

OPERATIONAL PERFORMANCE ASSESSMENT
OF A GRID-CONNECTED PHOTOVOLTAIC
SYSTEM IN SOUTHWESTERN BULGARIA

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Abstract

The increasing deployment of grid-connected photovoltaic (PV) systems highlights the need for performance assessment based on measured operational data. While PV modules are commonly characterized under Standard Test Conditions (STC), actual system performance depends on local climatic and operating conditions. This study presents a performance analysis of a grid-connected PV system in the Mikrevo region, Southwestern Bulgaria, using high-resolution operational data collected in 2025. The analysis uses measured energy production data at hourly, daily, and monthly scales. A data-driven approach was used to assess seasonal trends, short-term variability, and normalized performance indicators. Monthly production, daily variability, and diurnal profiles were examined to characterize system behaviour. Specific energy yield and capacity factor were calculated for normalized performance assessment. The results show clear seasonal variation and stable production patterns throughout the analysed year. A qualitative comparison with aggregated 2024 data indicates similar interannual production patterns. The findings demonstrate the value of high-resolution operational data for PV performance assessment and provide site-specific evidence from Southwestern Bulgaria.

Key words: grid-connected photovoltaic system, performance assessment, high-resolution operational data, temporal analysis, Bulgaria

Introduction. The rapid deployment of grid-connected photovoltaic (PV) systems has increased the need for performance assessment based on measured

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operational data. Although PV modules are commonly characterized under Standard Test Conditions (STC), actual system performance depends on local climatic, installation, and operating conditions. High-resolution production data therefore provide valuable information on temporal behaviour, seasonal variability, and overall system performance. Recent advances in monitoring and data acquisition enable analyses at multiple time scales, supporting the assessment of PV operation and grid integration [1, 2].

Despite the growing number of publications on PV performance, empirical studies based on high-resolution operational data remain limited for specific locations in Southwestern Bulgaria. This study investigates a grid-connected PV system located in the Mikrevo region, near Sandanski, Bulgaria, using measured hourly, daily, and monthly energy production data for 2025. The analysis focuses on temporal production patterns, seasonal variability, specific energy yield, and capacity factor. The study provides site-specific empirical evidence on PV system operation under real operating conditions and complements existing performance assessments for the region.

Theoretical background. Performance assessment of grid-connected photovoltaic (PV) systems commonly relies on field measurements and normalized indicators such as performance ratio (PR), capacity factor (CF), and specific energy yield, which facilitate comparison between systems of different sizes and configurations [1]. Field studies have demonstrated that PV performance is influenced by module technology and local environmental conditions. TAHRI et al. [2] analysed the technical and economic performance of thin-film grid-connected PV systems in Southern Spain, while ELIBOL et al. [1] examined different PV module technologies under real climatic conditions. These studies emphasize the importance of field-based measurements for reliable PV performance assessment.

Recent research has increasingly applied data-driven methods to PV systems, including solar radiation forecasting [3], control strategies for grid-connected systems [4], photovoltaic-thermal technologies [5], degradation assessment [6], and maximum power point tracking [7]. These approaches demonstrate the growing role of operational data and advanced analytical methods in understanding and improving PV system performance.

PV performance is also closely related to energy storage, grid integration, and distributed energy systems. Ageing-aware control strategies for grid-connected PV-battery systems have been investigated by ZHANG et al. [8], while KELEPOURIS et al. [9] examined shared photovoltaic projects and energy communities in Southeastern Europe. ZAPPAROLI et al. [10] highlighted the importance of distributed energy resources and operational data for future distribution grids. Together, these studies underline the relevance of reliable operational data at both system and energy-network levels.

System reliability and fault detection constitute another important research direction. TUFAIL and SARWAT [11] investigated dimensionality-reduction meth-

ods for inverter fault detection, while OBATOLA and JUNJIE [12] proposed a data-driven approach for PV system reliability assessment. KIŞECOK et al. [13] further demonstrated the potential of AI-based real-time monitoring for evaluating the operational performance of grid-connected PV plants.

Despite the extensive literature on the subject, empirical studies based on high-resolution operational data remain limited for specific locations in Southwestern Bulgaria. The present study addresses this gap by analysing hourly, daily, and monthly energy production data from a grid-connected PV system in the Mikrevo region. The analysis focuses on temporal production patterns, seasonal variability, specific energy yield, and capacity factor, providing a site-specific assessment based on measured operational data.

System description and data. The photovoltaic system analysed in this study is a grid-connected installation located in the Mikrevo region, Municipality of Strumyani, Southwestern Bulgaria. The system is fixed-mounted on the roof of an existing building, oriented southward with a tilt angle of approximately 15°, and connected to the low-voltage distribution network.

The installation has an installed DC capacity of 29.88 kWp and consists of 83 monocrystalline silicon modules rated at 360 Wp each, based on mono-PERC technology and manufactured by Canadian Solar. The system is equipped with a Huawei SUN2000-33KTL-A inverter with a rated AC power of 30 kW, corresponding to a DC-to-AC ratio of 0.996. The main technical characteristics are summarized in Table 1.

T a b l e 1
Main technical characteristics of the investigated photovoltaic system

Parameter	Specification
System type	Grid-connected photovoltaic system
Location	Mikrevo, Southwestern Bulgaria
Installed DC capacity	29.88 kWp
PV modules	83 × 360 Wp, monocrystalline silicon, mono-PERC
Inverter	Huawei SUN2000-33KTL-A
Rated AC power	30 kW
Mounting configuration	Fixed, rooftop-mounted
Array orientation	South-facing
Tilt angle	Approximately 15°
Grid connection	Low-voltage distribution network
Data resolution	Hourly, daily, and monthly energy production

The analysis is based on measured electrical energy production data collected in 2025 and available at hourly, daily, and monthly resolutions. The datasets were checked for completeness, chronological consistency, duplicated records, and consistency between temporal aggregations. Energy values represent electricity produced by the PV system under actual operating conditions.

Due to the absence of on-site measurements of solar irradiance and module temperature, the analysis focuses on energy-based performance indicators derived from measured production and system design parameters. Accordingly, performance ratio and temperature-corrected efficiency indicators are not calculated. The selected indicators, specific energy yield and capacity factor, provide a normalized assessment of system productivity and utilization under the available data conditions.

Methodology. The methodological framework is based on measured energy production data and the technical parameters of the photovoltaic system. A data-driven approach was applied at hourly, daily, and monthly time scales to assess temporal production patterns and normalized performance indicators. Data processing and visualization were performed in Python using the pandas, NumPy, and matplotlib libraries.

The datasets contained hourly, daily, and monthly energy production values. Prior to analysis, the data were checked for chronological consistency, missing or duplicated records, and consistency between temporal aggregations. Hourly data were used to characterize short-term and diurnal behaviour, while daily and monthly data were used to assess variability and seasonal production. All energy values were expressed in kilowatt-hours (kWh).

The specific energy yield is a normalized performance indicator that relates the electrical energy produced to the installed DC capacity of the photovoltaic system. It enables comparison between systems of different sizes and technologies operating under diverse conditions.

The specific yield Y_f was calculated as:

$$(1) \quad Y_f = \frac{E}{P_{DC}},$$

where E is the total electrical energy produced during the considered period (kWh), and P_{DC} is the installed DC capacity of the photovoltaic system (kWp).

Specific yield values were calculated on a monthly and annual basis and expressed in units of kWh/kWp. This indicator provides insight into the overall productivity of the system and facilitates comparison with reported values from similar photovoltaic installations in the literature.

The capacity factor (CF) represents the ratio between the actual energy produced by the photovoltaic system and the maximum possible energy output if the system were to operate at its nominal AC power continuously over the same period.

The capacity factor CF was calculated as:

$$(2) \quad CF = \frac{E}{P_{AC} * T},$$

where E is the total electrical energy produced during the considered period

(kWh); P_{AC} is the rated AC power considered for the performance assessment (kW); T is the duration of the considered period (hours).

Monthly capacity factor values were calculated to characterize seasonal variations in system utilization. Hourly production data were further used to construct representative diurnal profiles, while daily and monthly aggregations were used to characterize seasonal variability and cumulative energy production. The use of multiple temporal resolutions allows short-term production behaviour to be examined together with longer-term seasonal patterns.

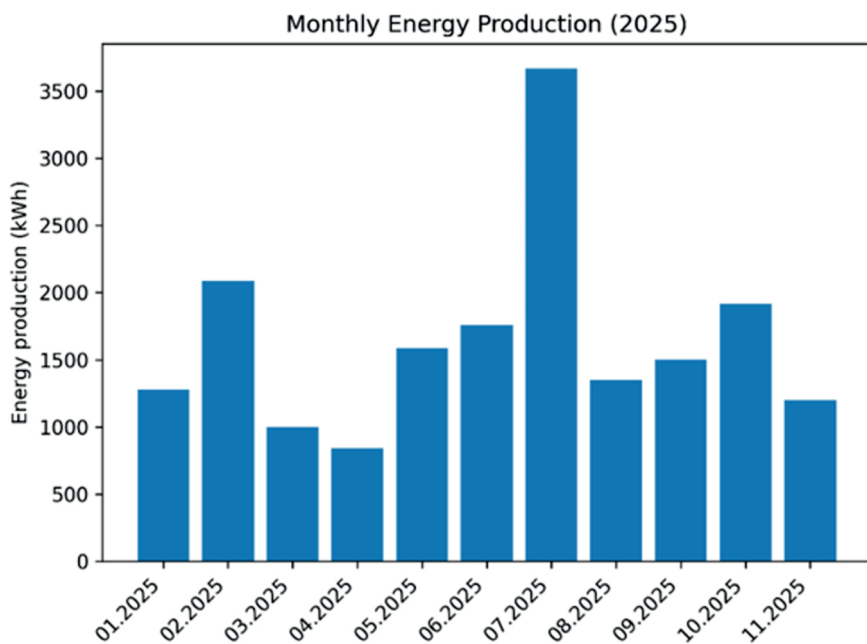
Since on-site measurements of solar irradiance and module temperature were not available, performance ratio and temperature-corrected efficiency indicators were not calculated. The analysis therefore focuses on the energy-based indicators of specific yield and capacity factor, which can be derived directly from measured production and the known system parameters.

Results and discussion. The analysis of hourly, daily, and monthly operational data collected in 2025 provides an assessment of the temporal and seasonal behaviour of the investigated photovoltaic system. For 2024, only aggregated monthly production data were available and were therefore used only for qualitative interannual comparison.

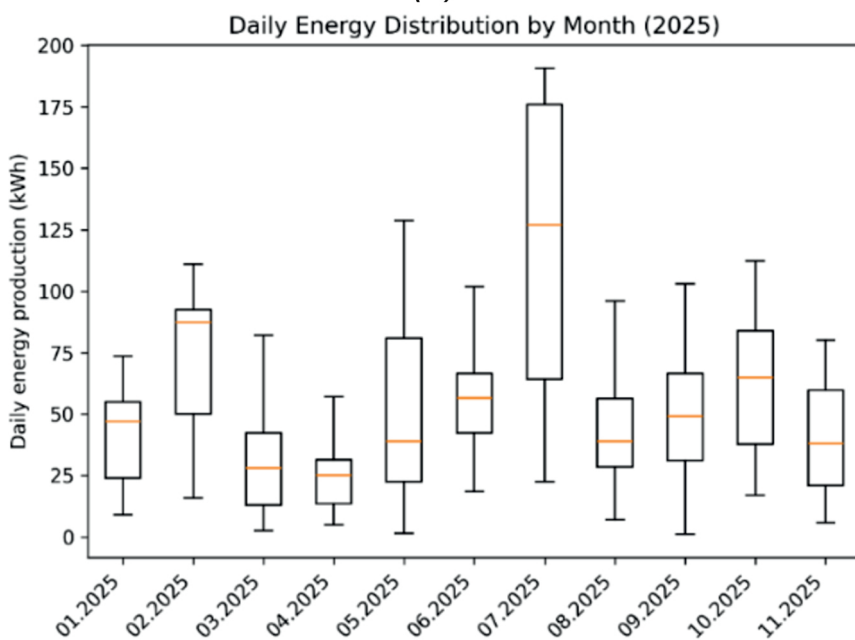
Figure 1 illustrates monthly energy production and the distribution of daily energy production of the photovoltaic system in 2025. A clear seasonal pattern is observed, with relatively low output in winter, increasing production in spring, a pronounced maximum in July, and a gradual decline toward autumn. This behaviour is consistent with seasonal variations in solar irradiance availability, day length, and solar elevation. Daily production shows substantial differences across seasons. Spring and autumn exhibit wider interquartile ranges, indicating greater variability, whereas summer combines higher median production with a narrower interquartile range, indicating more stable daily output. Winter shows lower median values and reduced absolute variability, consistent with shorter daylight hours and lower solar elevation.

The diurnal behaviour of the photovoltaic system is examined through median hourly production profiles for representative summer and winter periods, as shown in Fig. 2. The summer profile has a broader production window, with earlier onset, later termination, and higher peak values. In contrast, the winter profile shows a shorter production period and lower peak output. These differences are consistent with seasonal changes in daylight duration and solar elevation. The use of median values reduces the influence of atypical days and provides a representative view of seasonal system behaviour.

To assess system performance independently of installed capacity, normalized indicators were calculated. Figure 3a presents the monthly specific energy yield, expressed in kWh/kWp. The specific yield shows a clear seasonal pattern, with the highest values in summer and the lowest in winter. Figure 3b shows the corresponding monthly capacity factor, which follows a similar seasonal pattern



(a)



(b)

Fig. 1. Monthly energy production and daily production variability of the photovoltaic system in 2025. (a) Monthly energy production; (b) Distribution of daily energy production by month. Source: Author's presentation

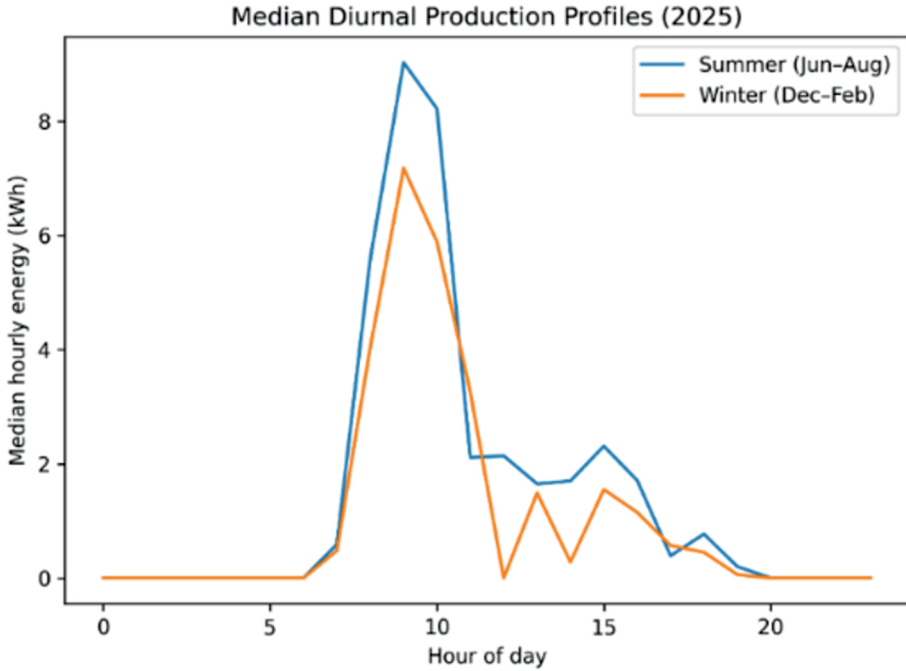
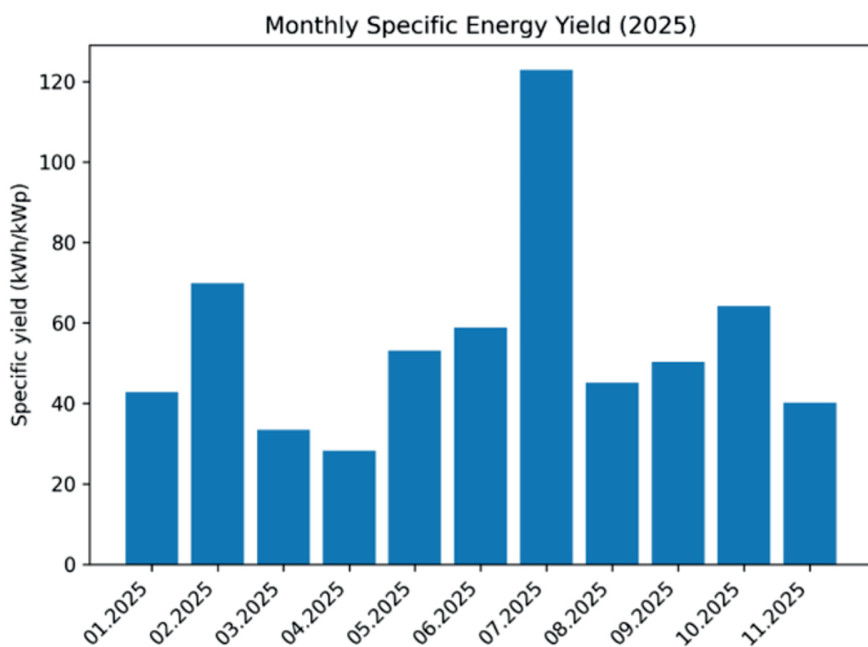


Fig. 2. Median hourly energy production profiles for summer and winter in 2025.
Source: Author's presentation

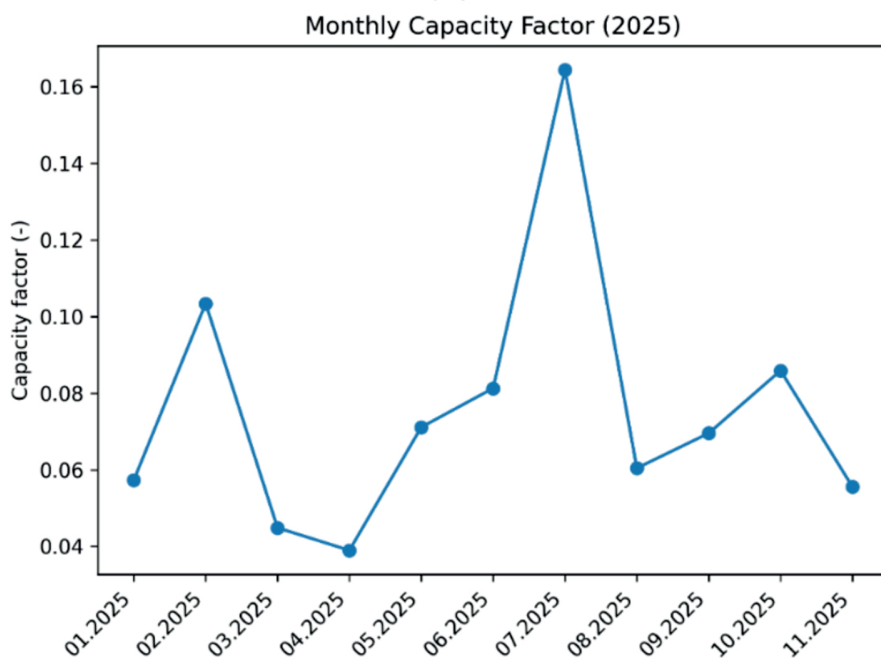
and reaches its maximum in mid-summer. Lower winter values are consistent with reduced solar availability and shorter daylight periods. Overall, both indicators show seasonal behaviour consistent with the expected operation of a fixed-tilt, grid-connected photovoltaic system.

The results obtained at the various temporal resolutions are consistent with one another. Higher production and normalized performance indicators occur in summer, while greater daily variability is observed mainly during the transitional seasons. A qualitative comparison with aggregated 2024 data indicates similar interannual production patterns. Overall, the results support the assessment of stable system operation throughout 2025.

Conclusion. This paper presented a performance assessment of a grid-connected photovoltaic system in Southwestern Bulgaria based on hourly, daily, and monthly operational data collected in 2025. The results showed clear seasonal variation, with maximum production in summer and reduced generation in winter. Daily and hourly analyses revealed greater variability during the transitional seasons, while median hourly profiles confirmed seasonal differences in production duration and intensity. The specific energy yield and capacity factor exhibited consistent seasonal behaviour, and comparison with aggregated 2024 data indicated similar interannual production patterns. Overall, the results support stable system operation throughout 2025 and demonstrate the value of high-resolution operational data for site-specific PV performance assessment.



(a)



(b)

Fig. 3. Monthly normalized performance indicators of the photovoltaic system in 2025. (a) Monthly specific energy yield; (b) Monthly capacity factor. Source: Author's presentation

The findings provide empirical evidence on photovoltaic system performance under actual operating conditions and a basis for further research on long-term monitoring and regional photovoltaic deployment.

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