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Impact of tilt angle on the performance of the photovoltaic systems for different row spacing

Farklı dizi aralığında eğim açısının fotovoltaik sistemlerin performansına etkisi

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Impact of Tilt Angle on The Performance of The Photovoltaic Systems for Different Row Spacing

Highlights

- *Optimum tilt angles for various PV panel row spacing for a fixed area*
- *Performance analysis of eight different instillation cases*
- *Comparison of the energy production for fixed and optimum tilt angles*
- *The 3 m panel row spacing at an optimum tilt angle of 21° was found to be the most feasible case*
- *The maximum IRR and ROI were obtained as 20.42% and 91.57%*

Graphical Abstract

Different photovoltaic instillation cases were investigated using fixed tilt angles of 35°, and optimum tilt angles of 1°, 15°, 21° and 28° for four different panel spacing as 2 m, 2.5 m, 3 m, and 4 m. Electricity production performance and economic analysis studies were conducted within the scope of the study.

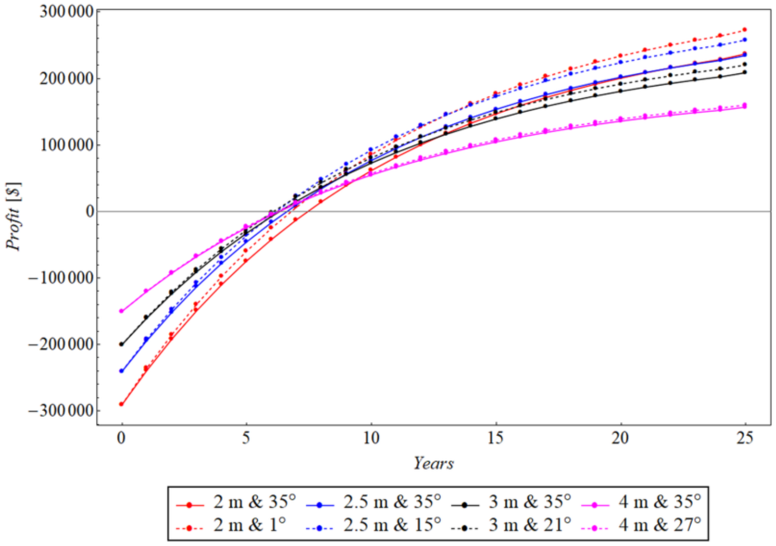

Figure. The NPV of projects at different photovoltaic instillation cases by year

Aim

It is aimed to examine the performance values and economic feasibility of photovoltaic systems using various panel row spacing and tilt angles for a constant application area.

Design & Methodology

PVsyst software was used within the scope of the study for a PV system in Konya, Turkey.

Originality

Studies examining panel row spacing with optimum tilt angles in fixed areas are very restricted in the literature. In Turkey, this study was conducted for the first time.

Findings

Various tilt angles and panel spacings were examined in terms of effective solar radiation, Electricity production, and performance ratio values. Furthermore, economic analyses were done by the basic payback, Net present value, and Internal Rate of return methods.

Conclusion

It is concluded that the PV system with a 3 m panel row spacing and tilt angle of 21° is the most proper one.

Declaration of Ethical Standards

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

Impact of Tilt Angle on The Performance of The Photovoltaic Systems for Different Row Spacing

Araştırma Makalesi / Research Article

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ABSTRACT

The optimum tilt angle for a photovoltaic (PV) system depends on the row spacing because it affects the amount of shading on the panels. This study modeled PV systems for four different panel row spacings of 2 m, 2.5 m, 3 m, and 4 m in a fixed 3000 m² area in Konya province, Turkey. For different panel row spacings, the system performances were compared using a constant tilt angle of 35°, expressed as a proper angle for PV installations at the considered location. In addition, the optimum tilt angle is found for four different cases in terms of electricity generation. In systems with 35° tilt angles at electricity were produced annually as 622.77 MWh, 566.49 MWh, 495.36 MWh, and 385.72 MWh, respectively, for panel row spacings of 2 m, 2.5 m, 3 m, and 4 m. In addition, these electricity productions are 6.19%, 4.41%, 2.56%, and 0.92% higher with optimum tilt angles as 1°, 15°, 21° and 27°. Similarly, the Performance Ratio (PR) values obtained with the optimum angles are 20.61%, 8.39%, 4.12%, and 1.44%, higher than the fixed tilt angle cases. According to the economic analysis, systems with a fixed tilt angle for these panel row spacings pay back themselves in 5.13, 4.67, 4.44, and 4.28 years, respectively, while systems at optimum angles pay back themselves in a shorter time by 5.83%, 4.26%, 2.49%, and 0.91%. Furthermore, the highest NPV/*INV*, IRR, and ROI values were obtained from the system with 3 m panel row spacing with the optimum tilt angle of 21° as 0.915, 20.42%, and 91.57%, respectively, which is techno economically found to be the most feasible case.

Keywords: economic analysis, photovoltaic panel, panel row spacing, shading losses, tilt angle.

Farklı Dizi Aralığında Eğim Açısının Fotovoltaik Sistemlerin Performansına Etkisi

ÖZET

Bir fotovoltaik (PV) sistem için optimum eğim açısı, panellerin üzerine gelen gölgeleme miktarını etkilediği için dizi aralığına bağlıdır. Bu çalışma, Konya ilinde 3000 m² sabit bir alanda 2 m, 2.5 m, 3 m ve 4 m olan dört farklı panel dizisi aralığı için PV sistemlerini modellemiştir. Farklı dizi aralıkları için sistem performansları, konumdaki PV kurulumları için uygun bir açı olarak ifade edilen 35° sabit bir eğim açısı kullanılarak karşılaştırılmıştır. Ayrıca elektrik üretimi açısından dört farklı durum için optimum eğim açısı bulunmuştur. 35° eğim açısına ve 2 m, 2.5 m, 3 m ve 4 m panel dizisi aralığı sahip sistemlerde yılda sırasıyla 622.77 MWh, 566,49 MWh, 495.36 MWh ve 385,72 MWh elektrik enerjisi üretilmiştir. Bunun yanında optimum eğim açıları olan 1°, 15°, 21° ve 27° durumlarında elektrik üretim değerleri %6.19, %4.41, %2.56 ve %0.92 daha fazladır. Benzer şekilde, optimum açılarla elde edilen Performans Oranı (PR) değerleri, sabit eğim açısı durumlarından %20.61, %8.39, %4.12 ve %1.44 daha yüksektir. Ekonomik analize göre, bu panel sıra aralıkları için sabit eğim açısına sahip sistemler sırasıyla 5.127, 4.67, 4.44 ve 4.28 yılda kendini amorti ederken, optimum açılara sahip sistemlerde ise %5.83, %4.26 %2.49, ve %0.91 daha kısa sürede amorti etmektedir. Ayrıca, en yüksek *NPV/INV*, IRR ve ROI değerleri, sırasıyla 0.915, %20.42 ve %91.57 değerleri ile 3 m panel dizi aralığına ve 21° eğim açısı sahip sistemden elde edildi ve bu sistem tekno-ekonomik olarak en uygun sistem bulunmuştur.

Anahtar Kelimeler: Ekonomik analiz, gölgeleme kaybı, panel dizi aralığı, fotovoltaik sistem, eğim açısı.

INTRODUCTION

Turkey has been experiencing significant economic growth, leading to an increase in energy demand. According to the latest data, Turkey's electricity consumption rose 8.7% in 2021 compared to the previous year [1]. In response, Turkey has been steadily increasing its energy production, focusing on renewable energy sources to meet the growing demand. As part of its target, the country has been increasing the proportion of renewable energy sources in its electricity installations [2]. Turkey also invests in energy efficiency measures to decrease energy consumption [3,4]. Since 2014, Turkey has prioritized adopting renewable energy sources, particularly solar and wind energy [5,6]. Table 1 overviews Turkey's energy output and the percentage of renewable energy sources used yearly. As seen renewable and solar energy shares are regularly increasing.

Solar energy is an increasingly popular renewable energy source, and photovoltaic (PV) cells are crucial in harnessing it. PV cells are used in various applications, including residential and commercial solar panel installations and large-scale solar power plants that

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supply electricity to the grid [9]. As indicated by Table 1, Turkey started generating electricity from PV systems relatively late, with a power output of 40.2 MW in 2014. However, the country has made significant progress since then, with an installed power output of 9425.4 MW in 2022, representing an increase of 23346%. This remarkable growth has enabled Turkey to surpass many European countries, ranking 7th in installed power as of 2021 [10]. Furthermore, Turkey has made significant progress in PV technology on a global scale, as shown in

Table 1. Installed renewable energy systems in Turkey by years [1,7,8].

Years	Hydro [MW]	Geothermal [MW]	Wind [MW]	Solar [MW]	Biomass [MW]	Total installed capacity [MW]	Renewable Share [%]	Solar Share [%]
2013	22289.0	310.8	2759.7	-	178.0	64007.5	39.9	-
2014	23643.2	404.9	3629.7	40.2	227.0	69519.8	40.2	0.06
2015	25867.8	623.9	4503.2	248.8	277.1	73146.7	43.1	0.34
2016	26681.1	820.9	5751.3	832.5	363.8	78497.4	43.9	1.06
2017	27273.1	1063.7	6516.2	3420.7	477.4	85200.0	45.5	4.01
2018	28291.4	1282.5	7005.4	5062.8	621.9	88550.8	47.7	5.71
2019	28503.0	1514.7	7591.2	5995.2	791.3	91267.0	48.6	6.57
2020	30983.9	1613.2	8832.4	6667.4	1105.3	95890.6	51.3	6.95
2021	31492.6	1676.2	10607.0	7815.6	1644.5	99819.6	53.33	7.83
2022	31571.2	1691.3	11396.2	9425.4	1921.3	103809.3	53.95	9.08

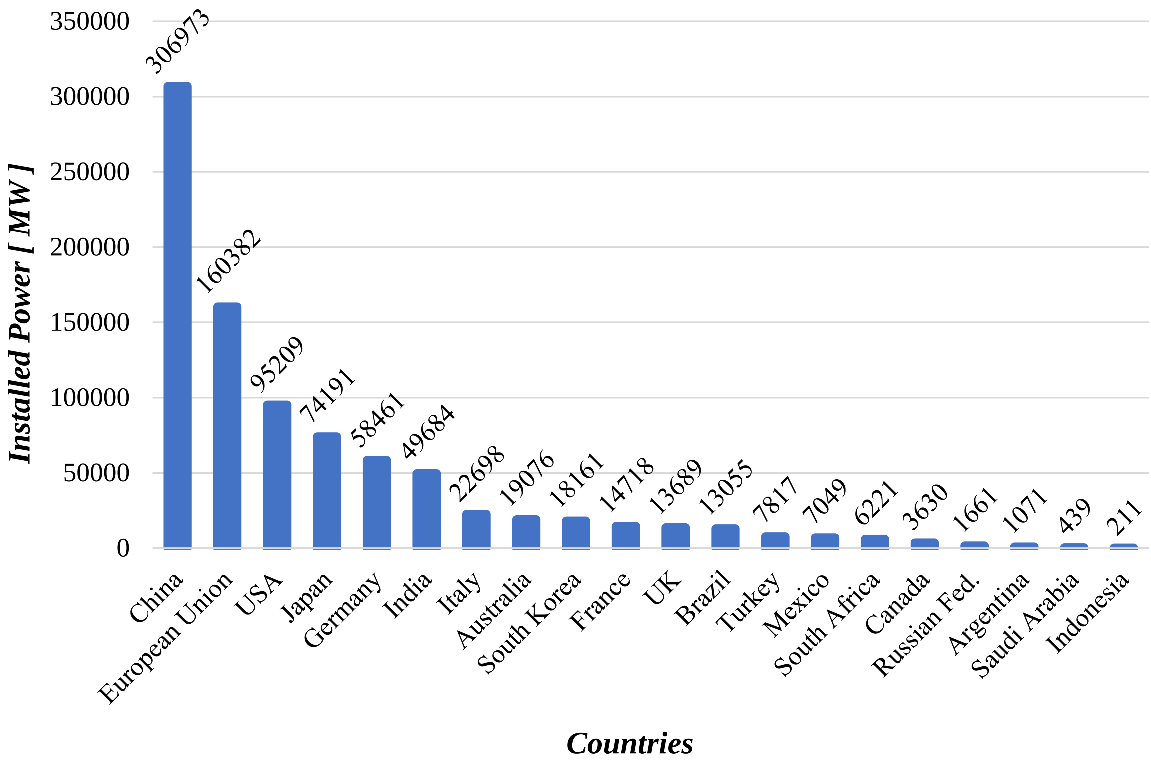

Figure 1. Installed solar capacity of G20 countries by 2021 [10,11)

Fig. 1, which depicts the solar energy installed power values of G20 countries in 2021.

The generation of electricity from PV cells and their performance are influenced by various parameters, including irradiation on the panel surface, sunshine duration, environmental factors, and the type of cell [12,13]. The location of the PV system significantly affects the amount of irradiation received from these parameters. Due to its geographical location, Turkey benefits from an annual irradiation of 3.6 kWh/m²day and an average of 7.2 hours/day of sunshine, which is higher than many European countries [14-16]. However, the amount of irradiation and sunshine duration varies within different regions of Turkey. The Central Anatolia region, mainly Konya province, has exceptional irradiation and sunshine hours, with approximately 1610 kWh/m² and 7.95 hours/day, respectively, as shown in Fig. 2 [17,18].

Shading is one of the most key facets that might decrease the effectiveness of PV systems in real-life situations. The quantity of electricity a solar panel produces can be dramatically reduced when even a small part of the panel is shaded. Therefore, designing PV systems with shade into account is crucial for reducing its impacts. Using solar tracking systems or tilting the panels can help to reduce shading effects and maximize the amount of sunlight that reaches the panels [19]. Keskin et al. [20] experimentally investigated the effects of shading on the PV system. The study considered the shading effect on a 30 kW installed PV system. An annual 307 kWh loss occurred, which corresponds to 0.66%.

Furthermore, they evaluated that this value would reach more significant depending on the system's lifetime. Alonso-García et al. [21] concluded that the PV system's current and power decreased with the shading percentage increase. They also saw that the shading of cells in the same string did not affect the maximum power point, but the losses increased significantly in the shading of different arrays. Further publications about shading effects can be found in the literature.

In recent years, there has been an increase in the use of software programs to model PV systems, with several options available. These include RETScreen, TRNSYS, HOMER, INSEL, PV F-Chart, PVsyst, NREL SAM, SolarDesignTool, SolarPro, PV DesignPro-G, and PV*SOL Expert [22]. The accuracy of these software programs is crucial in determining the performance and energy yield of PV systems. De Souza Silva et al. [23] conducted a study comparing experimental data with Pvsyst, HOMER, and PVSOL software to evaluate the accuracy of different software programs. The results indicated that PVsyst was the software with the most accurate results, with deviations of 1.02% in electricity production and a PR value of 84.1%. In contrast, the software HOMER had a deviation of -10.38% and a PR value of 90%, while PV*SOL had a deviation of 2.04% and a PR value of 87.91%. These findings emphasize the importance of selecting an accurate software program for PV system modeling to ensure reliable and accurate results.

The PVsyst software is used in this study due to its advantages, including orientation angles, comprehensive PV database, inverter and battery brands and models, serial and parallel directory selection, detailed irradiation, electricity generation and loss results, 3D modeling, shading, and economic analysis tools [24]. Some simulations can be found in the literature using PVsyst. For example, Aksoy et al. [25] modeled a bifacial PV system using PVsyst with various grounds, including white, sand, and asphalt in Konya. They found that bifacial systems in asphalt, white, and sand grounds can produce 3.5%, 15.9%, and 7.2% more electricity, respectively, compared to monofacial systems. In performance ratios, they achieved asphalt, white, and sand grounds 2.68%, 8.86%, and 4.55% higher values, respectively. In another study using PVsyst in Konya, the shading effects of a 100 kWp system were investigated using a fixed tilt angle of 33° with an azimuth angle of

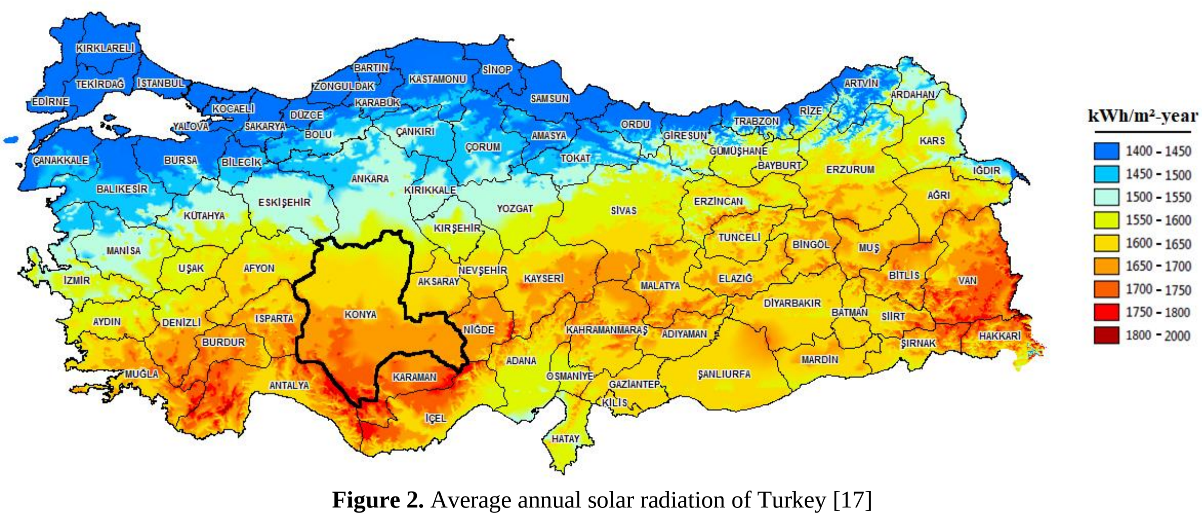

Figure 2. Average annual solar radiation of Turkey [17]

0°. In this context, two panel heights of 0.1 m and 1 m and panel row spacing of 4 m and 8 m were used. The highest electricity production was obtained from the 8 m panel row spacing system, with a value of 168.14 MWh. This value is 3.68% less than the system without shading losses [26]. Another study compared the performance and economic analysis of three different PV systems monocrystalline, polycrystalline, and amorphous silicon, with an installation power of 100 kWp using PVsyst. The study found that the monocrystalline system had a 1.91% and 3.07% higher annual electricity production value than the polycrystalline and amorphous silicon systems. In terms of economic analysis, the monocrystalline and polycrystalline systems had a payback period of about 6 years, while the amorphous silicon system took about 9 years to pay off [27]. In another study conducted for Konya, a 148 kWp PV system was modeled using PVsyst to evaluate its performance under different azimuth angles (-90°, 0°, 90°, and 180°) with a fixed tilt angle of 30°. The study also included an economic analysis. The results showed that the system with an azimuth angle of 0° achieved the highest effective irradiation, measuring 1964.4 kWh/m². This value was significantly greater (20.77%, 22.87%, and 73.48%, respectively) than the azimuth angles of -90°, +90°, and 180°. Additionally, the system's electricity production with an azimuth angle of 0° was 254.77 MWh, exhibiting a notable increase (19.66%, 22.55%, and 69.41%, respectively) compared to the other azimuth angles. The Basic Payback Periods for systems with azimuth angles of -90°, 0°, 90°, and 180° were determined as 4.88 years, 4.08 years, 5.00 years, and 6.92 years respectively [28]. The results of related studies using PVsyst are concluded in Table 2. The table provides a comprehensive comparison of PR from various studies. The table includes information on each study's installed power, cell type, location, and annual PR values. The installed power diversity ranges from 100 kWp to 1000 kWp. The location of each study also plays a significant role, as it affects the annual PR values. The results indicate variations in PR across different regions, such as Afghanistan, Morocco, United Arab Emirates, Turkey, and India. These differences could be attributed to variations in solar resources, climatic conditions, and environmental factors specific to each location. Comparing the present study with the other studies, it is evident that the PR values for the examined PV systems in Konya, Turkey, range from 0.694 to 0.843.

Table 2. The PR values of different studies using PVsyst

Author(s)	Installed power [kWp]	Cell Type	Location	Annual PR [-]
Baqir et al. [29]	700	Si-poly	Daykundi, Afghanistan	0.797
Kumar et al. [30]	100	Si-poly	N/A	0.800
Belmahdi et al. [31]	1000	Si-poly	Tetuan, Morocco	0.773
			Tangier, Morocco	0.778
			Larache, Morocco	0.776
			Al-hoceima, Morocco	0.781
Emziane et al. [32]	1325.3 – 1801.8	Si-mono Si-poly	Abu Dhabi, United Arab Emirates	0.700 – 0.081
Turan [33]	1000	Si-mono	Trakya, Turkey	0.818
Sharma et al. [34]	190	Si-poly	Khatkar-Kalan, India	0.740
Present Study	447 – 231	Si-poly	Konya, Turkey	0.694 – 0.843

This research examined the performance and economic aspects of PV systems with varying panel spacings on a fixed area. The primary objective was to generate electricity efficiently while maximizing economic feasibility. The distinctiveness and motivation of this study lie in exploring the economic and performance characteristics of different PV systems installed in fixed areas in Central Anatolia, with a particular focus on the Konya region. The research contributes to the knowledge gap in this area and sheds light on the region's most cost-effective and efficient PV system installations, offering practical insights to industry experts.

2. MATERIALS AND METHODS

This study simulated PV systems on a constant instillation land area of 3000 m² with 50 m and 60 m dimensions. The impacts of various tilt angles on the systems were investigated using four panel row spacings of 2 m, 2.5 m, 3 m, and 4 m. In these panel row spacing, the fixed tilt angle of 35° and the optimum tilt angle is obtained with the optimization tool of the PVsyst software, and results are compared. Panels of the CW Energy brand with model number CWT275 - 60P, each of which is 275 Wp, were used in the simulations. In a 3000 m² fixed area, used the number of modules, the installed power of the systems, and the optimum tilt angles determined with optimization are given in Table 3

Table 3. The optimum tilt angles and number of modules for different row spacing

Panel row spacing	Number of modules [-]	Installed power [kWh]	Optimum tilt angle
2 m	1624	447	1°
2.5 m	1344	370	15°
3 m	1120	308	21°
4 m	840	231	27°

Since a lower number of modules are used due to the increase in panel row spacing in a fixed area, the installed power of the systems decreases with the increase in panel row spacing. Therefore, one of the crucial parameters obtained with PVsyst is the Performance Ratio (PR). This value is calculated as the ratio of the generated electricity (E_G) to the multiplying the panel with unit power at STC and the amount of radiation on the surface as given in Eq. (1).

$$PR = \frac{E_G}{I_G \times P_{PV}} \tag{1}$$

Where, P_{PV} is the installed power of the system. Solar radiation reaching the Earth can be calculated mathematically monthly or daily. Daily solar radiation can be calculated as follows.

$$H_0 = \frac{24 \times 3600 G_{SC}}{\pi} \times \left[1 + 0.033 cos\left(\frac{360n}{365}\right) \times cos\varphi cos\delta cos\omega_s + \frac{2\pi\omega_s}{360} sin\varphi sin\delta\right] \tag{2}$$

The abovementioned formula comprises variables such as n, φ, δ, and ω_s, where n represents the number of days starting from January 1st. Additionally, φ indicates the latitude angle of the location where the solar panel system is intended to be installed, while δ and ω_s denote the declination angle and sunset time angle for the mean day of the month, respectively. In order to evaluate these variables, the following formulas can be used to calculate the declination and sunset time angles

$$\omega = 15(ST - 12) \tag{3}$$

$$\delta = 23.45\, sin\left(360\frac{284 + n}{365}\right) \tag{4}$$

In equation (3), ST denotes the local time in hours and is equivalent to 12 at midday, a crucial methodology component. Regarding the PVsyst algorithm, the transposition method used to calculate the radiation amount reaching the inclined plane from horizontal radiation data is executed using the provided positional values. Specifically, the Perez model was employed as the transposition method within the PVsyst software, with simulations utilizing this model demonstrating a commendable level of accuracy, with an error rate of only 2% when compared to experimental values [35]. The Meteonorm 8.0 tool, available in PVsyst software, was employed to determine the location. Alternatively, NASA data can be utilized within PVsyst to achieve the same purpose.

Economic analysis of the energy conversion systems is essential, as well as performance analysis. There are many parameters in the economic analysis of the PV systems, such as material supply, production, transportation, and operation. In addition, after the installation of the system, the monitoring of meteorological events such as clouding, dusting, rain, and snow should be well calculated [36].

In economic analysis, the Basic Payback Period (BPB) is a commonly used financial tool to evaluate the risk and return of an investment. It calculates the time required for the investment to recoup its initial cost, which is determined by dividing the investment amount by the annual net income, as shown in Eq. (5) [37].

$$BPB = \frac{INV - SV}{net\ annual\ income} \tag{5}$$

In the Equation, *INV* is the initial investment cost, and *SV* is the salvage value. In financial analysis, the Net Present Value (NPV) is a crucial concept used to evaluate the profitability of a project or investment, considering the current value of expected cash inflows and outflows while considering inflation. The NPV is expressed in Eq. (6) [37, 38].

$$NPV = \sum_{0}^{n} \frac{I_n - M_n}{(1 + i)^n} \tag{6}$$

Where, M_n is the n^{th} year expenses, I_n is the n^{th} year income, and i is the discount rate. Another crucial parameter used in economic evaluation is the Internal Rate of Return (IRR). This method aims to find the discount rate that makes the NPV zero, as given in Eq. (7) [37].

$$\sum_{0}^{n} \frac{I_n}{(1 + i)^n} = \sum_{0}^{n} \frac{INV}{(1 + i)^n} \tag{7}$$

The ratio of the net profit from the system to the total investment is known as the Return on Investment (ROI). If this value is negative, the system should not be installed and must be positive. ROI is a financial indicator used to measure the profitability of an investment or project. It is calculated by dividing net profit by the investment cost and expressing the result as a percentage, as given in Eq. (8).

$$ROI(\%) = \frac{N_P}{INV} \times 100 \qquad (8)$$

Where, N_P is the net profit in the lifecycle of the project.

RESULTS AND DISCUSSION

The electricity production in PV systems is contingent upon various parameters such as geographical location, sunshine duration, and irradiation density. Before installing such systems, a meticulous performance analysis should be conducted utilizing these pertinent parameters. Economic analysis is also imperative, entailing the computation of payback periods and annual profits. This section delves into two distinct analytical facets: performance analysis and economic analysis of the system, culminating in presenting the obtained results.

3.1 Performance Analysis

The objective of this study was to investigate the impact of panel row spacing on the performance of a PV system. The amount of solar radiation received by each panel is influenced by the panel row spacing, which in turn, can affect the overall power output of the system. The systems were tested at a tilt angle of 35° and the optimized tilt angle for each panel row spacing. The azimuth angle was kept constant at 0° for all systems. The amount of irradiation received by the panel surface was measured using direct, diffuse, and reflected irradiation and is defined as I_G. The total annual average monthly I_G for the systems at a tilt angle of 35° and the optimized tilt angles are presented in Fig. 3.

Solar irradiation reaches the Earth in winter at a narrower angle than in summer. Therefore, the radiation reaching the panel surfaces increases as the tilt angle increases. This is the opposite in summer. It is seen in Fig.3 that while the maximum I_G value is in the winter months at the systems with a tilt angle of 35°, it decreases to the minimum level in the summer months. The maximum amount of radiation coming to the system's surface with a tilt angle of 35° occurred in August as 214.1 kWh/m². With the tilt angles of 1°, 15°, 21° and 27° obtained with the optimization, the maximum total radiation occurs in July with the values of 230.2 kWh/m², 229.7 kWh/m², 226.2 kWh/m², 222.1 kWh/m², respectively. The annual I_G values for systems with a fixed tilt angle of 35° and tilt angles of 1°, 15°, 21° and 27° determined by the optimization tool are 2008.2 kWh/m², 1770 kWh/m², 1935.7 kWh/m², 1977.7 kWh/m² and 1999.4 kWh/m², respectively. According to the system with a tilt angle of 35°, the most considerable difference is -11.4%, while the lowest is -0.4%.

The effective radiation (I_E), which represents the amount of useful irradiation reaching the panel surface, highly depends on the tilt angle. The I_E values for different panel row spacings with tilt angles of 35° and those optimized through the optimization process are presented in Fig. 4.

The system obtained the maximum I_E value of 193.7 kWh/m² in July with a fixed tilt angle of 35 ° with a panel row spacing of 2 m. In the system with an optimum tilt angle of 1°at panel row spacing of 2 m, the maximum I_E value is similarly seen in July as 220.7 kWh/m². This value is 13.94% higher than that obtained with the fixed tilt angle. Annually, 1573.2 kWh/m² is seen in the system with a tilt angle of 35°, while it is 6.22% higher, is seen in the system with a tilt angle of 1°. Unlike the systems with 2 m panel row spacing, the maximum I_E values are seen in July in systems with 35° fixed tilt angles with 2.5 m, 3 m, and 4 m panel row spacing, while the maximum I_E value is seen in June in the optimum tilt angles. In systems with 2.5 m, 3 m, and 4 m panel row spacing and with a 35° fixed tilt angle, the maximum I_E values are also seen in July, with 201.2 kWh/m², 202.7 kWh/m² and 204.2 kWh/m² values, respectively, while the maximum I_E values at optimum tilt angles are seen in June, with 222.1 kWh/m², 218.2 kWh/m² and 213.3 kWh/m² values, respectively. These values are 10.39%, 7.65%, and 4.46% higher than the fixed tilt angle values.

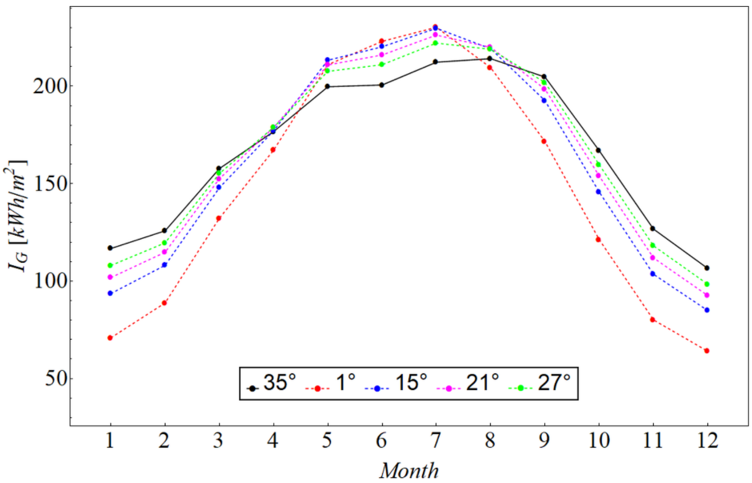

Figure 3. The monthly average I_G at different tilt angles

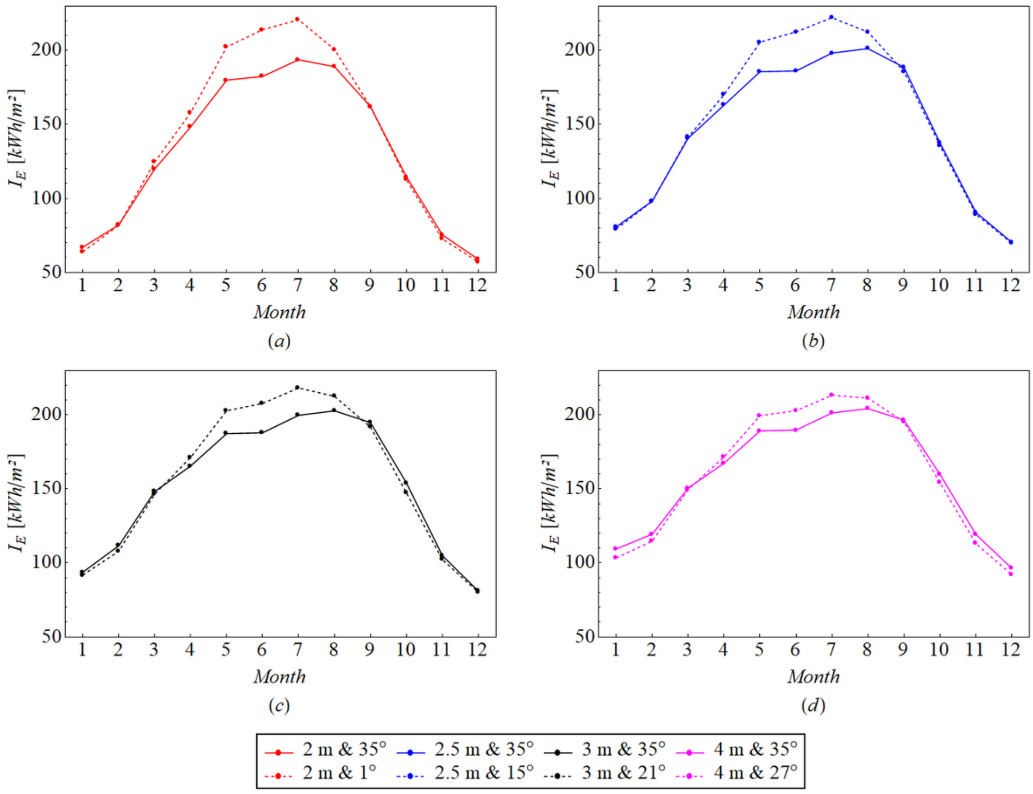

Figure 4. The I_E values of a) 2 m, b) 2.5 m, c) 3 m, and d) 4 m panel row spacing with a fixed tilt angle of 35° and optimum angles

Annually, the I_E values obtained at the optimum tilt angles in systems with 2.5 m, 3 m, and 4 m panel row spacing are 4.65%, 2.67%, and 0.97% higher, respectively, compared to the system with the fixed tilt angle of 35°. It is known that I_E values directly affect the E_G of the systems. The E_G values obtained from systems with a fixed tilt angle of 35° and optimum tilt angles at various panel row spacings are given in Fig. 5.

Since the maximum I_E values with the fixed tilt angle of 35° and the tilt angle determined by the optimization tool in the 2 m panel row spacing system were in July, the maximum E_G values were obtained as 72.03 MWh and 82.21 MWh, respectively. Similarly, the minimum E_G was obtained in December as 25.43 MWh and 24.75 MWh, respectively. Therefore, the E_G obtained from the system at the optimum tilt angle is 14.13% greater than the system with a fixed tilt angle of 35° in July. In December, this value was -2.67% lower. When viewed annually, E_G obtained 622.77 MWh for the system with a 35° tilt angle, while E_G obtained 661.31 MWh with the optimum tilt angle.

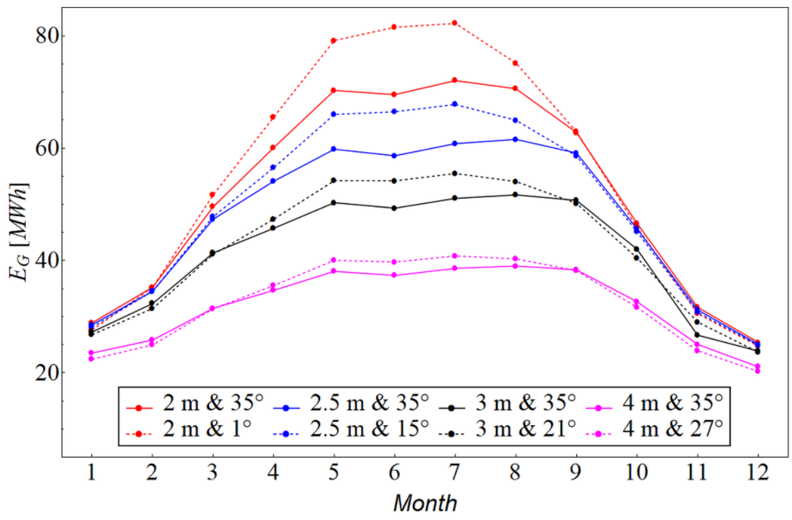

Figure 5. Average monthly E_G values with various tilt angles and panel row spacings

The difference between them is 6.19%. In other words, as in I_E, it takes positive values in summer and negative values in winter. Better results are achieved annually. In systems with 2.5 m, 3 m, and 4 m panel row spacing and 35° fixed tilt angle, the maximum E_G values were obtained in August with the values of 61.57 MWh, 51.68 MWh, and 39.02 MWh, respectively, while, in the systems determined by the optimization tool, the maximum E_G values were obtained in July with the values of 67.78 MWh, 55.49 MWh, and 40.81 MWh, respectively. In 2.5 m, 3 m, and 4 m panel row spacings, in systems with the fixed tilt angle of 35° annual E_G values as 566.49 MWh, 495.36 MWh, and 385.72 MWh, respectively, while in systems with optimum angles, annual E_G values observed as 591.72 MWh, 508.03 MWh, and 389.26 MWh. Annually, the E_G values obtained at the optimum angles with 2.5 m, 3 m, and 4 m panel row spacing are 4.45%, 2.55%, and 0.92% higher, respectively, compared to the system with a fixed tilt angle of 35°. Since fewer panels are used in the area determined by the increase of the panel row spacing, it is seen that the E_G values also decrease.

The monthly average PR value obtained with various panel row spacings and tilt angles using values in Fig. 4 and Fig. 5 is given in Fig. 6.

In systems with 35° fixed tilt angle and 2 m, 2.5 m, and 3 m panel row spacing, PR increases towards summer and decreases towards winter. However, since the E_G values in the system with 4 m panel row spacing are lower than the other panel row spacing systems, the PR values are lower in summer. In addition, since the number of panels decreases with the increase of the panel row spacing and less E_G is produced, it is calculated that the PR values increase with increasing panel row spacing in systems with a fixed 35° tilt angle. Because E_G and PR are inversely proportional. Since E_G values are reached at higher levels in systems with tilt angles obtained with the optimization tool, PR values decrease towards summer months and increase towards winter months in all panel row spacing systems. Maximum PR values of 0.788 in May, 0.829 in April, 0.875 in March, and 0.890 in February were obtained in systems with 35° tilt angle and 2 m, 2.5 m, 3 m, and 4 m panel row spacing, respectively.

On the other hand, the maximum PR values of 0.888, 0.890, and 0.904 were obtained in February for systems with 2 m, 3 m, and 4 m panel row spacing with optimum tilt angles. In the system with 2.5 m panel row spacing, the maximum PR value was obtained in March with a value of 0.875. When viewed annually, the PR values of the systems with a tilt angle of 35° and 2 m, 2.5 m, 3 m, and 4 m panel row spacing are 0.694, 0.763, 0.801, and 0.831, respectively. These values show that the PR values increase with the panel row spacing for systems with fixed tilt angles. The annual PR values obtained with tilt angles at optimum tilt angles with 2 m, 2.5 m, 3 m, and 4 m panel row spacing are 0.837, 0.827, 0.834, and 0.843. Compared with fixed tilt angles of 35°,

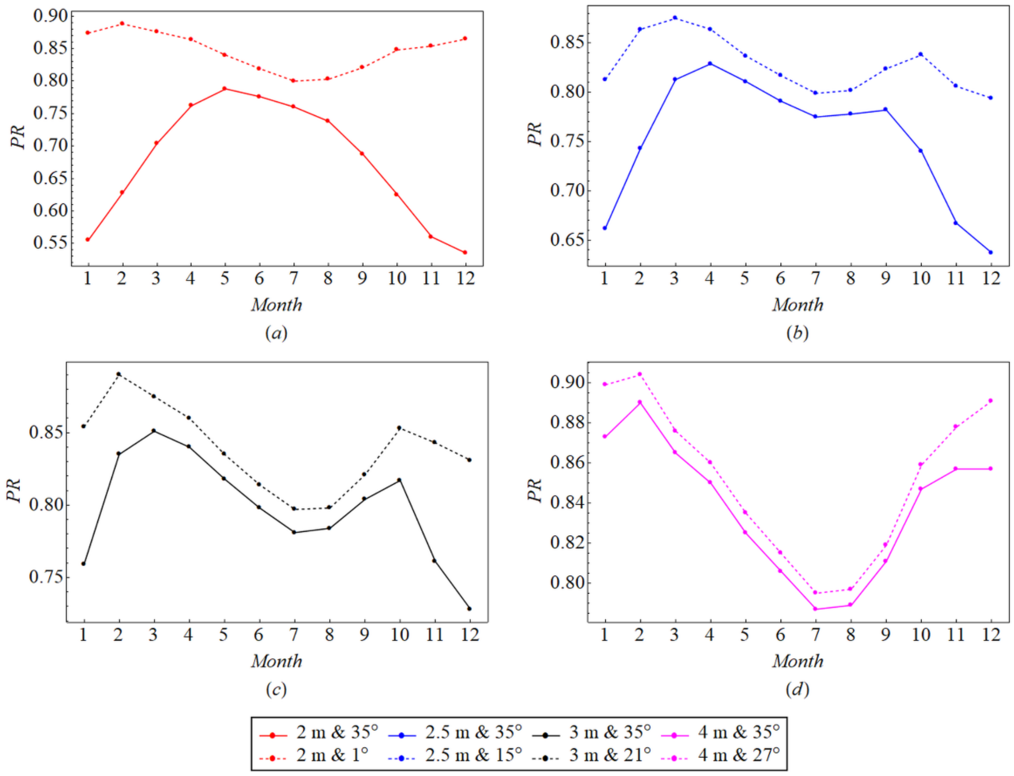

Figure 6. The PR values obtained from systems with a) 2 m, b) 2.5 m, c) 3 m, and d) 4 m panel row spacing using 35° tilt angle and at optimum tilt angles

these values are 20.61%, 8.39%, 4.12%, and 1.44% greater, respectively. With the increase of the panel row spacing, the electricity generation decreases, and therefore the differences between the tilt angles decrease.

Economic Analysis

In addition to technical feasibility, this study also assessed the economic feasibility of the eight systems. The economic analysis was based on several assumptions, including a 25-year system lifetime [39], a discount rate of 9.75% announced by the Central Bank of Turkey for 2022 [40], an electricity price of $0.091, which is the current electricity price in Turkey [41], and annual labor and maintenance costs of $5000. The total ready-to-use cost of the PV systems, including logistics and cabling, was assumed to be 0.65 $/Wp [42].

Table 4. The investment costs and BPBs with various tilt angles and row spacing

Row Spacing	Invest-ment cost [*10^3 $]	Tilt 35° [year]	Opti-mum angle [year]	Rel. Diffe-rence [%]
2 m	447	5.13	4.83	-5.83
2.5 m	370	4.67	4.47	-4.26
3 m	308	4.44	4.33	-2.49
4 m	231	4.28	4.24	-0.91

Since considering a fixed land area, the installed power decreases with the increase of the panel array spacing. Therefore, the investment costs of the systems and the panel row spacing are inversely proportional. Investment costs of systems, BPBs, and differences between these BPBs found with both the fixed and optimum tilt angles are given in Table 4 using Eq. (5) and unit price.

The system that pays for itself in the shortest time is 4 m panel row spacing case, both in the system with both tilt angles. The difference between the BPBs produced with various tilt angles decreases with the increase of the panel row spacing. Therefore, when BPBs are considered, it is seen that the best system that can be installed with 4.24 years is the system with 4 m panel row spacing at an optimum tilt angle. However, it should be noted that a small number of panels are used. Using these assumptions and Eq. (6), the NPVs of eight systems are given in Table 5.

NPVs obtained from systems with optimum angles for 2 m, 2.5 m, 3 m, and 4 m panel row spacings are 17.04%, 11.03%, 6.18%, and 2.30% higher, respectively; those obtained from a fixed 35° tilt angle. The highest NPV value was $ 222937 with a panel row spacing of 2 m with the optimum tilt angle. However, the systems' investment costs are not the same. When the NPV/INV_{base} ratio is considered, it is seen that the highest value is 0.915, obtained from a 3 m panel row spacing system at the optimum tilt angle of 21°. Therefore, it is seen that the most feasible system to be installed is 3 m panel row spacing with the tilt angle of 21°. Furthermore, the difference in NPV of systems decreases with increasing panel row spacing, as in BPB. Another important parameter within the scope of economic analysis is the IRR. In this method, a discount rate is found at the income and expenses of the project are equalized. The IRR values obtained using Eq. (7) are given in Table 6.

Table 5. The IRR of the projects

Row Spacing	Tilt 35° [%]	Optimum angle [%]	Rel. Difference [%]
2 m	17.500	18.759	7.19
2.5 m	19.137	20.123	5.16
3 m	19.822	20.416	2.99
4 m	19.851	20.073	1.16

Since all the values in Table 6 are greater than the discount rate of 9.75%, all projects can be applied feasibly. The highest IRR value was obtained from the system with 3 m panel row spacing with optimum tilt angle. As in NPV and BPB, the difference between systems decreases with increasing panel row spacing. Another economically important parameter is ROI at various tilt angles, and panel row spacing using Eq. (8) is given in Table 7.

Table 6. The NPVs and NPV/INV_{base} of different orientations

Row Spacing	NPV at 35° [*10^3 $]	NPV at Optimum angle [*10^3 $]	Rel. Difference [%]	NPV/INV_{base} for 35° [-]	NPV/INV_{base} for optimum angle [-]	Rel. Difference [%]
2 m	190.481	222.937	17.04	0.656	0.767	16.92
2.5 m	192.646	213.893	11.03	0.801	0.889	10.99
3 m	172.650	183.320	6.18	0.862	0.915	6.15
4 m	129.878	132.859	2.30	0.865	0.885	2.31

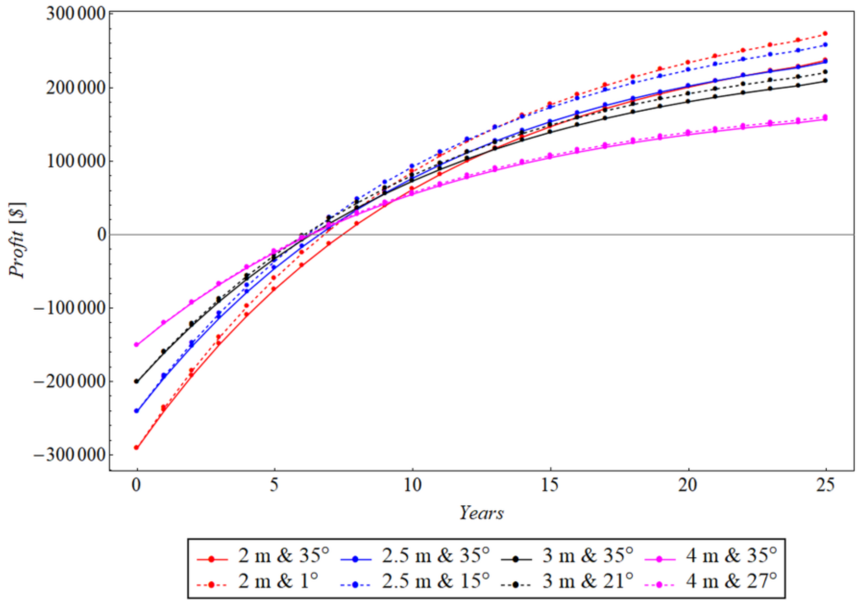

Figure 7. NPV of considered projects by year

Table 7. ROIs at various tilt angles and panel row spacing

Row Spacing	ROI at 35° [%]	ROI at Optimum angle [%]	Rel. Difference [%]
2 m	65.56%	76.73%	17.04%
2.5 m	80.10%	88.94%	11.03%
3 m	86.24%	91.57%	6.18%
4 m	86.5%	88.48%	2.29%

The maximum ROI value of 91.57% was obtained from the system with a panel row spacing of 3 m at the optimum tilt angle. In this case, it was concluded that the most feasible system to install is the system with 3 m panel row spacing. It is also seen that the difference between the ROI values obtained from two different tilt angles decreases as the panel row spacing increases. The annual NPV of the systems in the lifespan with a discount rate of 9.75% is shown in Fig 7.

Since the fixed area is used, the installed system's power increases with the panel row spacing decrease. In this case, the installation cost of the systems increases with the decrease in the panel row spacing. However, the income to be obtained from the systems is directly proportional to the installed power of the systems. Installation costs for systems of 2 m, 2.5 m, 3 m, and 4 m panel row spacing are $290550, $240500, $200200, and $150150, respectively. At the end of 25 years, for the system with a fixed tilt angle of 35°, the total net profit obtained from the systems with 2 m, 2.5 m, 3 m, and 4 m panel row spacing is $237105, $234649, $208813, and $157038, respectively. These values are $272726, $257968, $220523, and $160310 for the tilt angles obtained at the optimum tilt angles.

This study reveals that for a fixed area in Konya, Turkey, the optimal inclination angle for a PV system is 21°, based on the results of performance and economic analyses.

4. CONCLUSION

The PV systems were simulated for four panel row spacings of 2 m, 2.5 m, 3 m, and 4 m on a total area of 3000 m² in Konya Province, Turkey. First, system characteristics were obtained using a 35° tilt angle, and then the optimum tilt angles were determined for each panel row spacing. The results obtained are listed below.

- The annual total solar radiation to the panel surfaces was obtained as 2008.2 kWh/m² in the system with a fixed tilt angle of 35°, while it was obtained with 1999.4 kWh/m² in the tilt angles determined by optimization.
- In the system with a fixed tilt angle of 35°, the maximum I_E value was seen with a panel row spacing of 4 m with a value of 204.2 kWh/m². Similarly, in systems with optimum angles, a maximum I_E value of 213.3 kWh/m² was observed in the system with 4 m panel row spacing. When looked at annually, these values are 1903.2 kWh/m² and 1921.7 kWh/m², respectively. The optimum angle value is 0.97% larger than the fixed angle and can be ignored.
- Annual E_G values obtained with the tilt angle of 35° in 2 m, 2.5 m, 3 m, and 4 m panel row spacings are 622.77 MWh, 566.49 MWh, 495.36 MWh, and 385.72 MWh, respectively, while the annual E_G values obtained with the tilt angles obtained at optimum angles are 661.31

MWh, 591.49 MWh, 508.03 MWh, and 389.26 MWh, respectively.

- The annual PR values with a 35° tilt angle are 0.694, 0.763, 0.801, and 0.831 for 2 m, 2.5 m, 3 m, and 4 m panel row spacings, respectively. The tilt angles obtained with the optimization tool are 0.837, 0.827, 0.834, and 0.843, respectively. Optimum angle values are 20.61%, 8.39%, 4.12%, and 1.44% greater than fixed angle values.
- For 2 m, 2.5 m, 3 m, and 4 m panel row spacing, systems with 35° fixed angle have a BPB of 5.13, 4.67, 4.44, and 4.28 years, while systems with optimum angles are 4.83, 4.47, 4.33, and 4.24 years.
- The systems at optimum angles have 17.04%, 11.03%, 6.18%, and 2.30% higher NPV values compared to the fixed-angle case. Therefore, it was concluded that the highest NPV/INV_{base} ratio is obtained from the system with 3 m panel row spacing and at the optimum tilt angle of 21°, with a value of 0.915.
- Furhermore, the maximum IRR and ROI values were obtained with values of 20.416% and 91.57%, respectively, in the system with an optimum tilt angle of 21° and 3 m panel row spacing.

In conclusion, this study has demonstrated that the row spacing of a photovoltaic (PV) system significantly impacts the optimum tilt angle. The findings indicate that wider row spacing necessitates a lower tilt angle to capture more sunlight, while narrower row spacing necessitates a higher one. Furthermore, a narrower row spacing implies that the sunlight strikes the panels at a steeper angle, necessitating a higher tilt angle to capture more energy. Based on the results of the technical and economic analyses performed on the examined systems, a panel spacing of 3 m and a tilt angle of 21° are recommended. It is worth noting that the methodology employed in this study can be replicated in similar investigations conducted in other regions.

DECLARATION OF ETHICAL STANDARDS

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

AUTHORS' CONTRIBUTIONS

Muharrem Hilmi Aksoy: Prepared the structure of the article. Evaluated the results and contributed to the writing process.

Murat Ispir: Analyzed the results and made the writing process of the article.

Emin Yesil: Performed the analysis.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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