angle increases, it is observed that the solar exergy potential increases up to a 48° slope and decreases at higher slope angles.
- In the months of May, June, and July, it was determined that the solar exergy potential decreases as the slope angle increases.
- As the slope angle increases in March and October, it is observed that the solar exergy potential increases up to 39° slope and decreases at higher slope angles.

- As the slope angle increases in April and August, it is observed that the solar exergy potential increases up to a 21° slope and decreases at higher slope angles.
- In September, as the inclination angle increases, it is observed that the solar exergy potential increases up to 30° inclination and decreases at higher inclination angles.

These results provide an important guide for solar energy investments in Turkey. By determining the optimal tilt angles for the design and layout of solar collectors, energy efficiency can be increased, and energy costs can be reduced. Future research in this area may benefit from the application of additional machine learning techniques to more accurately determine the exergy potential outside of the measurement locations, considering the assessments conducted. Furthermore, the solar energy exergy potential map may be updated using software that integrates newly measured data, which undergoes annual changes.

The solar maps developed in this study are thought to provide information on total solar radiation levels that can be used as a database for future investments in the solar energy sector in Turkey. The results of this study can be used as a guide for solar panel manufacturers and installation companies for exergy potential-based evaluation methods, unlike the method that allows investment decisions to be made based only on the energy potential of the sun.

Declaration of Ethical Standards

Authors declare to comply with all ethical guidelines including authorship, citation, data reporting, and publishing original research.

Credit Authorship Contribution Statement

AUTHOR-1: Methodology, Conceptualization, Supervision.

AUTHOR-2: Resources, Investigation, Writing -review & editing,

AUTHOR-3: Methodology, Conceptualization, Resources, Investigation, Writing -review & editing,

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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