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# Evaluation of Solar Irradiation and Energy Production of a Photovoltaic System on Bawean Island using Pyranometer Measurements and PVsyst Simulation

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**ABSTRACT**

The increasing demand for electrical energy and the importance of transitioning to renewable energy sources have driven the development of solar photovoltaic (PV) systems, particularly in island regions with limited access to the electricity grid. This study analyzes the solar radiation characteristics and energy production effectiveness of a PV system installed on Bawean Island, East Java, Indonesia, by combining pyranometer field measurements with simulations conducted using PVsyst. The primary objective is to compare the performance of the simulated system with the actual system and identify key factors influencing energy output variations. Data collected during January 2026 included daily solar radiation readings from pyranometers and energy production data from a 408.24 kWp PV system featuring three Sungrow SG110CX inverters. Solar radiation values were calculated from the daily average irradiance, while system performance was assessed using specific yield and performance ratio (PR) as key metrics. The PVsyst simulations used Meteonorm meteorological information to model the system under optimal conditions. During the observation period, the actual PV system produced a total of 24,326.7 kWh, averaging 261.6 kWh per day, with an average irradiance of 344.6 W/m². The simulation showed an expected annual energy output of 681,545 kWh, a specific yield of 1,669 kWh/kWp/year, and a performance ratio of 84.09%, reflecting strong system efficiency in the ideal scenario. A comparison of the simulated and actual data for January shows a discrepancy of approximately 37.5%, largely due to the use of long-term synthetic meteorological data in PVsyst rather than current weather variations, such as cloud cover and rainfall. Other influencing factors include losses due to temperature variations, changes in inverter efficiency, and periods of system downtime that were not accounted for. A scatterplot analysis indicates a positive relationship between solar irradiance and energy production; however, the non-linear dispersion suggests that additional environmental and technical factors also play a role. These results highlight the importance of combining real field data with simulation results to achieve an accurate evaluation of PV system performance, especially in tropical regions with significant climate variability.

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## 1. Introduction

In recent decades, the escalating global demand for electrical energy combined with growing concerns over the environmental consequences of fossil fuel dependency has driven the rapid development of renewable energy technologies across numerous countries [1,2]. Solar energy has emerged as one of the most promising renewable energy sources owing to its abundant natural availability and its inherently environmentally friendly characteristics compared to conventional energy sources. Solar photovoltaic (PV) technology enables the direct conversion of sunlight into electrical energy without generating greenhouse gas emissions during operation, positioning it as one of the cleanest electricity generation technologies currently available. As a result, the adoption of PV systems has expanded significantly worldwide as a sustainable alternative to address the continuously growing demand for electrical energy [1].

Indonesia's geographical position within the equatorial tropics endows the country with relatively high and consistent solar energy potential throughout the year. The average daily solar irradiation across Indonesia ranges between 4 and 5.5 kWh/m²/day, demonstrating that solar energy holds considerable promise for optimal utilization in electricity generation across the archipelago [2], [3].Among the various parameters governing the performance of a Solar Power Plant (PLTS) system, the amount of solar irradiation received by the PV module surface is considered one of the most critical determinants of system output. Solar irradiation is defined as the total solar radiation energy incident upon a unit surface area over a defined period of time, commonly expressed in units of kWh/m² [3]. Consequently, a thorough analysis of solar irradiation constitutes a fundamental element that must be carefully considered both during the system planning stage and throughout the ongoing evaluation of solar power plant performance [3].

In solar power plant systems, solar radiation is typically measured using dedicated instruments such as pyranometers, which are capable of directly quantifying the intensity of solar radiation reaching the module surface [4]. The data acquired from pyranometer measurements can be processed to derive both solar irradiance and solar irradiation values, which are subsequently analyzed to characterize the solar energy potential at a specific location [4]. Alongside field measurement approaches, simulation software platforms such as PVsyst have been extensively utilized to estimate energy production of PV systems by incorporating meteorological parameters, system configuration details, and local environmental conditions into the modeling framework. PVsyst is broadly acknowledged as a reliable and robust tool for PV system performance analysis due to its ability to model individual system components and simulate various categories of energy losses under realistic operating conditions [5,6].

Numerous previous studies have investigated solar energy potential and PV system performance across diverse geographical regions by combining solar radiation datasets with simulation-based modeling approaches [7]. for instance, conducted a comprehensive performance analysis of PV systems utilizing solar radiation data integrated with PVsyst simulations to evaluate energy production outcomes. In a related study, Yadav and Bajpai demonstrated that PVsyst simulations are capable of yielding reasonably accurate energy production estimates when underpinned by valid and high-quality solar radiation data[8]. More recent investigations have further corroborated that the integration of field-measured data with simulation models substantially enhances the reliability and accuracy of PV system performance assessments [9-11].

Despite the growing body of literature addressing solar energy potential and PV system energy production, studies that specifically combine direct solar irradiation measurements obtained from pyranometer instruments with PVsyst-based simulation models remain relatively scarce, particularly for PV systems deployed in archipelagic settings such as Bawean Island. The distinctive geographical characteristics and localized climatic conditions of such regions can produce significant spatial and temporal variations in the solar irradiation received by PV modules, which may not be adequately captured by generalized simulation inputs. Therefore, a more comprehensive and site-specific analytical framework is necessary to accurately assess PV system performance in these environments [12-14]. Driven by this identified research gap, this study aims to evaluate the solar irradiation characteristics and estimate the energy production of the PV system on Bawean Island by leveraging pyranometer measurement data validated through PVsyst simulation outputs.

## 2. Methodology

### *2.1 Research Flowchart*

The method used in this study is systematically designed to assess the performance of a solar power generation system by integrating real-world measured data with simulation output. This study adopts a quantitative approach that combines field measurements, data processing, and computer-based simulations to evaluate the operational performance of a photovoltaic (PV) system installed on Bawean Island. The overall research workflow is illustrated in Figure 1 and explained in detail below.

The research process was initiated with a comprehensive literature review to establish the theoretical foundation and identify relevant performance indicators used in PV system evaluation. Following this, primary data were collected from two main sources: irradiance data measured using a pyranometer installed at the site, and energy production data obtained directly from the solar power plant monitoring system. The collected data were subsequently subjected to a validation process to ensure accuracy, consistency, and completeness before further analysis was conducted.

After validation, the irradiance data went through a processing phase where the original irradiance measurements were transformed into solar radiation values that could be used as simulation inputs. The PVsyst program was then used to simulate energy generation using the processed data along with system specifications and geographic location parameters. By integrating component features, array arrangement, and a variety of loss parameters, PVsyst, a well-known simulation tool created for the design and performance analysis of photovoltaic systems, can replicate system behavior under real climatic conditions [15-17].

System performance parameters, such particular yield and performance ratio, which are important indicators for assessing the efficiency and effectiveness of the PV system, were determined after the simulation process. The performance ratio, on the other hand, represents the overall system efficiency in comparison to the theoretically available solar energy, whereas the specific yield reflects the net energy output per unit of installed capacity. In order to facilitate a fair and unbiased comparison between the two datasets, these parameters were calculated for both the real measured data and the PVsyst simulation outputs.

The research concluded with a comparison of the simulation results with the real operational data. The purpose of this comparison was to determine any differences between simulated and actual performance, pinpoint possible loss variables, and assess the simulation model's validity in tropical operating circumstances. Following this study, the results were applied to ascertain the overall efficacy of the solar power plant system on Bawean Island.

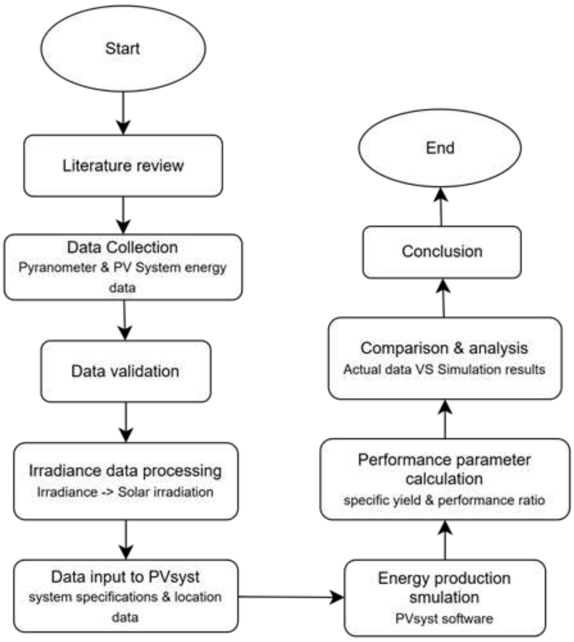


**Fig. 1.** Research methodology flowchart

### *2.1 Research Location and Data Source*

The study presented in Figure 2 was conducted at a Solar Power Plant system located on Bawean Island, Gresik Regency, East Java. The location was selected based on the fact that Bawean Island possesses relatively high solar irradiation potential as an archipelago situated in the Java Sea, making it a suitable site for solar energy research. In addition to its favorable solar resource characteristics, the island also hosts a well-functioning photovoltaic power plant system, which allows for a comprehensive and reliable analysis of the relationship between solar irradiation and electricity production. Data collection was carried out over a one-month period, combining direct field measurements with system operational data to ensure that the dataset captured a representative range of operating conditions.

The data utilized in this study consisted of both primary and secondary data obtained from different sources to support a thorough performance assessment. Primary data were derived from solar irradiance measurements conducted using a pyranometer, an instrument specifically designed to measure the total solar irradiance incident on a horizontal surface, providing values in W/m² along with corresponding measurement timestamps. The pyranometer was installed at the site to ensure that the irradiance data recorded were representative of the actual solar resource available at the specific location of the PV system. These primary measurements served as the fundamental input for evaluating the correlation between available solar energy and the electrical output generated by the system.

Secondary data encompassed a broader range of information necessary to support the overall performance analysis of the PV system. This included records of the daily energy production of the solar power plant in kWh, the total installed system capacity expressed in kWp, and the detailed technical specifications of both the solar modules and the inverter units. Geographic information pertaining to the system's location, including latitude, longitude, and module orientation, was also incorporated to accurately characterize the site conditions within the simulation model. Furthermore, ambient and module temperature data were utilized as supplementary data, where available, to support the analysis of the system's thermal performance and to provide a more complete understanding of the factors influencing energy output under tropical operating conditions.

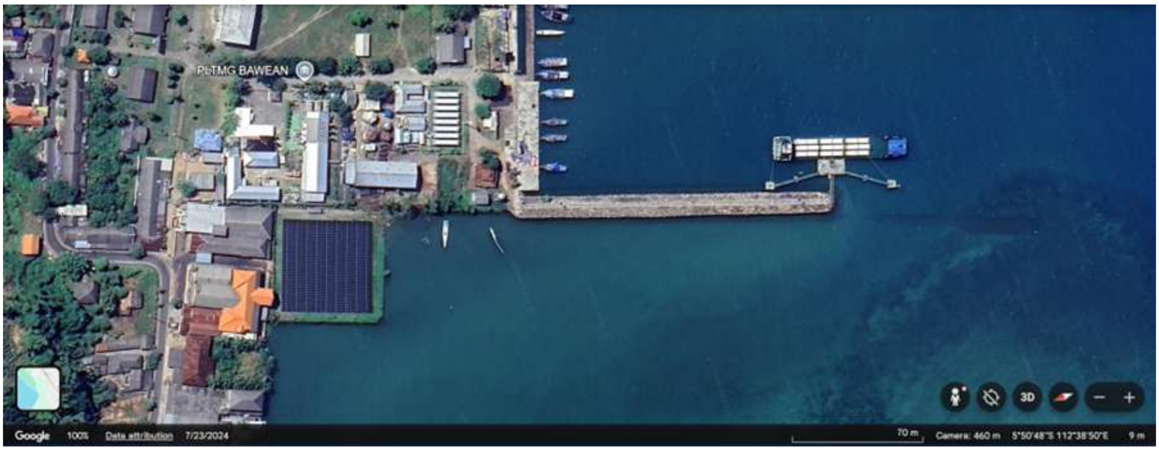


**Fig. 2.** PLTMG Bawean

### *2.2 Solar Power System Data and Specifications*

The data used in this study includes field measurements and technical specifications of the Solar Power Plant (PLTS) system on Bawean Island. These measurements include solar irradiance data obtained from a pyranometer in W/m², as well as daily data on electrical energy production in kWh. Irradiance data is used to calculate solar irradiance (kWh/m²/day), while energy production data is used to assess the performance of the PLTS system.

Information on energy production is obtained from the PLTS monitoring system, which consists of three generating units: PLTS 1, PLTS 2, and PLTS 3. Total daily energy is calculated by summing these three units. In addition, average daily irradiance data is used as the primary parameter in the analysis of the relationship between solar radiation and electrical energy production.

The PLTS system studied has a maximum installed capacity of 408.24 kWp (±1%). The technical specifications of the PLTS system can be seen in Table 1.

**Table 1**
Bawean Island solar power system specifications

| Parameter | Value |
|---|---|
| System Capacity | 408.24 kWp |
| PV Module | LR5-72HPH-540M |
| Module Power | 540 Wp |
| Maximum Power Voltage (Vmp) | 41.65 V |
| Maximum Power Current (Imp) | 12.97 A |
| Open Circuit Voltage (Voc) | 49.50 V |
| Short Circuit Current (Isc) | 13.85 A |
| Inverter | Sungrow SG110CX |
| Inverter Capacity | 100 kW |
| AC Voltage | 380/400 V |
| Frequency | 50 Hz |
| Battery | LiFePO4 (Samsung SDI) |
| Battery Capacity | 1.3 MWh |
| Battery Efficiency | >95% |

In addition to system details, the daily measurement information used in this study includes energy yield and average irradiance data. Examples of the measurement data can be seen in Table 2. Sample of Daily Energy Production and Average Solar Irradiance Data of the PV System

**Table 2**
Sample of daily energy production and average solar irradiance data of the PV system

| Avg Irradiance (W/m²) | Total Energy (kWh) | Date |
|---|---|---|
| 291.00 | 149.2 | 01-Jan-26 |
| 398.0 | 144.6 | 02-Jan-26 |
| 180.5 | 345.2 | 03-Jan-26 |
| 404.7 | 644.2 | 04-Jan-26 |
| 181.9 | 520.1 | 05-Jan-26 |

Data gathered during the observation phase in January 2026 were then examined to establish daily solar radiation levels and important system performance metrics, such as specific yield and performance ratio. In addition, the collected information was applied as input variables for simulations using PVsyst software, facilitating a comparison between the real operating conditions of the solar photovoltaic system and the related simulation results.

*2.3 Solar Irradiation Data Processing Method*

The solar radiation data used in this study comes from measurements taken with a pyranometer, which produces solar irradiance values in W/m². This measured value reflects the intensity of solar radiation at a specific time, requiring further processing to obtain the solar irradiance value [8].

Solar irradiance is defined as the total amount of solar radiation energy received by a surface over a specific time period, and is measured in kWh/m² [9]. Based on this definition, the solar irradiance value is obtained by integrating the irradiance data over the measurement period taken by the pyranometer.

In this case, data processing is carried out by summing all irradiance values at each time interval within a single observation day, then converting them into energy units. The calculation of daily solar irradiance refers to the following formula [8]:

$$H = \sum_{i=1}^{n} G_i \times \Delta t \tag{1}$$

To obtain the value in kWh/m²/day units, the calculation results are converted by dividing by 1000, so that we obtain [1]:

$$H_{day} = \frac{\sum_{i=1}^{n} G_i \times \Delta t}{1000} \tag{2}$$

In this study, the available irradiance data is in the form of daily average irradiance, so the calculation of daily solar irradiation is performed by multiplying the average irradiance value by the duration of effective solar radiation in one day, which is taken as 24 hours representing the full daily averaging period [3]. This approach is widely accepted and commonly applied in solar energy analysis, especially in conditions where the availability of measurement data is limited to daily resolution [3,20].

### *2.4 System Simulation Using PVsyst*
#### *2.4.1 Single-line diagram*

The electrical configuration of the PV system installed on Bawean Island is illustrated by the one-line diagram presented in Figure 3, generated using PVsyst software version 7.4.8. This diagram provides a systematic and simplified schematic representation of the entire power conversion chain, from solar energy capture at the module level to the final electrical energy delivery at the grid injection point. One-line diagrams are essential components in PV system documentation, as they convey the structural and electrical relationships between system components in a standardized format that is universally recognized in the fields of electrical engineering and renewable energy. Understanding the configuration depicted in this diagram is fundamental to interpreting simulation results and evaluating the overall performance of the system under study.

The PV array, as shown in the diagram, uses LR5-72HPH-540M G2 photovoltaic modules configured in 18 parallel strings, with each string consisting of 14 modules connected in series. This series-parallel arrangement is determined based on the electrical characteristics of the selected modules and the input voltage and current requirements of the inverter units, to ensure optimal compatibility and power transfer between the array and the inverters. The DC power generated by the PV array is then fed to three SG110-CX inverter units with a total rated capacity of 330 kVA. These inverters perform the critical function of converting the varying DC output from the PV array into stable AC power at voltage and frequency levels that meet grid interconnection requirements. The generated AC power is then fed to the injection point, which is the interface between the PV system and the local electricity distribution network.

The system architecture depicted in the one-line diagram reflects a well-structured grid-connected PV system design and follows standard engineering practices for utility-scale solar installations. This configuration ensures that the DC-to-AC power conversion process is carried out efficiently, with each inverter unit handling a proportional portion of the total system capacity to maintain operational balance. Furthermore, this diagram serves as a basis for validating the system model built in the PVsyst simulation environment, confirming that the simulated configuration accurately represents the physical installation on Bawean Island. Consistency between the simulated and actual system configurations is a prerequisite for ensuring the reliability and applicability of simulation results in assessing real-world PV system performance.

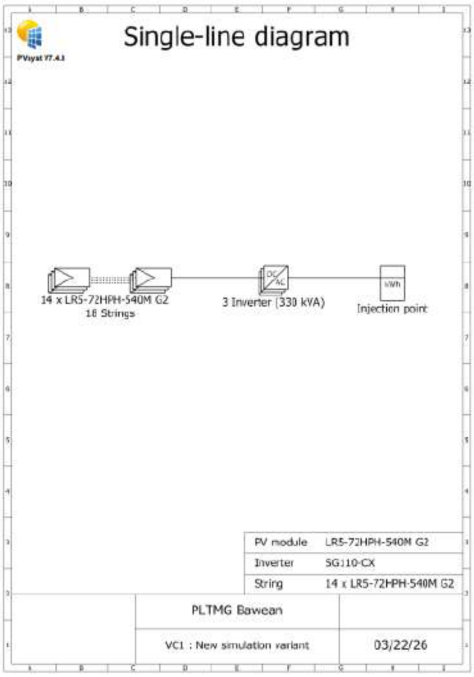


**Fig. 3.** Single-line diagram of a solar power system simulated using PVsyst

### *2.4.2 System configuration (summary)*

The configuration of the PV system employed in the PVsyst simulation was established based on site location parameters, component specifications, and the operational conditions of the system. These parameters encompass geographical site data, installed system capacity, array configuration, and inverter characteristics incorporated into the simulation model. This simulation approach is widely adopted for evaluating the performance of photovoltaic systems under actual operating conditions using both measured and simulated data [10,11]. The use of simulation software such as PVsyst enables a more comprehensive assessment of PV system performance both prior to and following field installation.

The main system parameters and simulation results of the PV system are summarized in Table 3. Based on these results, the simulated PV system is located on Bawean Island at coordinates 5.84° S and 112.66° E, with an installed capacity of 408 kWp and three inverter units with a combined AC capacity of 330 kWac. The simulation results indicate that the system is capable of generating 681,545 kWh of electrical energy annually, with a specific yield of 1,669 kWh/kWp/year and a performance ratio of 84.09%. These values reflect the overall operational conditions of the system based on the input parameters defined within the simulation model.

The high performance ratio indicates that the PV system operates efficiently in converting solar irradiation into electrical energy under the given site conditions. This suggests that energy losses within the system are relatively minimal, allowing the system to operate close to its optimal capacity. Similar performance characteristics have been reported in recent studies on PV systems operating in tropical environments [18,19]. The consistency of these results further reinforces the validity of the simulation approach applied in this study.

**Table 3**
Summary of PV system simulation parameters and results

| Category | Parameter | Value |
|---|---|---|
| General Information | Location | Bawean Island, Indonesia |
| | Latitude | -5.84° |
| | Longitude | 112.66° |
| | Altitude | 11m |
| | Simulation Software | PVsyst V7.4.8 |
| | Weather Data | Meteonorm 8.1 (Synthetic) |
| System Configuration | System Type | Grid-Connected |
| | PV Array Capacity | 408 kWp |
| | Number of Module | 756 Units |
| | Inverter Capacity | 330 kWac |
| | Number of Inverter | 3 units |
| | Tilt Angle | 30° |
| | Azimuth Angle | 0° |
| Simulation Result | Annual Energy Production | 681,545 kWh/year |
| | Specific Yield | 1,669 kWh/kWp/year |
| | Performance Ratio | 84.09% |

The detailed configuration of the PV system, encompassing the system setup, component specifications, and loss parameters, is presented in Table 4. The PV system comprises 756 photovoltaic modules of type LR5-72HPH-450M G2 with a total installed capacity of 408 kWp. These modules are organized into 54 strings, with each string consisting of 14 modules connected in series. This arrangement was determined to ensure optimal voltage and current characteristics that align with the operational requirements of the inverter units.

The system utilizes three Sungrow SG110CX inverter units, each with a rated capacity of 110 kW. A DC-to-AC ratio of 1.24 indicates that the system is designed with a slight overloading configuration in order to maximize energy production, particularly during periods of low irradiance. This type of configuration is commonly applied in PV system design as a strategy to improve overall energy yield and enhance system performance [10,11]. The selection of this ratio reflects a deliberate design decision aimed at optimizing the utilization of available solar resources throughout varying irradiance conditions.

Furthermore, the simulation incorporates several system loss factors, including temperature losses, mismatch losses, and electrical losses. Each of these loss components contributes to a reduction in the overall energy output of the system under real operating conditions. Among these factors, temperature loss is identified as one of the dominant contributors to performance degradation, particularly in tropical regions that are characterized by persistently high ambient temperatures [9]. Accounting for these loss parameters in the simulation ensures that the predicted system output more accurately reflects the actual performance of the PV system in the field.

**Table 4**
PV system configuration and simulation parameters

| Category | Parameter | Value |
|---|---|---|
| General System Configuration | System Type | Grid-Connected |
| | PV Field Orientation | Fixed Plane |
| | Tilt Angle | 30° |
| | Azimuth Angle | 0° |
| | Horizon | Free horizon |
| | Shading Condition | No Shading |
| | Simulation Model | Perez, Meteorm |
| | PV Module Type | LR5-72HPH-450M G2 |

| | | |
|---|---|---|
| PV Array and Inverter Specification | Number of PV Modules | 756 units |
| | Total PV Capacity | 408 kWp |
| | Module Configuration | 54 strings x 14 modules |
| | Inverter Model | SG110-CX |
| | Number of Inverter | 3 units |
| | Total Inverter Capacity | 330 kWac |
| | Operating Voltage | 200-850 V |
| | DC/AC Ratio | 1.24 |
| System Loss Parameters | Thermal Loss Factor (Uc) | 20.0 W/m$^2$K |
| | Thermal Loss Factor (Uv) | 0.0 W/m$^2$K |
| | Module Mismatch Loss | 2.0% |
| | String Mismatch Loss | 0.1% |
| | DC Wiring Loss | 1.5% |
| | Module Quality Loss | -0.8% |

### *2.5 Calculation of System Performance Parameters*

Assessment of the functionality of a Solar Power Plant (PLTS) system involves measuring a few important factors, including specific yield, reference yield, and performance ratio (PR). These factors help to evaluate how efficient the system is and its performance in relation to the energy generated and the solar radiation it captures.

#### *2.5.1 Specific yield*

Specific yield refers to the measure of electrical energy generated by a solar energy system for each unit of its installed capacity. This measure is essential for assessing the technical efficiency of the system.
The calculation of specific yield is performed using the equation below:

$$Y_f = \frac{E_{AC}}{P_{rated}} \tag{3}$$

Where:
- $Y_f$ = Specific yield (kWh/kWp)
- $E_{AC}$ = AC energy output (kWh)
- $P_{rated}$ = Installed capacity of the PV system (kWp)

A high specific yield value indicates that the solar power system is capable of producing electrical energy optimally relative to its installed capacity.

#### *2.5.2 Reference yield*

Reference yield refers to a measurement that indicates the quantity of solar energy captured by a PV module, expressed in kWh/kWp equivalent units. This measurement is determined by utilizing prior solar irradiation data.

Reference yield is determined by the formula:

$$Y_r = \frac{H_t}{G_{ref}} \tag{4}$$

Where:
- $Y_r$ = Reference yield (kWh/kWp)
- $H_t$ = Total solar irradiation (KWh/m$^2$)
- $G_{ref}$ = Reference irradiance (1kW/m$^2$)

Since $G_{ref}$ = 1 kW/m$^2$, it follows that practically

$$Y_r = H_t \tag{5}$$

*2.5.3 Performance Ratio (PR)*

The performance ratio (PR) serves as a measure to assess how well a solar energy system operates by contrasting the real energy produced with the expected energy calculated from solar radiation [12].

The performance ratio can be determined through this equation :

$$PR = \frac{Y_f}{Y_r} \tag{6}$$

Or can be written as:

$$PR = \frac{E_{AC}}{P_{rated} \times H_t} \tag{7}$$

The PR value is commonly expressed either as a decimal or a percentage. A well-performing PV system typically exhibits a PR in the range of 0.70 to 0.85. A lower PR value may be attributed to several contributing factors, including elevated module temperature, inverter losses, and suboptimal environmental conditions.

*2.6 Percentage Error Analysis*

To evaluate the deviation between simulated and actual energy production, a percentage error analysis was employed in this study. This method is widely used in PV system performance evaluation to quantify the difference between predicted and measured values, providing a simple and effective metric for assessing simulation accuracy under real operating conditions [20-22].

The percentage error was calculated using the following equation .

$$Error = \frac{E_{sim} - E_{actual}}{E_{sim}} \times 100\% \tag{8}$$

Where $E_{sim}$ represents the simulated energy output from PVsyst and $E_{actual}$ represents the measured energy output from the actual PV system. This method enables a direct quantitative comparison between simulation results and real word performance, allowing the identification of discrepancies cause by environmental conditions, system loss, and modelling assumption. The use of percentage error analysis has been widely applied in recents studies to validate PV system simulations and asses their reliability [11,12].

## 3. Results

*3.1 Analysis of Actual Solar Power Plant Data*

The real operational data of the Photovoltaic (PV) system was analyzed using daily measurement data collected from the monitoring system and pyranometer sensors during the month of January 2026. Daily electrical energy output from three PV system units and daily average irradiance values, which were later transformed into solar irradiation in units of kWh/m2/day, make up the dataset.

The PV system's total electrical energy output throughout the observation period was 24,326.7 kWh, or 261.6 kWh per day, according to the data gathered. These data show that the PV system operated during the observation period, with the majority of energy production changes depending on the daily solar radiation. Additionally, due to the effects of tropical weather on Bawean Island's fluctuating solar radiation characteristics, the daily average irradiance was found to be 344.6 W/m2.

The conversion of irradiance data into solar irradiation revealed that daily irradiation values ranged from 0.102 kWh/m²/day to 6.617 kWh/m²/day. This considerable variation reflects the significant difference in solar resource availability between clear-sky days and days with high cloud cover. On days with low irradiation values, such as January 11, 2026, electrical energy production also declined substantially, underscoring the sensitivity of the PV system to prevailing solar radiation conditions.

The daily variation in electrical energy production throughout the observation period is illustrated in Figure 4. The figure clearly demonstrates that energy production tends to increase on days with high irradiation values and correspondingly decreases when irradiation levels are low. And the distribution of daily solar irradiation over the study period is presented in Figure 5. The figure reveals pronounced fluctuations in irradiation values, driven by atmospheric conditions such as cloud cover and varying solar intensity.

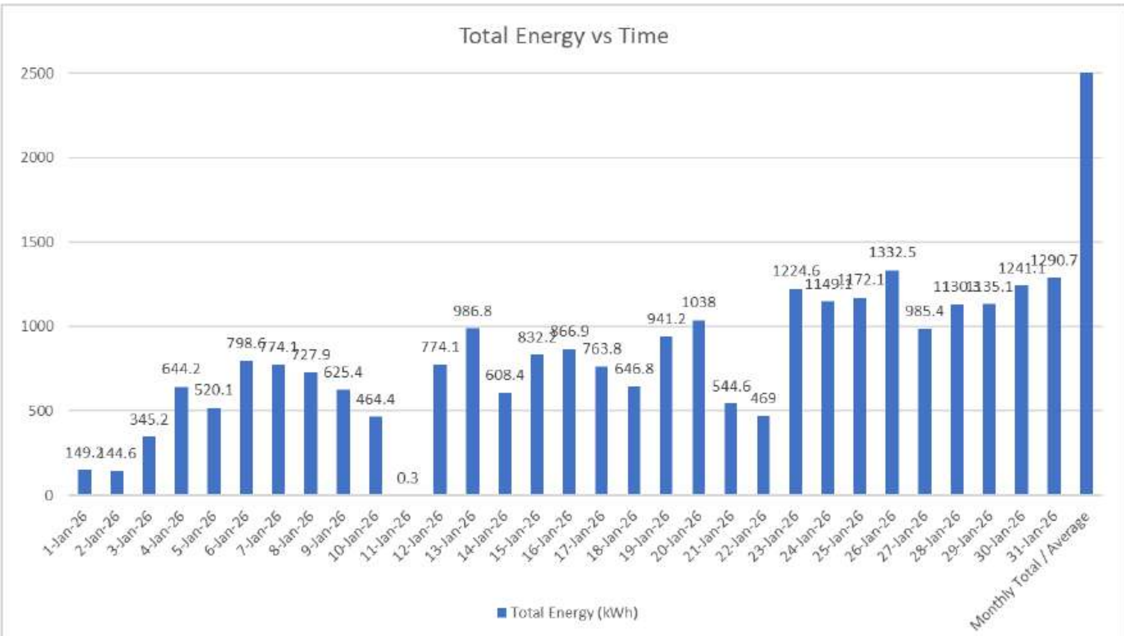


**Fig. 4.** Daily electrical energy production of the PV system during January 2026

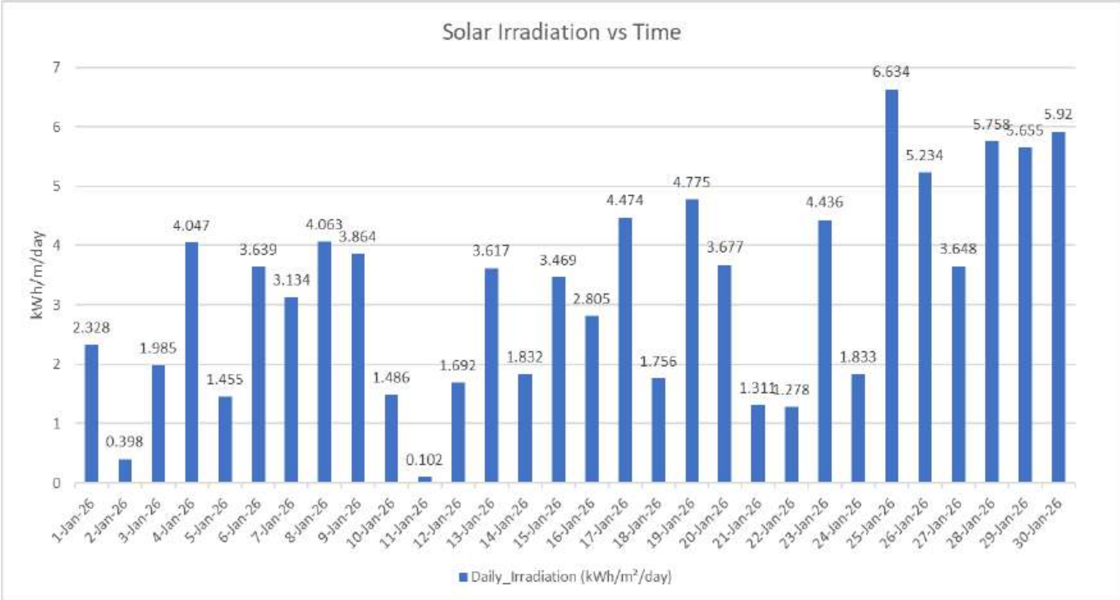


**Fig. 5.** Daily solar irradiation variation during January 2026

To further investigate the relationship between solar radiation and electrical energy production, a correlation plot between daily solar irradiation and total daily energy output is presented in Figure 6. The figure reveals a clear positive correlation between the two variables, whereby an increase in solar irradiation is consistently accompanied by a corresponding increase in electrical energy production from the PV system.

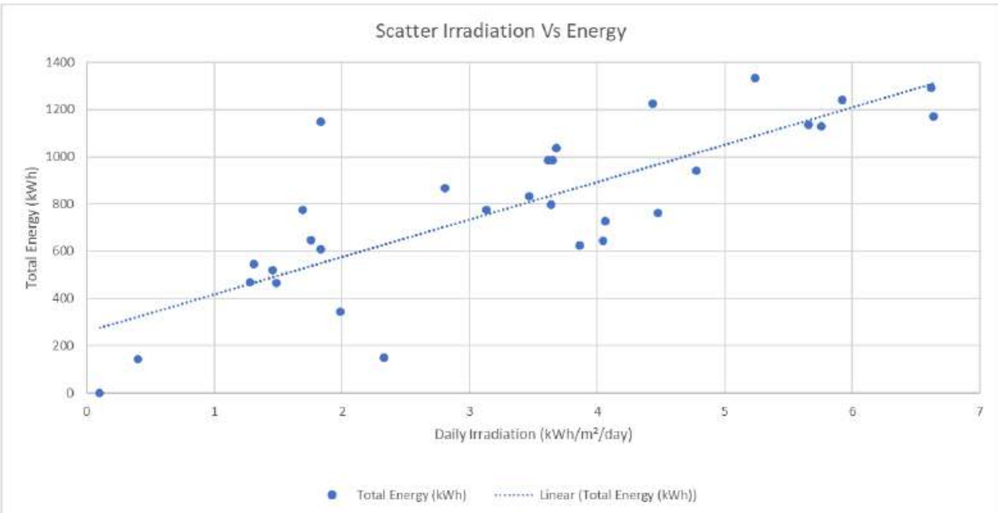


**Fig. 6.** Relationship between solar irradiation and daily electrical energy production of the PV system

These findings confirm that solar irradiation constitutes the primary determinant of PV system performance. Nevertheless, certain data points exhibit deviations from the general trend, indicating that in addition to solar radiation, other contributing factors such as module temperature, system losses, and operational conditions also exert a measurable influence on electrical energy production.

### *3.2 PV System Simulation Result using PVsyst*

The photovoltaic (PV) system was simulated using PVsyst software to assess system performance based on Bawean Island's site conditions and technical parameters. The simulation employed meteorological data based on Meteonorm, as well as a system setup designed to replicate real-world field circumstances [23].

According to the simulation results, the PV system with an installed capacity of 408.24 kWp is expected to produce 681,545 kWh of electricity each year. The simulated specific yield of 1,669 kWh/kWp/year is consistent with the features of tropical areas, where the intensity of solar radiation is comparatively high, and indicates that the system is very productive.

Additionally, the simulation produced a performance ratio (PR) of 84.09%, suggesting that the PV system is efficient at converting solar radiation into electrical energy. The PR value of this system is in the acceptable range for well-performing photovoltaic systems, which is typically between 70% and 85%.

The monthly distribution of simulated electrical energy production is illustrated in Figure 7. The figure shows that energy production varies throughout the year in accordance with the seasonal pattern of solar radiation distribution. Peak energy production occurs in August at approximately 70,698 kWh, while the lowest production is recorded in January at approximately 38,936 kWh.

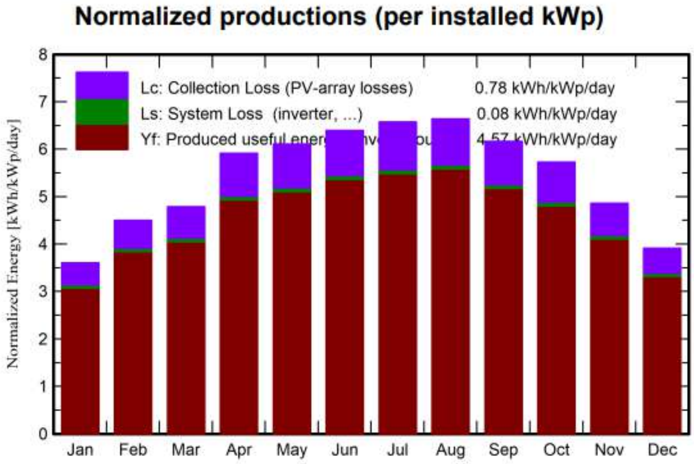


**Fig. 7**. Monthly electrical energy production from PVsyst simulation

The monthly performance ratio derived from the simulation is presented in Figure 8. The PR remains relatively stable throughout the year, ranging between 0.834 and 0.853, demonstrating that the PV system operates consistently despite variations in solar radiation conditions.

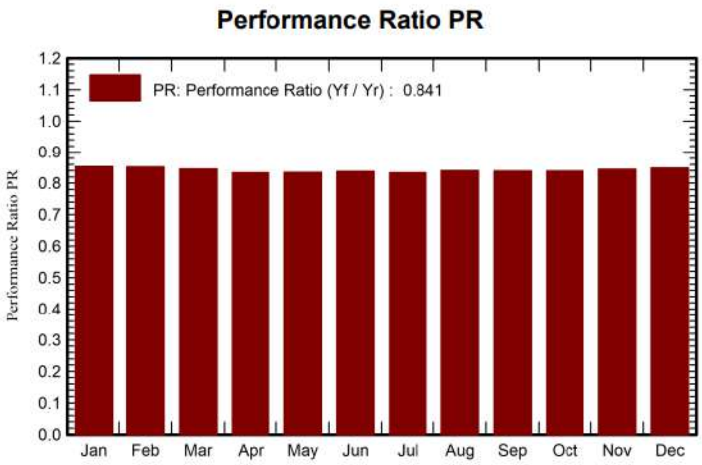


**Fig. 8.** Monthly performance ratio of the PV system from PVsyst simulation

A detailed analysis of system losses is presented through the loss diagram in Figure 9. The diagram reveals that the largest loss contribution originates from temperature-related losses at 9.73%, followed by module mismatch losses at 2.05%, and inverter losses at approximately 1.72%.

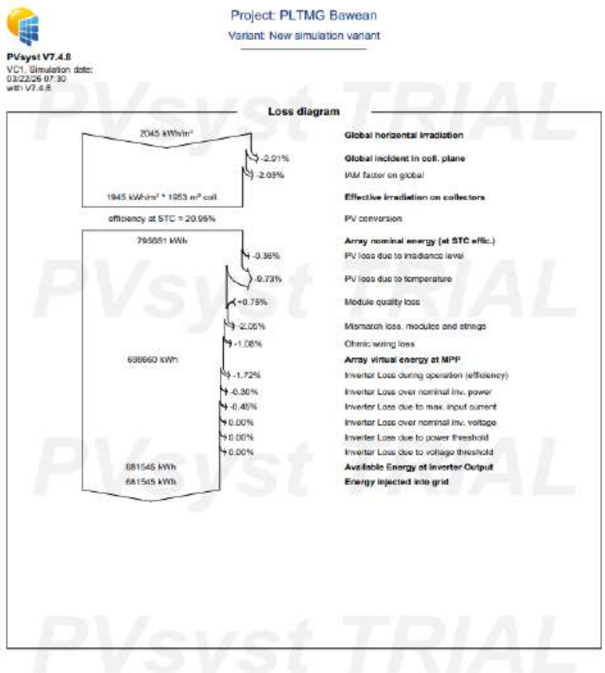


**Fig. 9.** Energy loss diagram of the PV system based on PVsyst simulation

Temperature-induced losses constitute the dominant factor contributing to PV system performance degradation, particularly in regions with relatively high ambient temperatures such as tropical climates. This finding is consistent with previous studies reporting that elevated module temperatures reduce the energy conversion efficiency of photovoltaic systems.

Overall, the simulation results demonstrate that the analyzed PV system exhibits good performance and is capable of generating electrical energy optimally in accordance with the solar radiation conditions at the study site. These results subsequently serve as the reference basis for comparing simulated system performance against actual measured data in the following section.

### *3.3 Comparison of Actual Data and PVsyst Simulation Result*

A comparative analysis between actual measured data and PVsyst simulation results was conducted to evaluate the degree of agreement between the simulation model and the actual operating conditions of the PV system in the field. This analysis was carried out descriptively and quantitatively by calculating the deviation and percentage error between the two datasets. This comparison aims to identify the extent to which the simulation model accurately reflects the actual performance of the PV system under field conditions. Such a comparative evaluation is crucial in validating the applicability of a simulation-based approach for grid-connected PV system performance assessment.

Based on the PVsyst simulation results, the PV system is projected to produce 681,545 kWh of electrical energy per year, with an estimated monthly production of 38,936 kWh for January. In contrast, the actual measured energy production recorded during January 2026 was 24,326.7 kWh, resulting in a percentage error of 37.5%. This significant deviation indicates that the simulation model is not fully capable of representing the actual operating conditions of the PV system, particularly regarding daily weather variability and system operational factors. This large deviation underscores the importance of integrating actual field data in evaluating PV system performance in tropical environments.

One of the main causes of this deviation is the use of Meteonorm-based meteorological data in PVsyst, which represents synthetic data derived from long-term averages of climate conditions, rather than direct measurements. The actual data used in this study were obtained from direct field measurements reflecting specific weather conditions during January 2026, which may differ significantly from the long-term averages used in the simulation. Atmospheric variations such as cloud cover, rainfall, and high humidity levels during the measurement period can result in actual irradiance values being significantly lower than those projected by the simulation model. These climatic factors are particularly pronounced in tropical island environments such as Bawean Island, where weather conditions can be highly dynamic and unpredictable.

Beyond meteorological factors, the observed deviations can also be attributed to technical and operational system factors not accounted for in the PVsyst simulation model. These include additional cable losses, inconsistent inverter efficiency under varying load conditions, and potential system disturbance events that may occur during the measurement period. Overall, these factors contribute to a reduction in actual energy output relative to simulated values. This analysis shows that although PVsyst provides a fairly reliable estimate of system performance under ideal conditions, an integrated approach combining simulated data with actual field measurements is necessary to achieve a more accurate and representative evaluation of PV system performance under real-world operating conditions.

### *3.4 Analysis of Solar Irradiation Influence on Energy Production*

A further analysis was conducted to evaluate the influence of solar irradiation on the electrical energy production of the PV system. The relationship between these two variables was examined using a scatter plot of daily solar irradiation against daily electrical energy output, as presented in Figure 10.

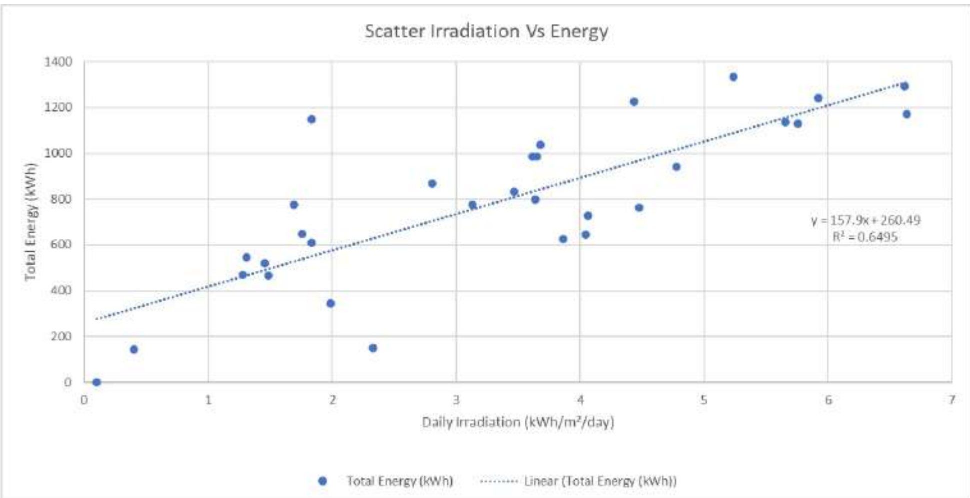


**Fig. 10.** Relationship between solar irradiation and daily electrical energy production of the PV system

A positive correlation is observed between solar irradiation and electrical energy production. The scatter plot reveals an upward trend indicated by the regression line, indicating that higher solar irradiation values are generally associated with greater electrical energy output. This finding is consistent with the fundamental operating principle of photovoltaic systems, in which solar radiation constitutes the primary input driving energy conversion.

A linear regression analysis yields the equation $y = 157.9x + 260.49$ with a coefficient of determination $R^2 = 0.6495$, indicating a moderate to strong correlation between solar irradiation and energy production. This result quantitatively confirms that solar irradiance is a dominant factor influencing PV system performance.

However, the data distribution in the scatterplot shows considerable dispersion around the regression line, indicating that the relationship between the two variables is not strictly linear. Some data points deviate significantly from the trend line, with energy output values not increasing proportionally with increasing solar radiation levels. This dispersion pattern provides quantitative evidence that solar radiation, while dominant, is not the sole determinant of PV system energy production.

The observed dispersion can be attributed to several contributing factors. High module temperatures are known to reduce photovoltaic conversion efficiency, a phenomenon that is particularly pronounced in tropical climates where high radiation is often accompanied by high ambient temperatures. Consequently, days with high radiation do not always produce proportionally high energy output. Furthermore, system-level losses such as inter-module mismatches and varying inverter efficiencies further contribute to the observed dispersion in the data.

These findings indicate that while solar radiation is a primary determinant of electrical energy production in PV systems, overall system performance is governed by the combined interaction of environmental conditions and system technical characteristics. Therefore, accurate performance evaluation requires consideration of all contributing loss factors beyond solar radiation alone.

## 4. Conclusions

This study evaluated the solar radiation characteristics and energy generation performance of a photovoltaic (PV) system on Bawean Island using real-world measurement data and PVsyst simulations. Analysis of actual operational data showed that the PV system generated 24,326.7 kWh of electrical energy in January 2026, indicating that solar radiation is a major factor influencing daily energy production.

Findings from the PVsyst simulations revealed that the system exhibits significant performance potential, with an annual energy output of 681,545 kWh, a specific yield of 1,669 kWh/kWp/year, and a performance ratio of 84.09%. These results demonstrate that the system is capable of operating efficiently in tropical conditions.

However, a comparative evaluation of the simulated and actual data revealed significant deviations, resulting in an error of approximately 37.5%. This difference is primarily due to the different meteorological data sources used, where PVsyst uses Meteonorm data representing long-term climate averages, while the actual data captures real-time weather variability including cloud cover and precipitation events [13]. Furthermore, additional factors such as temperature losses, variable inverter efficiency, and inherent system losses contribute to the observed performance gap between simulated and actual operating conditions [12].

Analysis of the relationship between solar radiation and electrical energy production further confirms the positive correlation between the two variables; however, deviations from a strictly linear behavior indicate a measurable influence of additional environmental and technical factors on system output. High module operating temperatures, in particular, have been well established as a factor reducing photovoltaic conversion efficiency under high irradiance conditions, a phenomenon that is particularly pronounced in tropical climates [14,15].

In conclusion, PVsyst can reliably predict photovoltaic (PV) system performance under ideal conditions, however, actual field measurement data is crucial to achieve accurate and realistic system performance evaluation. Therefore, combining simulation results with real-world operational data is crucial to improve the design, optimization, and performance assessment of PV systems, especially in areas known to have significant climate variability [16,22,23].

The PV system demonstrates good agreement between simulated and actual performance, validating the effectiveness of the adopted simulation approach. Minor discrepancies are attributed to inherent weather variability and system losses, which are typical in real-world PV applications.

This study is limited to data from January 2026, representing a short-term assessment of system performance. While the dataset provides useful initial insights, it may not fully capture seasonal variability in solar irradiance and weather conditions. Future work should incorporate longer observation periods across multiple months or seasons to improve the robustness and generalizability of the analysis.

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