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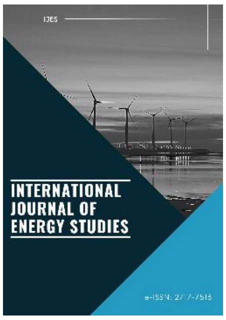

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Investigation of production performance of a solar power plant according to the optimum panel tilt angle

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Highlights

- Solar power plant production performance
- The effect of panel tilt angle on production performance
- The comparison with real production data

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ABSTRACT

Solar energy is one of the most important renewable energy sources with its clean, unlimited and low operating costs. In solar power plants, factors such as climatic conditions of the region, panel placement and system design are very important. In particular, examining the performance differences between fixed tilt systems and systems adjusted according to optimum tilt angles plays a critical role in the optimization of investment decisions. In this study, the production increase that can be achieved by systems adjusted according to optimum tilt angles compared to fixed systems is analyzed in terms of technical and economic dimensions on the example of a 3.6 MW fixed tilt angle solar power plant located in Elmadağ district of Ankara. Considering the location of the power plant, the optimum tilt angles of the photovoltaic (PV) panels are determined monthly using MATLAB software; thus, it is aimed to maximize the solar radiation falling on the panel surface and increase electricity generation. At the same time, the monthly electricity generation potential of the system was analyzed in PVGIS simulation. In the light of the data obtained, the performances of the fixed system and the system adjusted according to the optimum tilt angles were compared and the economic and technical contributions were evaluated. As a result, it was determined that 11.3%, 16.2% and 14.5% higher revenues can be obtained compared to 2022, 2023 and 2024, respectively, if the system is adjusted to the optimum monthly inclination angle and maintained under ideal conditions.

Keywords: Solar power plant, Panel tilt angle, Photovoltaic, PVGIS, MATLAB

1. INTRODUCTION

Solar energy is the most fundamental and environmentally friendly renewable energy source. It offers unlimited energy to our world and is also the basis for many different types of energy. One of the effective ways to utilize this unlimited energy of the sun is to use photovoltaic cells and panels that convert solar radiation directly into electricity. In solar panel systems, fixed and solar tracking systems are used to obtain the highest efficiency from solar radiation. The tilt angle of the panels varies depending on the geographical location of the region where the system is installed and seasonal changes. Therefore, energy production can be increased by determining the optimum tilt angle to maximize the benefit from sunlight throughout the year [1]. One of the most important parameters affecting the efficiency of solar power plants is the panel tilt angle. In recent years, there have been many studies examining the production performance of solar power plants and panel tilt angles.

They compared the production characteristics of two solar energy systems in Konya, a high solar energy potential area, in order to analyse the effects of different design methods in solar energy systems. In the fixed-axis system, the optimum angle and orientation of the panel were observed to be 27° and south (azimuth 0°), respectively, whereas in the dual-axis tracking system, different angles and orientations (0°, 80° and azimuth -120°, 120°) were utilized for the panel to follow the sun in horizontal and vertical directions. According to simulation results with PVSyst software, the dual-axis tracking system showed a 16.7% higher performance in terms of annual electrical energy production than the fixed-axis system [2]. In Siirt province, which has a high insolation potential, the electrical energy generation efficiency of single-axis solar tracking systems compared to fixed systems was experimentally investigated. The movable panel is equipped with a tracking system designed to follow the position of the sun from sunrise to sunset. Experimental results have shown that the movable panel produces 30-35% more electrical energy than the fixed panel [3]. The energy production of PV panels positioned in different directions (east, west and south) and at optimum tilt angles were compared. According to the findings, the panels facing in the direction of intense solar radiation produced 25-32% more energy on average than the panels in the fixed south direction. In addition, simulation studies have shown that solar tracking systems can increase energy production efficiency by about 20% on an annual basis [4]. In order to evaluate the performance of photovoltaic systems, different solar tracking systems were modelled in PVSOL software. The annual energy production of fixed, uniaxial and biaxial systems with the same geographical location and power ratings were comparatively analyzed under various meteorological conditions (cloudiness, temperature, etc.). The analysis shows that the annual energy production of the dual-axis tracking system is 52.35% higher than the fixed system and 8.57% higher than the single-axis system. The single-axis system produced 40.33% more energy than the fixed system [5].

In order to increase the efficiency of solar energy systems, the performance of three photovoltaic panels positioned at different angles was analysed. According to the geographical location of Diyarbakır and solar angle calculations for November, the optimum tilt angle was determined to be 58 degrees. The current and voltage values of the panels placed at three different angles close to this value were measured continuously during the day. In the light of the data obtained, it was determined that the panel positioned at the optimum angle provided higher energy production than the others. This result emphasizes the importance of sun angle in the design of solar energy systems [6]. Inan et al. (2024) [7] calculated the optimum panel tilt angles for seven different locations in Turkey on an annual and seasonal basis using a photovoltaic geographic information system program. It was shown that seasonal adjustment of the panel tilt angle would provide up to 4.20% more profitability and monthly adjustment would provide up to 5.05% more profitability.

Ukoima et al. (2024) [8] used PVGIS software to investigate the optimum photovoltaic tilt angle in Southern and Southeastern Nigeria and compared the results with experimental data. It was found that the installation of PV panels with the optimum tilt angle maximizes the amount of solar radiation incident on the panel surface, thus generating more electricity. Babatunde et al. (2018) [9] investigated the performance of PV systems for dust effect, different tilt angles and orientations. Five different PV plants with a power of 1280 kWp installed at the International University of Northern Cyprus were analysed and annual measured data, simulated data and analytically calculated data were compared. It was observed that the application of the cleaning procedure on the panel surface resulted in a 2.5% increase in system performance. At the same time, production data for different tilt angles were compared experimentally and theoretically.

In this study, the cases of keeping the photovoltaic panels at a fixed angle throughout the year and monthly or seasonal angle adjustments were compared. In each case, the optimum tilt angles are determined and the total amount of annual energy that can be produced accordingly is calculated and compared. In addition, considering the sales price per kWh of electricity generated, the revenues of the power plant in 2022, 2023 and 2024 are compared with the data obtained from the simulation results. In this way, the performances of the fixed system and the system adjusted according to the optimum slope angles were compared and the economic and technical contributions were evaluated.

2. MATERIAL AND METHOD

In this study, the technical specifications and electricity generation data of a 3.6 MW solar power plant located at 39.9º North and 33.2º East coordinates in Elmadağ district of Ankara were used. Technical information of the power plant is shown in Table 1.

Table 1. Technical specifications of the power plant

Power Plant	
System Capacity	3604 kWp
Mounting Angle	30º
Modules	
Manufacturer	Hanwha Solar
Type	Polycrystalline
Maximum Module Power	265 Wp
Dimensions	1670 x 1000 x 32 mm
Total Number of Modules	13600 pieces
Permissible Operating Temperature	-40 (ºC) – (+85ºC)
Inverters	
Manufacturer	Fronius Symo
Type	20.0-3-M
Total Number of Inverters	180
Output Power (AC)	20 kW
Inverter Input Voltage	1000 V (DC)

The solar power plant has a power of 3.6 MWp and the equipment used was selected considering this value. For the project, 13600 PV panels were used to obtain approximately 3.6 MW from panels with an output power of 265 W. 13600 solar panel power is equivalent to 3604 kWp power. In order to convert the DC current (Direct Current) from the PV panels to AC current (Alternating Current) in order to supply it to the grid, 180 inverters, each with an output power of 20 kW, were used.

The optimum tilt angles of photovoltaic (PV) panels for the Elmadağ region were determined in order to increase the electricity generation efficiency. Accordingly, the optimal panel tilt angles were calculated using MATLAB software. The azimuth angle was taken as Zs=0º since the panels were placed facing south. In addition, the hour angle was set as h=0º since the calculations were performed at noon when the solar radiation is the steepest and the efficiency is the highest. Based on these fixed parameters, the optimum tilt angle (β) for each day to maximize solar utilization was obtained by using Equation 1-2 [10]. Here, the solar incidence angle θ is taken as 0 to find the panel tilt angle at which the solar rays are perpendicular to the surface. The obtained results provide important information for the most efficient positioning of PV panels at different time periods throughout the year. Thus, it becomes possible to utilize solar energy more effectively in residential areas with a specific geographical location such as Elmadağ. Incidence angle equation for south-facing surfaces in the northern hemisphere (for Zs=0);

$$\cos(\theta) = \sin(L)\sin(\delta)\cos(\beta) - \cos(L)\sin(\delta)\sin(\beta) + \cos(L)\cos(\delta)\cos(h)\cos(\beta) + \sin(L)\cos(\delta)\cos(h)\sin(\beta) \quad (1)$$

When the equation is simplified, it can be given as follows:

$$\cos(\theta) = \sin(L-\beta)\sin(\delta) + \cos(L-\beta)\cos(\delta)\cos(h) \quad (2)$$

Here; θ is the solar incidence angle, L is the latitude angle, β is the panel tilt angle, δ is the declination angle, h is the hour angle.

The declination angle is calculated by the following Equation 3 [10];

$$\delta = 23{,}45\sin\left[\frac{360}{365}(284+n)\right] \quad (3)$$

Where n is days of the year (1-365).

Based on geolocation data, the web-based PVGIS tool provides individuals with an extensive dataset that is necessary for solar energy system evaluation and design. Solar radiation, atmospheric temperature, radiation values at different angles and inclinations, and shading analysis are included in the data provided. In this manner, individuals can more accurately estimate the likely performance of their photovoltaic systems and get the information needed to optimize their performance. For a 3.6 MW grid-connected system, PVGIS 5.3 online platform has been utilized to design and compare.

3. RESULTS AND DISCUSSIONS

In this study; the monthly optimum panel tilt angle for the solar power plant under study is calculated. The variation of the incidence angles of solar radiation during the year is given comparatively according to the fixed tilt angle and optimum tilt angles. In addition, the production data of the solar power plant and the data obtained as a result of the simulation are compared and analyzed economically. The monthly average optimum tilt angles obtained using MATLAB software for the solar power plant located in Elmadağ district of Ankara are given in Table 2. The calculations were made for the noon hour when the sun is at its peak by taking the hour angle h=0.

Table 2. Monthly average optimum tilt angle (Elmadağ, Ankara)

Months	**Optimum tilt angle (β)**
January	60.42
February	52.89
March	41.96
April	30.08
May	20.76
June	16.49
July	18.47
August	26.28
September	37.58
October	49.42
November	58.62
December	62.66

As a result of the calculations, tilt angles ranging from 16.12° to 62.66° per day throughout the year were obtained. The annual optimum tilt angle for south oriented panels was found to be 39.56° at 0° azimuth angle. According to the results, the optimum tilt angle was calculated as 41.64° in spring, 19.93° in summer, 48.54° in fall and 58.66° in winter. It is seen that the panel tilt angle is smaller in summer due to the steeper incidence of solar radiation, while the panel tilt angle is larger in winter due to the more oblique incidence of solar radiation. At the same time, monthly average solar incidence angle (θ) values for two different inclination angles (β=30°) and (β=monthly average=opt.) were calculated for Elmadağ/Ankara by using MATLAB software. The variation of the solar incidence angle throughout the year is shown in Figure 1. Small incidence angles (θ) indicate that the panels are well positioned and the sunlight is more perpendicular to the panel, thus generating more efficient energy. At constant inclination (β=30°), the angle of incidence is quite low in months such as April (2.75°), August (3.96°) and September (7.58°). In these months (β=30°), the fixed tilt receives the sun's rays quite efficiently. At the optimum tilt (β=monthly average=opt.), the incidence angle values are generally quite low (monthly maximum 3.17°). This shows that every month the panel tilt is adjusted in the most suitable way for the solar radiation. Especially in April, the fixed and adjustable tilt results are almost identical (θ=2.75°). This is because the optimum tilt in April (β=30.08°) is already very close to 30°.

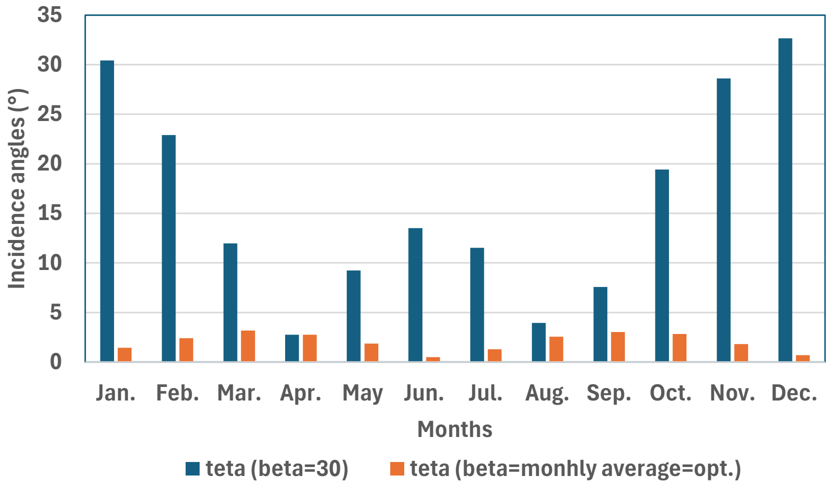

Figure 1. Monthly variation of solar incidence angles for (β=30°) and (β=monthly average=opt.)

At constant tilt angle (β=30°), there are large fluctuations in the solar incidence angle throughout the year. Especially in winter months (December, January) the angle of incidence is very high. This shows that the panel receives sunlight obliquely and the efficiency decreases. At the optimum tilt (β=monthly average=opt.), the solar incidence angles are very low and balanced, and the sun's rays are almost vertical every month. It clearly shows that the adjustable panel tilt provides optimum performance every month.

The actual electricity generation data (β=30°) for 2022, 2023 and 2024 for the solar power plant located in Elmadağ district of Ankara province are compared with the monthly generation forecasts obtained using the PVGIS online simulation program. Simulations were performed for both a fixed tilt angle of 30° (β=30°) and an optimum tilt angle (β=opt.), which is determined to provide maximum efficiency of the system. These production data are given in Table 3.

When Table 3 is analyzed, it is observed that in some months, the simulations made with a 30° inclination angle are very close to the actual production values, while in some months they are below or above these values. However, when evaluated on an annual basis, it is found that PVGIS simulation results are higher than the actual production amounts for all three years. This difference may be due to the fact that the simulations assume ideal conditions; factors such as adverse weather conditions, contamination on the panel surface, system failures or equipment efficiency losses that are encountered in real life may adversely affect production. In the simulations with the optimum tilt angle, higher production amounts were achieved as expected. This shows that positioning the panels in a way to receive solar radiation at a steeper angle throughout the year increases the production amount.

Table 3. Monthly electricity generation for 2022, 2023 and 2024 (B=30⁰) and PVGIS simulation monthly electricity generation (beta=30⁰) and (beta=Opt)

Months	**Electricity Production Amount (kWh)**			**Electricity Production Amount (kWh) (β=30⁰, PVGIS simulation)**	**Electricity Production Amount (kWh) (β=opt, PVGIS simulation)**
	2022	**2023**	**2024**		
January	210,000	302,000	196,000	241,211	268,747
February	285,000	297,000	326,000	317,459	337,724
March	396,000	327,000	388,000	429,354	434,305
April	487,000	402,000	444,000	486,636	486,599
May	497,000	448,000	471,000	512,387	525,067
June	468,000	468,000	623,000	539,193	565,528
July	606,000	588,000	546,000	610,358	633,635
August	559,000	585,000	558,000	601,100	604,246
September	535,000	468,000	441,000	532,372	535,607
October	415,000	430,000	457,627	441,538	466,645
November	323,000	223,000	235,000	350,754	397,104
December	201,000	232,000	158,000	250,091	287,813
Total	4,982,000	4,770,000	4,843,627	5,312,453	5,543,020

The sales price of the electricity generated at the power plant is 0.133 dollars per kilowatt-hour (kWh). Monthly revenues for the years 2022, 2023 and 2024, calculated based on the generation values obtained by PVGIS simulation (β=optimum tilt angle) are presented in Table 4. Table 4 shows that 2022 has the highest total production and therefore the highest total revenue in the last three years. In 2023, there was a decrease of approximately 4.3% in both production and revenue compared to 2022. In 2024, there is a decrease of approximately 2.77% compared to 2022, but an increase of approximately 1.55% compared to 2023. This shows that the system performance has fluctuated over the years. It is clear that this fluctuation cannot be explained solely by meteorological factors. Annual production changes may also be significantly affected by system maintenance planning, inverter failures, frequency of panel cleaning and other operational processes. Therefore, it is of great importance to improve operational efficiency in order to sustainably increase production performance. According to PVGIS simulation data, it is seen that significant increases in the annual revenue of the system can be achieved if the panels are installed with the optimum tilt angle.

Table 4. Monthly revenues from the sale of electricity generated in 2022, 2023 and 2024 and PVGIS simulation (beta=opt.) conditions

Months	**Revenues from the Sale of Electricity Generated at the Power Plant ($)**			
	2022	**2023**	**2024**	**β=optimum (PVGIS simulation)**
January	27,930	40,166	26,068	35,743
February	37,905	39,501	43,358	44,917
March	52,668	43,491	51,604	57,763
April	64,771	53,466	59,052	64,718
May	66,101	59,584	62,643	69,834
June	62,244	62,244	82,859	75,215
July	80,598	78,204	72,618	84,273
August	74,347	77,805	74,214	80,365
September	71,155	62,244	58,653	71,236
October	55,195	57,190	60,864	62,064
November	42,959	29,659	31,255	52,815
December	26,733	30,856	21,014	38,279
Total	662,606	634,410	644,202	737,222

Comparisons with simulated data point to making approximately $74,616 more money in 2022, $102,812 more money in 2023 and $93,020 more money in 2024. These are the differences that unequivocally show that the current installation and operating conditions of the system are trailing behind the possible performance. Proportionally, if the system had been installed with the optimum inclination angle (β=opt.) and maintained under ideal conditions, approximately 11.3% more income in 2022, 16.2% more in 2023 and 14.5% more in 2024 could have been achieved. These findings indicate how crucial it is to optimize the inclination angle while designing and operating the system and improve maintenance and performance management practices for economic returns.

4. CONCLUSION

In this study, the actual generation data obtained from a solar power plant in 2022, 2023 and 2024 and PVGIS simulation results are analyzed comparatively. The findings clearly show that the current generation performance of the system lags behind the potential performance. In particular, the fact that the simulation results predict 11%-16% higher annual revenues compared to the actual data supports the need for improvement in the system.

In this context, the following suggestions can be developed:

•Monthly and Seasonal Optimization of Panel Tilt Angles: Optimizing panel tilt angles on a monthly and seasonal basis in fixed systems can contribute to more effective utilization of total sunshine hours on an annual basis. Therefore, it is recommended to encourage system designs that allow monthly and seasonal angle adjustments to be performed by manual or semi-automatic mechanisms.

•System Design Based on Local Climate Data: In order to increase the production performance of the system, it is of great importance to design the system by taking into account local climatic data such as monthly and seasonal sunshine hours, cloudiness and temperature profile of the region where the system will be installed.

•Development of Regular Maintenance and Operation Strategies and Cleaning Programs: Contamination, shading or physical damages that may occur on the panel surface lead to loss of production. These losses should be minimized through periodic maintenance and cleaning activities. Therefore, regular maintenance programs should be established throughout the life of the system and rapid response strategies should be developed against possible failure situations.

•Performance Monitoring Systems: Monitoring system performance with instant and historical data is critical to accelerate fault detection and optimization processes.

•Annual Performance Audits: Comparing system performance with PVGIS or similar simulation data on an annual basis will be useful for setting production targets and evaluating performance.

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Zahit Furkan Gules: Investigation, performed the calculations, writing the manuscript.

Ismail Bozkurt: Investigation, methodology, revised- review & editing the manuscript.

Faruk Kurker: Analyse the data, visualization, writing the manuscript.

Murat Pala: Analyse the data, methodology.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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