

PERFORMANCE AND ENVIRONMENTAL IMPACT
ANALYSIS OF A GRID-CONNECTED PV POWER PLANT
USING AI-BASED REAL-TIME MONITORING

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Abstract

In this study, the performance evaluation of grid-connected photovoltaic systems with a capacity of 4101.12 kWp installed by Baykan Denim company in Malatya province is carried out. The performance ratio, temperature, energy, radiation values used in the evaluation of the analysis are obtained every five minutes with the Solarify artificial intelligence-based performance monitoring network. The system efficiency is 16.53% and the performance ratio is 0.81. In addition, it was determined that 3022.61 tons of CO₂ emissions were reduced annually thanks to the installed SPP (Solar power plant). It is concluded that the installation of PV systems provides considerable environmental and economic benefits.

Key words: renewable energy, solar power plant, performance analysis

Introduction. Today, countries continue to search for environmentally friendly, clean and renewable energy sources to reduce the negative environmental impacts of non-renewable energy sources such as fossil fuels and to meet the significant increase in global energy demand [1]. Among renewable energy sources, solar energy is a sustainable alternative that has the capacity to meet the energy needs of developing countries and has been identified as a critical pathway to achieve the International Energy Agency's (IEA) net zero emission target by 2050 due to its advantages such as being abundant and not harming the ecosystem [2].

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Considering the diversity of available energy resources, Turkey stands out with its high solar energy potential [3]. According to Turkey's Solar Energy Potential Atlas (SEPA), the total sunshine duration is 2.741 hours per year, the total incident solar energy is 1.527 kWh/m^2 , and the daily average is 4.18 kWh/m^2 per day [4]. While regular monitoring of the time-varying energy production and efficiency of photovoltaic (PV) systems with performance analysis contributes to the creation of effective maintenance plans, accurate estimation of the lifetime energy production of the systems is critical in terms of cost in the rapidly growing PV industry. GOVINDARAJAN et al. [5], in their study, aimed to evaluate the efficiency of a grid-connected solar energy system installed with a 6.9 MWp photovoltaic system at Tun Hussein Onn University (UTHM) in Batu Pahat, Johor. The researchers monitored the PV system during the years 2021–2022 and reported that it produced 8529 MWh of energy. They emphasized that the installed PV system has an efficiency of 11.86%, a final efficiency of 108.28% and a performance ratio of 0.78, respectively. They also stated that it would reduce CO₂ emissions by 5450 tons per year. ADAN et al. [6] analyzed the performance of a 3 kW grid-connected photovoltaic system at Eskiehir Technical University. The researchers emphasized that the production amount of the PV system is 4839 kWh/year, the energy sent to the electricity grid is 4648 kWh/year, the performance rate of the system is 84.8% and the production is 4.08 kWh/kWp/day. ANANG et al. [7] conducted a performance analysis of a grid-connected rooftop solar PV system in Malaysia. The researchers analyzed the 2018–2019 performance parameters of the installed 7.8 kWp PV system and used PVsyst software. From the data they recorded, they found that the best performance ratio was 75.72% and the average loss was 1.68 kWh/kWp/day. KHARESAXENA et al. [8] conducted simulation and energy analysis of a grid-connected 100 kWp solar photovoltaic power plant installed on the roof of an institute building in Bhopal, India. The researchers emphasized that the plant's standard performance ratio and capacity factor were 80.72% and 19.27%. They also stated that the plant installation has the capacity to reduce 136 tons of CO₂ emissions per year. GOEL and SHARMA [9] compared the observed and simulated performance of an 11.2 kWp grid-connected rooftop solar PV system installed in Bhubaneswar, India. As a result of their analysis, they found that the annual energy produced by the PV system was 15.33 MWh. In their study, BAQIR and CHANNI [10] designed and analyzed a 700 kWp PV system with PVsyst software connected to the grid in Daikundi province of Afghanistan. As a result of the study, the researchers calculated the performance ratio as 0.797 and the system electricity generation as 1266 MW/year. ALAZAZMEH et al. [11] analyzed the performance of a 425 kW PV system installed on the roof of a building in Saudi Arabia. They found that the PV system produces an annual DC and AC power output of 835.60 MWh and 814.88 MWh, respectively, and the system performance is 78.09%. They also calculated that the project will save 15.666 tons of CO₂ over its lifetime.

In this study, the performance evaluation of the 4.1 MWp PV system installed on the Baykan Denim factory roof is carried out by obtaining real-time data through the Solarify monitoring system. The performance ratio, efficiency factors, capacity factor and annual energy production of the plant are analyzed. The study includes general characteristics of the plant, site details, system configuration, detailed performance analysis, relationship and comparison of parameters and results.

Material and method. Features of the solar power plant. A Solar Power Plant was commissioned in 2021 at Baykan Denim Company located in Malatya province. Its installed power is 4101.12 kWp. According to the data of the Ministry of Energy and Natural Resources, the average annual sunshine duration at coordinates 38.380026 is estimated to be approximately 2500–3000 hours/year. The annual average radiation value per square meter is approximately 1600–1900 kWh/m² [12]. Figure 1 shows the view and location of the SPP site.



Fig. 1. Top view of the SPP site

System elements are mounted on the ground to prevent damage to the panels due to adverse weather conditions and to place and hide the cables in an organized manner [13].

The mechanical and electrical characteristics of the installed PV system are given in Table 1.

With photovoltaic systems, grid-dependent and off-grid electricity generation can be achieved. One of the widely preferred methods of electricity generation from solar energy today is the On-Grid System. In this method, photovoltaic cells made of semiconductor materials produce direct current by creating electron current with the sunlight falling on them with the photovoltaic effect. Grid-connected photovoltaic systems (On-Grid) are systems in which the electricity generated with the help of solar panels can be consumed instantaneously and without storage, and the excess is supplied to the grid. In the solar power plant installed in Baykan Denim Company, a total of 9216 modules consisting of 144 monocrystalline cells, each measuring 166×83 mm, and 32 3-phase inverters were used. The angle of the photovoltaic panels is 8° . The panels were installed facing south with a tilt of 8° to optimize yearly solar energy yield in Malatya (latitude $\approx 38.3^\circ$ N). This inclination ensures a balanced capture of sunlight throughout both summer and winter months for a fixed-tilt setup.

T a b l e 1
PV module electrical characteristics

Panel electrical characteristics (Monocrystal 166 mm × 83 mm)		
Model	1000 V	PS445M4-24/TH
	1500 V	PS445M4H-24/TH
Module efficiency (%)		20.39
Panel power		445 Wp
Number of modules		9216
Cell type		Monocrystalline silicone
Number of inverters		32
Inverter power		100 kWe
Total installed power		3200 kWe
STC (Standard test conditions): irradiance 1000 W/m ² , AM1.5, cell temperature 25 °C		
NOCT (Nominal operating cell temperature): irradiance 800 W/m ² , ambient temperature 20 °C, spectrum AM1.5, wind 1 m/s		

Three-phase inverters are used in the plant. The maximum efficiency of the inverters used is 98.9%. In order to keep the inverters in the plant at appropriate operating temperatures, fans with a speed of 2280 RPM and 240 W power are used. In addition, the bidirectional meter measures the electrical energy in both directions and stores the measured data so that the stored data can be accessed when needed. The data logger collects data from components such as inverters, energy meters and sensors and enables them to be monitored and managed in a centralized system.

Performance parameters. A performance analysis of the 4.1 MWp rooftop solar panel installation of Baykan Denim, established on a 170 000 m² area, is being carried out between January 2024 and December 2024. For the analysis, various parameters such as solar radiation in the region, energy production and auxiliary data on ambient conditions are obtained. For the evaluation, the performance is tracked with the Solarify program and in addition, the performance parameters of the PV installation are calculated. The XGBoost algorithm was employed as the estimation model, and its performance was evaluated using 70–30 data splitting and 10-fold cross-validation methods. XGBoost achieved the lowest error metrics (MAE, MSE, RMSE) and the highest R^2 value. Particularly under 10-fold cross-validation, the model exhibited excellent performance with MAE of 0.0066, RMSE of 0.0112, and R^2 of 0.9983.

Results and discussion. Phono Solar Twinplus 445 panels and Huawei Sun2000-100KTL-M1 inverters were used in the Solarify-based photovoltaic system simulation. Figure 2 shows the monthly variation of the energy amount, irradiance, performance ratio and temperature values obtained.

The monthly average amount of energy produced shows the highest value with 741163.04 kWh in July and the lowest value with 135905.78 kWh in December.

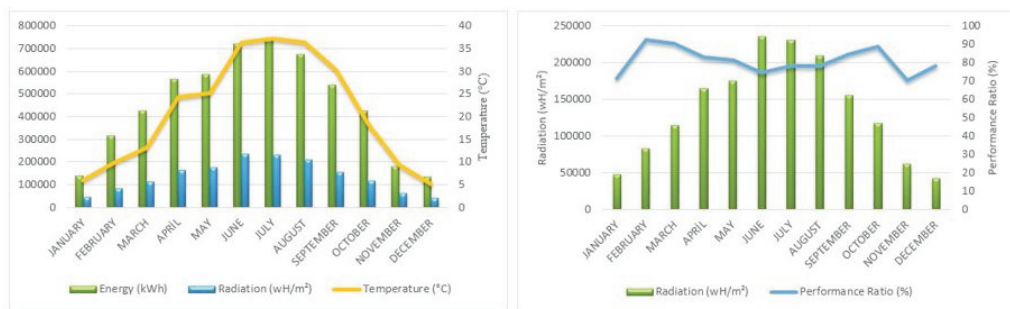


Fig. 2. Monthly variation of the amount of energy produced, irradiance, performance ratio and temperature values

The maximum temperature is 37.16°C in July and the minimum temperature is 5.18°C in December. As seen in Fig. 2, November has the lowest PR (70.60%) and the third lowest irradiance value of the year with 61930.06 Wh/m^2 . On the other hand, when we look at the average for 2024, the highest performance ratio is in February with 92.50% and the irradiance in this month is 83327.16 Wh/m^2 . In Malatya, a distinct inverse relationship was identified between ambient temperature and the efficiency of the photovoltaic system. As ambient temperatures rose, panel efficiency declined, mainly due to elevated module surface temperatures that reduced the open-circuit voltage. On average, system efficiency was found to decrease by around 0.45% for every 1°C increase in ambient temperature. This reduction became more significant during the summer period, when module temperatures frequently surpassed 50°C , limiting overall energy conversion performance despite high solar radiation levels.

Figure 3 shows the baseline and final efficiency change for the period January-December 2024.



Fig. 3. PV performance parameters

Figure 3 demonstrates that the maximum final efficiency is reached in July. The monthly average final efficiency ranges from a minimum of $33.14 \text{ kWh/kWp-month}$ in December to a maximum of $180.72 \text{ kWh/kWp-month}$ in July. The average reference efficiency ranges from a minimum of $42.34 \text{ kWh/kWp-month}$ in

December to a maximum of 236.09 kWh/kWp-month in June. The amount of CO₂ emissions reduced by photovoltaic system operation is measured as 3022.61 tons in 2024 by the PVsyst-based Solarify program. Capacity factor (Cf) values vary between 4.45–24.40%. The variation in Cf can also be explained by the value of the final efficiency, which depends on how much electricity is generated. The minimum value of Cf is 4.45% in December and 4.55% in January. In the data for 2024, the maximum value of Cf is in June with 24.40%. The capacity factor is directly related to the amount of radiation and system efficiency. Performance ratio refers to the internal efficiency of the system and is independent of irradiance. Although the PR value is 92.50% in February, the Cf value is 11.08%. The reason for this situation is that the technical efficiency of the system is high but the irradiance is low. In June, the PR is 74.40% and the Cf value is 24.40%, indicating that the irradiance of this system is high and the technical efficiency is low. The reasons for this situation are air and panel temperature, inverter losses and pollution. The efficiency of the 4.1 MWp PV system in 2024 is calculated as 16.53%. The observed system efficiency of 16.53% is slightly below the typical range of 17–20% for crystalline silicon PV systems. This reduction is mainly due to high ambient temperatures, partial shading, and dust accumulation, which aligns with operational experiences reported in the literature. There are many factors that negatively affect the system efficiency. It is known that the optimum temperature of solar panels is around 25 °C [14]. With the increase in panel temperature, the amount of energy produced and the speed of the electric current decreases. This situation causes a decrease in efficiency. The effect of shading on the power output of a solar plant is highly variable. The loss rate caused by shading in PV systems is around 7%. The pollution effect affects the system efficiency by 2% [15].

Conclusion. Increasing environmental problems on a global scale and efforts to combat climate change have gained importance in prioritizing renewable energy sources in energy production. The desire to significantly reduce greenhouse gas emissions worldwide by 2050 encourages countries to turn to clean energy alternatives by reducing fossil fuel dependency. As a clean energy, solar energy stands out with its low environmental impact, long-term economic advantages, and wide applicability. In this study, the performance analysis, methods and findings of a grid-connected PV system with an installed capacity of 4.1 MWp on the roof of Baykan Denim Company are examined. In the system, electricity generation in excess of consumption is transmitted to the grid. This system plays an important role in reducing carbon emissions as electricity is generated from solar energy, one of the renewable energy sources. With the artificial intelligence-based Solarify program used to analyze the system performance, the performance parameters were evaluated and the applicability of the system was discussed. The findings show that the PV system generates 5446145.798 kWh per year, has a system efficiency of 16.53%, a PR of 0.81 and efficient sunlight conversion. The energy production and efficiency assessment shows that these existing losses need to be

minimized. In addition, with the presence of the PV system, a total of 3022.61 tons of CO₂ emissions were reduced in 2024, proving that it has significant environmental impacts. The study serves as an example for enterprises with high energy consumption in the region.

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