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Performance analysis of a solar power plant: Simulation and experimental validation

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ABSTRACT

This paper analyses the performance of a 30 kWp rooftop solar power plant located in Čačak, Serbia. The study covers 12months, comparing electricity generation with simulations obtained using the System Advisor Model (SAM). The photovoltaic system was modelled with local meteorological conditions, such as solar irradiation, temperature, and wind, as well as the technical characteristics of modules, inverters, and other installed components. In addition to energy performance assessment, a thermographic inspection of the panels was carried out after one year of operation to detect potential defects that could affect efficiency. The inspection revealed thermal anomalies such as hot spots, defective cells, and mechanical damage, which may compromise long-term reliability. By comparing simulation and measurement results, the model's accuracy was evaluated across different seasons. Deviations between simulated and actual values were smallest in summer, while larger discrepancies occurred in winter due to lower solar irradiation, adverse weather, and possible losses from snow and moisture. The obtained results confirm the reliability of SAM software for evaluating and predicting solar power plant performance, while also emphasizing the importance of complementary long-term monitoring and diagnostic methods, such as thermographic inspection.

KEYWORDS

Photovoltaic System, Solar Power Plant, System Advisor Model(SAM), Performance Analysis, Experimental Validation

1. INTRODUCTION

The deployment of photovoltaic (PV) systems for electricity generation has grown rapidly in recent years, particularly in urban settings where they are increasingly used for both energy generation and distribution. By the end of 2023, global PV capacity surpassed 1.6 TW, and long-term projections indicate that it may reach 5–10 TW by 2050. According to international energy outlooks, renewable capacity worldwide is expected to expand by more than 5.5 GW between 2025 and 2030, representing a 2.6 times larger increase than that achieved in the preceding six years (2017–2023). PV is anticipated to contribute nearly 80% of this new renewable capacity, with growth driven primarily by declining technology costs, faster permitting procedures, and rising societal acceptance [1].

Simulation models play a central role in assessing the performance of PV systems, as they enable accurate forecasting of electricity generation and support techno – economic optimization. Their applications range from evaluating the solar resource potential of a site to fine-tuning system design under real operating conditions. Depending on the objective, models can be relatively simple – using broad assumptions regarding component behaviour and system losses, or advanced, integrating manufacturer specifications, parameter estimation, and empirical relationships. The selection of an appropriate model depends on the accuracy requirements, data availability, and the system's configuration. The use of complex models is justified only when a high level of precision is required [2].

The academic literature provides extensive contributions on the modelling, simulation, and validation of PV systems. Numerous studies have refined numerical modelling approaches, developed algorithms for estimating energy losses, and proposed methods for optimizing system configuration. Comparative analyses with experimental data have been particularly important, as they help evaluate model accuracy and reveal critical factors that influence system operation. Growing access to solar resource datasets and improvements in simulation software further enhance the reliability of performance assessments and support better planning of PV projects across different climates and geographies [3–6].

In this study, we present an analysis of the performance of a 30 kWp rooftop photovoltaic power plant installed on the roof of the Faculty of Technical Sciences in Čačak. The research includes an evaluation of monthly electricity generation during the first year of operation, with monitoring data compared to simulations conducted using the System Advisor Model (SAM).In addition to energy generation analysis, experimental investigations were carried out to validate system performance, including infrared thermography measurements of the PV modules to assess their quality and detect potential operational irregularities.

2. SYSTEM CHARACTERISTICS AND ENERGY PERFORMANCE OF THE PV PLAN

At the Faculty of Technical Sciences in Čačak, the installation of a 50 kW solar power plant has been planned, to be implemented in two phases. In the first phase, a 30 kW plant was installed, while the second phase, representing an expansion of the capacity by an additional 20 kW, is currently in progress. In the global geodetic coordinate system, the location of the plant is at latitude 43°53'49" N and longitude 20°20'42" E (Figure 1). The purpose of the photovoltaic system is to generate electricity to cover the faculty's own consumption needs, while any surplus energy produced is delivered to the power grid. The Faculty of Technical Sciences has officially obtained the status of a prosumer, which enables both consumption and delivery of electricity to the grid.

Figure 1: Layout of the solar power plant

The solar plant is mounted on the flat roof of the faculty building, on the third floor (Figure 2). The supporting structure is fixed, without a sun-tracking mechanism, and positioned at an angle of 10° relative to the horizontal plane, with modules oriented southeast and northwest in line with the roof surfaces. The system consists of monocrystalline photovoltaic modules, Jetion Solar JTSGh455W, with dimensions of 2094 mm × 1038 mm × 35 mm and an individual rated power of 455 Wp. The connection between solar panels is made using SOLAR PV CABLE 1×6 mm^2 type cables. The installed PV modules are designed for a service life of 30 years, with minimal maintenance requirements and a very low probability of failure.

The building of the Faculty of Technical Sciences in Čačak is located on flat terrain, without surrounding structures that could cause shading of the area where the solar power plant is installed. On the roof of the faculty, there is a technical space designated for the elevator equipment, which is elevated compared to the surface where the solar power plant is placed, and therefore can partially shade the solar modules during certain parts of the day and year. In addition, several tall fir trees are located next to the building, which during the winter months may partially shade the nearby solar modules.

The installed inverter is a Huawei SUN2000-50KTL-M3 with a rated power of 50 kW, to which 66 solar modules with a total capacity of 30 kWp were connected in the first phase, arranged in strings of 18 and 15 panels per string. The inverter is mounted on the exterior wall beneath the roof canopy, while the AC distribution cabinet is located inside the faculty building, in the room where the switchboards are installed. The connection of the remaining 20 kW of solar modules to the inverter will be carried out in the second phase of the power plant expansion. The inverter is equipped with a Maximum Power Point Tracking (MPPT) system, which enables adaptation to optimal changes in the electrical parameters of the cells caused by variations in solar irradiation, thereby increasing the utilised power. It allows controlled modulation of the alternating current waveform and automatically adjusts to the available power and changes in the input voltage of the modules, caused by fluctuations in solar radiation and temperature.

Figure 2: 30 kWp rooftop PV plant at the Faculty of Technical Sciences, Čačak

Figure 3 shows the monitoring data of the electricity generation of the faculty's solar power plant, which was commissioned on January 18, 2024, as well as the consumption, i.e., the amount of electricity purchased from the distribution grid. The imported electricity data are provided for both 2023 and 2024 to allow a comparison of monthly consumption between the analysed periods. The values of purchased electricity were derived from monthly electricity bills and refer exclusively to the higher tariff, that is, electricity predominantly consumed during daytime hours. In 2023, the total amount of electricity purchased from the distribution grid during the higher tariff was 98.63 MWh, corresponding to an average monthly consumption of 8.22 MWh. In 2024, after the commissioning of the solar power plant, the annual electricity consumption from the grid decreased to 76.31 MWh, i.e., an average of 6.36 MWh per month. At the same time, the total electricity generation of the plant in 2024 amounted to 30.36 MWh. Based on the presented data, it can be concluded that, after the commissioning of the solar power plant, electricity purchased from the distribution grid during the higher tariff was reduced by 22.6%.

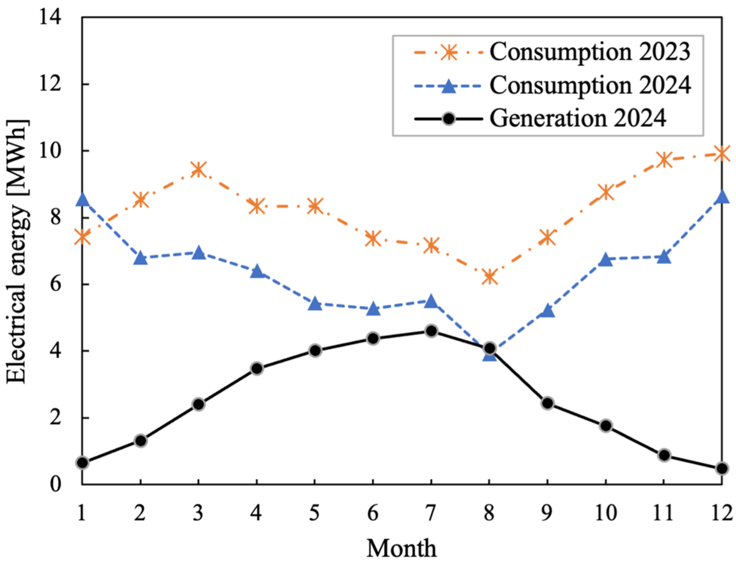

Figure 3: Monthly electricity consumption and generation – monitoring data

In order to assess the current condition of the solar modules and verify the proper operation of the system, a thermographic analysis of the modules was performed (Figure 4). The purpose of the investigation was to identify potential irregularities, such as hot spots or uneven temperature distribution, which could indicate damage, material degradation, or reduced efficiency. Thermal imaging conducted on sunny days in February 2024 under stable irradiation conditions confirmed the absence of thermal anomalies on the panels.After one year of operation, the absence of damage confirmed the stable and reliable functionality of the solar modules. Regular maintenance during the first year of operation, including periodic inspections and cleaning of the module surfaces, contributed to preserving their performance and preventing potential degradation. Moreover, the modules were installed in compliance with technical standards and operated under stable grid conditions, which further reduced the likelihood of defects. The lack of thermal anomalies therefore verifies the correct operation of the system and the uniform load distribution across all cell segments, ensuring the optimal efficiency and long-term reliability of the modules.

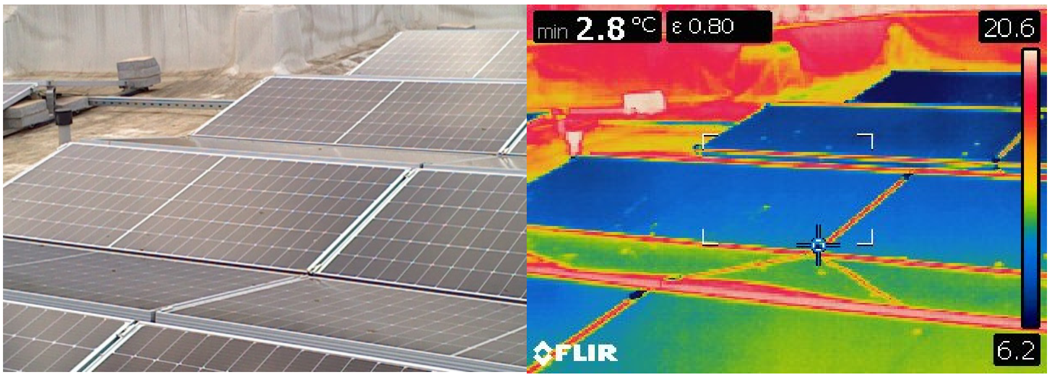

Figure 4: Thermographic image of solar modules

3. SAM-BASED MODELLING OF THE PV PLANT

Numerous software tools are currently in use for simulating the performance of photovoltaic (PV) systems, enabling the analysis and optimization of their operation under various working conditions. The utilization of these tools allows efficient evaluation of energy system performance, ensuring high accuracy with minimal cost [7-8].In this study, the System Advisor Model (SAM) software was employed to simulate the operation of the PV power plant at the Faculty of Technical Sciences in Čačak [9]. SAM is designed to evaluate the energy performance and economic feasibility of renewable energy systems. The software includes libraries of PV system components, incorporating technical specifications of solar modules, inverters, as well as meteorological parameters and other data required for system design. The program allows for parametric analyses, statistical data processing, and exceedance probability analysis. Models developed in SAM calculate the system's hourly electricity generation, producing a dataset of 8,760 values that represent the electricity output of the system over the course of one year [10,11].

SAM contains meteorological databases for PV plants in the United States, but it also allows for expanding the database by adding European locations. For modelling the rooftop PV power plant at FTN in Čačak, the nearest location, the city of Kraljevo, was selected. Figure 5 shows the distribution of surface solar irradiance on an hourly basis over one year for the chosen location as used in the SAM software, which relies on ASHRAE meteorological input data.

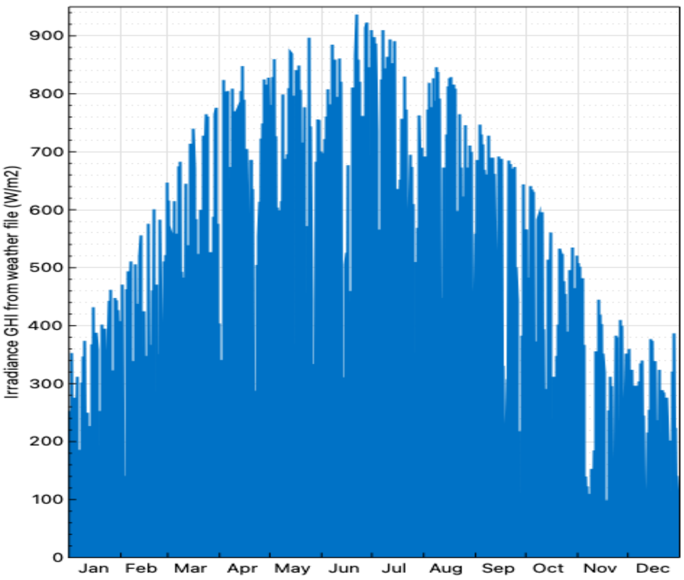

Figure 5: Hourly global solar irradiance on a horizontal surface

The SAM software contains databases of various equipment manufacturers, allowing users to select solar modules and inverters based on defined technical specifications. These databases include key performance parameters which facilitate the design and optimization process of solar power plants. In addition to using predefined databases, the software also enables manual definition of module and inverter operating parameters, thereby providing users with the flexibility to input the characteristics of equipment not included in the database but for which manufacturers provide technical specifications that can be directly entered into the software.

In developing the simulation model of the faculty's solar power plant, the characteristics of the modules and inverters installed in the actual system were used. These characteristics were taken from the manufacturer's technical documentation, ensuring the reliability of the model and the accuracy of the simulation. The basic parameters of the simulation model are presented in Table 1.

Table 1: Input parameters and equipment specifications of the SAM Advisor PV model

Geographical location	43.7°N, 20.7°E
Solar power plant	
Installation type	Prosumer
Capacity	30 kWp
Location	Rooftop
Shading	Partial
Solar module	Monocrystalline / Jetion Solar JTSGh455 W
Number of modules	66 - 2 strings
Tilt	10°
Orientation	Southeast and Northwest
Solar module characteristics	
Dimensions	2094 mm × 1038 mm × 35 mm
Maximum power Pmax	455 Wp
Voltage at maximum power point (Umpp)	41.6 V
Current at maximum power point (Impp)	10.94 A
Open-circuit voltage (Uoc)	50.2 V
Short-circuit current (Isc)	11.51 A
Temperature coefficient of Uoc	−0.27 % / °C
Temperature coefficient of Isc	0.048 % / °C
Temperature coefficient of Pmpp	−0.35 % / °C
Number of cells	144
Nominal operating cell temperature	4 °C
Efficiency	20.9 %
Inverter characteristics	
Model	Huawei SUN2000-50KTL-M3
Weighted efficiency	98 %
Maximum output power (P_{acmax})	50 kW
Nominal output voltage (U_{ac})	400 V
Maximum input voltage (U_{dcmax})	1100 V
Maximum input current (I_{dc})	20 A
Operating voltage range	200 V – 1000 V
Nominal input voltage (U_{dc})	600 V
Maximum number of inputs per MPPT	8
Nighttime consumption	5.5 W

Once the technical specifications of the solar module were entered, the current–voltage (I–V) characteristic was generated, as shown in Figure 6.

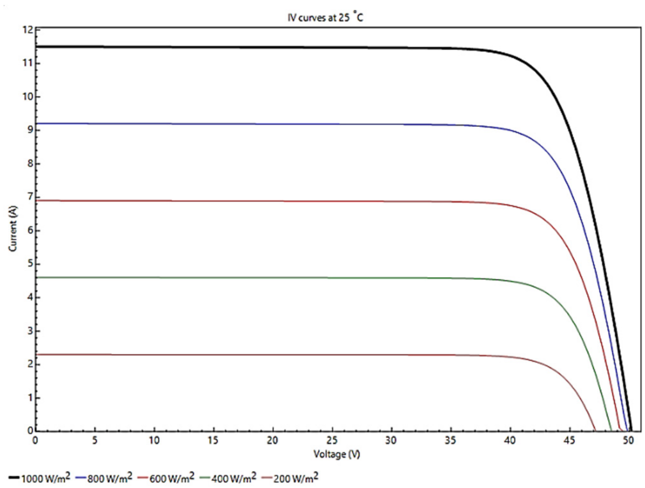

Figure 6: The current-voltage (IV) curve for JTSGh455 W module

In the simulation model of the PV power plant, the 50 kW inverter was oversized. Its maximum output power was utilized at 45.33 % of capacity, since the total installed system capacity in the first phase was 30 kW out of the planned 50 kW. Assuming total system losses of 9 %, the simulation of the plant's operation at the selected location was performed.

4. SIMULATIONRESULTS AND COMPARISON WITH MONITORING DATA

Using the operational and design parameters of the PV power plant, the SAM model was developed, and a simulation was performed. The results indicated an annual electricity generation of 35167 kWh, corresponding to an average annual yield of 1171 kWh per kW of installed capacity. Figure 7 presents the simulation results of the monthly electricity generation for an average year. In June and July, the system achieved the highest monthly generation of 4400 kWh, whereas the lowest value was recorded in December at 1118 kWh. These values were expected due to significant differences in monthly solar insolation between summer and winter months, as illustrated in Figure 5.

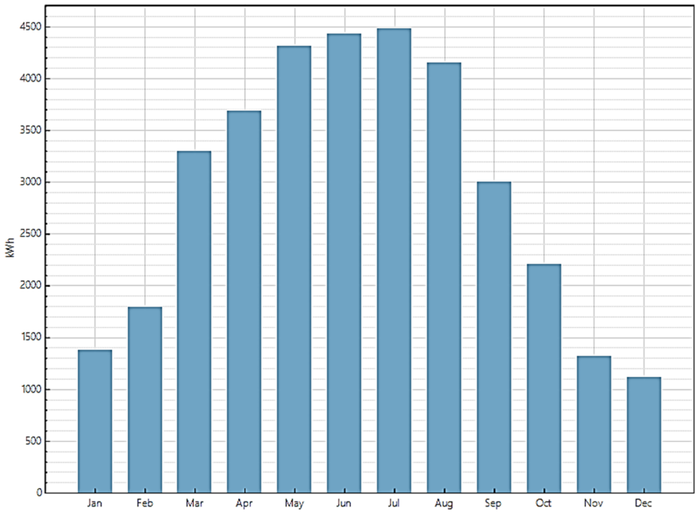

Figure 7: Average monthly electricity generation of the PV power plant – simulation results

Validation of the simulation model was performed by comparing simulated and monitoring electricity generation data to evaluate the accuracy of the developed model. The rooftop PV power plant at the Faculty of Technical Sciences in Čačak has been in operation since January 2024, and its performance has been continuously monitored. The electricity generation data are recorded via the FusionSolar platform, a software solution developed by Huawei for monitoring and managing solar power plants. This platform enables reliable validation of the simulation model by providing effective tracking of PV system performance, data analysis, and real-time optimization of plant operation (Figure 8). In addition to real-time monitoring, FusionSolar incorporates advanced diagnostic functions, such as Smart I-V Curve Diagnosis and full-link analysis, which enable the rapid detection of irregularities and the accurate identification of performance losses, thereby enhancing system reliability and reducing maintenance costs. Furthermore, the platform integrates artificial intelligence algorithms for the optimization of operational parameters, including energy storage management and inverter control, which contribute to more efficient energy balancing and facilitate long-term planning of solar plant operation [12].

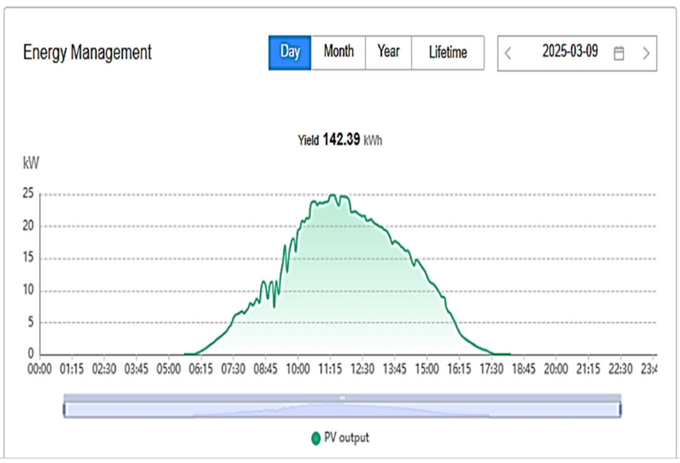

Figure 8: Huawei FusionSolar platform for monitoring electricity generation

Figure 9 shows a comparison between the electricity generation obtained using the simulation model of the power plant and the monitoring electricity generation values. The difference between the simulated and monitored electricity generation varies throughout the year. During simulations, the model relies on specific assumptions regarding the operating conditions of the plant, which may not fully account for real variations such as unexpected shading, panel soiling, or the actual performance of system components.

During the period from April to August, solar irradiation is significant, characterized by extended daily sunshine hours and maximum levels in the summer months, resulting in differences between the compared values of up to 8%. Under conditions of high solar irradiation, the simulation results are closer to the actual monitoring values of electricity generation, primarily due to more stable atmospheric influences and lower sensitivity of the model to short-term fluctuations. During the period of reduced solar irradiation, from February to March, the difference between simulated and monitoring data reaches up to 26%, while in September and October it increases to 35%. During the winter months, this discrepancy becomes more pronounced, exceeding 53%, with the maximum deviation observed in December. Such deviations are largely attributed to lower module efficiency under diffuse radiation, increased impact of snow, fog, and humidity, as well as potential soiling of modules, all of which are not fully captured by the assumptions applied in the simulation model.

Analysis of available studies on the application of the SAM model for simulating PV plant operation has shown that the SAM Advisor model tends to yield significantly higher values compared to monitoring during the winter months [7]. The simulated annual electricity generation was 35.17 MWh, while the measured production reached 30.36 MWh, indicating an agreement level of approximately 85% between the SAM model and the actual system performance. Comparable findings have also been presented in previous research involving models generated by various simulation software, which supports the validity of the results obtained in this study [13].

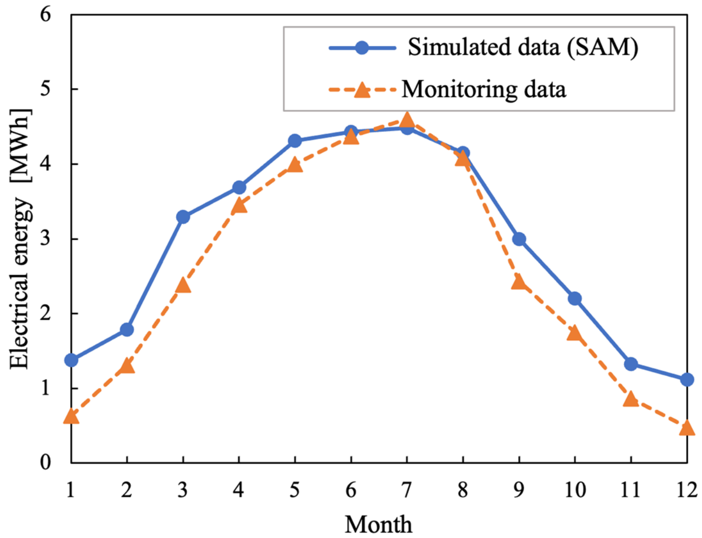

Figure 9: Monthly electricity generation – comparison of simulated and monitoring data

5. CONCLUSION

This study presents the applicability of the System Advisor Model for simulating the performance of a 30 kW rooftop photovoltaic system installed at the Faculty of Technical Sciences in Čačak. The comparison of simulated and measured electricity generation showed an overall agreement level of about 85% for the year under study. Deviations were relatively small during the summer months, not exceeding 8%, which can be attributed to stable weather conditions and higher solar irradiation, while larger differences were observed in winter due to the influence of variable atmospheric factors. These findings confirm that SAM provides a reliable basis for performance evaluation of PV systems and can serve as a valuable tool for planning, optimization, and integration of renewable energy technologies.

Although the one-year analysis provides valuable insights into the accuracy of the model, a more precise validation of the simulation results would be possible if experimental data over a longer time period were available. Long-term measurements would allow the inclusion of seasonal and annual variations, the identification of system degradation trends, and the assessment of the impact of extreme weather conditions on the performance of photovoltaic modules, thereby improving the predictive capability of the model and its applicability under real operating conditions.

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