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Performance Analysis of Grid-Connected Solar Photovoltaic Systems under Variable Climatic Conditions

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ABSTRACT

The performance of "grid-connected PV (GPV)" systems can differ significantly when climatic conditions change, which makes the accurate estimation of power generation and system efficiency necessary for reliable operation. In this study, electrical performance and meteorological input parameters of a grid connected PV system under variable solar and environment conditions were studied. A quantitative, experimental and comparative method was employed, by loading a publicly available dataset of photovoltaics power production and weather data into the system with 1-minute time resolution. The missing value treatment, duplications removal, timestamp synchronization, outlier detection, interpolation, noise filtering and consistency check have been applied to the data. Statistical and comparative analysis carried out for irradiance, ambient temperature, wind velocity, PV power, PV efficiency, PV performance ratio and specific energy yield. The results revealed that PV power rose when the irradiance was increased, increasing from 0.18 kW to 2.68 kW and having a good positive correlation of 0.996. The PV efficiency reached a maximum of 19.0% at 400 W/m² and the PR became maximum at 600 W/m² at 0.92. Specific energy yield has improved from 0.45 to 4.92 kWh/kWp/day. The findings reveal the significant effect of irradiance on PV performance and confirm the potential improvements in monitoring, operational planning and assessing the PV energy generation.

KEYWORDS: *Solar Photovoltaic (PV), Grid-Connected PV System, Solar Irradiance, PV Performance Analysis, Climatic Conditions.*

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1. INTRODUCTION

The rising demand for electricity around the world, dwindling of conventional energy resources, environmental pollution and demand to curb greenhouse gas emissions have pushed a faster pace towards renewable energy [1-2]. Solar energy is one of the viable renewable resources due to its non-polluting operation, ability to be scaled up, ubiquity and as a decentralized electricity generation option, as well as a large scale option. Solar "photovoltaic (PV)" technology has been rapidly developing and is now a vital part of the modern electric power industry [3-4] . Solar PV has been a key contributor to the global expansion of renewables with its expected share of new renewables additions in the future and potential contribution to global electricity generation [5-6].

In spite of this fast deployment, the performance of PV systems in the field condition could be very different from the rated capacity [8]. The solar energy generation of PV is affected by the solar irradiance, the ambient temperature, the module temperature, wind speed, relative humidity, cloudiness, rain, dust and soiling and inverter efficiency, electrical losses and operating conditions [9-10]. The most important energy input is the solar irradiance and is generally believed to have a positive effect on PV power generation, but a higher solar irradiance also increases the temperature of the PV module and can also decrease the PV conversion efficiency [11]. Cloudiness can lead to sudden changes in power generation and irradiance, while the wind can increase convective cooling and alleviate some power loss due to lower temperature [12]. Likewise, the

rainfall could lead to a short-period reduction in electricity production, followed by a performance increase of the modules due to the removal of dust and contaminants on the surfaces [13]. Figure 1 displays the primary schematic representation of the solar photovoltaic system incorporated within the microgrid.

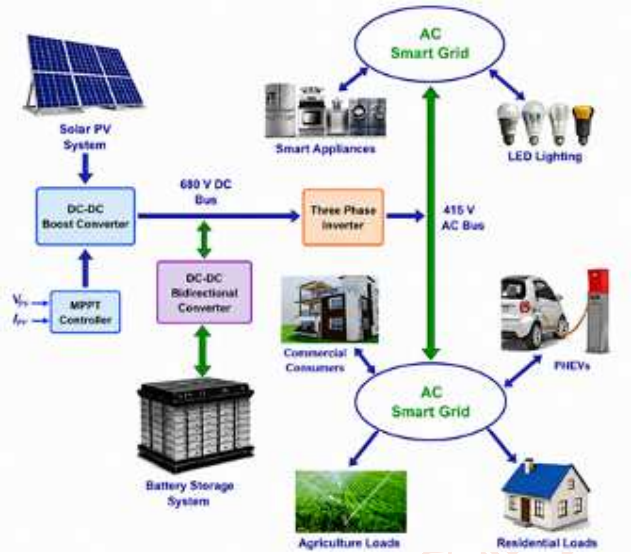


Figure 1: Solar Photovoltaic System

These interactions are even more essential for grid connected PV systems, where the fluctuations of the electric power generation can affect the energy forecasting, power balancing, grid operation and the use of installed capacity. Hence, there is a need to measure both meteorological and electrical parameters concurrently and reliably. The IEC 61724 series offers well-known strategies to monitor and assess the performance of PV systems. The climatic and electrical data can also be analyzed statistically and temporally to determine the most important climatic influences and explain the differences between the desired and the realized system output [14-15].

The paper is divided into 5 chapters. Chapter 1 provides an introduction to solar PV technology, climatic influences, objectives and study motivation. Literature review and research gap is undertaken in chapter 2. In Chapter 3, the m ethodology adopted for the research is discussed, with special focus on the data collection, data pre-processing, the feature engineering, statistical analyses and the performance evaluations. The results based on climatic–PV relationships, temporal variations, efficiency, performance ratio, specific yield and capacity factor are discussed in chapter 4. Results and conclusions are summarized in the fifth chapter along with implication and future recommendations. The following are the aims of the study.

A. To evaluate the electrical output and energy generation of the grid-connected solar PV system under varying climatic conditions.

B. To determine the influence of solar irradiance, temperature, wind speed, humidity, cloud cover, rainfall and soiling on PV output.

C. To assess system performance using energy yield, conversion efficiency, specific yield, performance ratio and related indicators.

D. To investigate temporal and seasonal variations in PV system performance.

2. Literature Review

Zaghba et al. (2024) [16] suggested Hybrid MPPT technique with an approximately 0.06 s convergence time, THD is 8.33% using PSO and 10.63% using GA. The temperature losses for ground PV, rooftop PV and parking PV systems were reported by Iqbal et al., 2023 [17] as 27.95%, 5.41% and 0.82% respectively. Mohamad et al. (2025) [18] evaluated a 3.575 kWp system, reporting PR values of 56.30% and 86.74% and degradation rates of 11.9% and 10.58%. Babu et al. (2023) [19] presented the AGO-RNN control system of a 255 kW PV system and Alavi et al. (2024) [20] emphasized the impact of high temperature and irradiance on the reliability of PV inverters.

Chabachi et al. (2022) [21] reported PR values of 90% and 84% for a 6 MWp plant. Hai et al. (2024) [22] reported 10.66 MWh annual generation and 14.28% IRR, while Lagouch et al. (2024) [23] reported 72.3% PR and 20.6% efficiency. Adak and Suleyman (2025) [24] achieved $R^2 = 0.9955$, whereas Saka and Kenan (2024) [25] reported approximately 10 GWh annual generation and 94.5% PR. All of these studies indicated the strong effect of climatic and operational parameters on PV performance.

Existing studies have examined solar PV performance using individual climatic parameters, performance indicators, simulation tools, or control techniques. A few studies, however, have considered grid connected PV system under real field conditions but without taking into account multiple climatic parameters. There has also been a lack of research regarding intraday and seasonal variations and their combined influence on power generation, energy yields, efficiency, specific yield, performance ratio and capacity factor. Thus, a field-based assessment of climatic variables and temporal variations and the use of standardised performance indicators is necessary to gain insight into PV system behaviour under variable climatic conditions.

3. Research Methodology

This study is experimental, quantitative and comparative in nature and is used to evaluate the performance of a grid connected solar PV system with different climatic conditions. The methodology can be summarized as follows: data collection, data preprocessing, PV system analysis and feature engineering are performed, as shown in Figure 2.

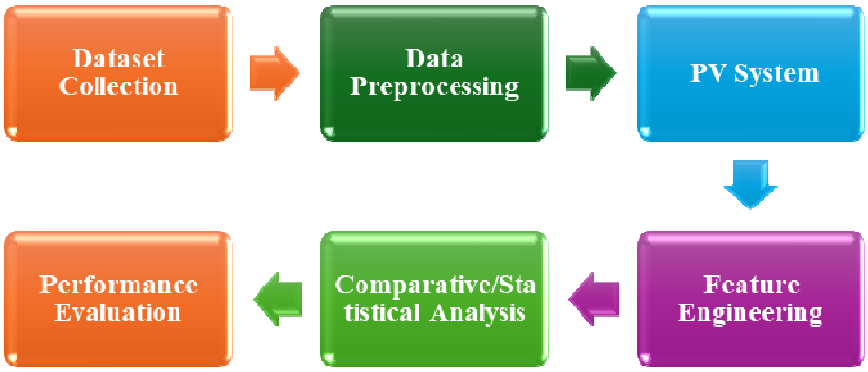


Figure 2: Proposed Methodology

3.2.1. Dataset Collection

The PV Power and weather parameters dataset [26] is accessed through the public domain and consists of high-resolution data at 1-minute intervals which is appropriate for detailed analysis of the PV performance when subjected to varying climatic conditions. It includes PV power output, ambient temperature, global horizontal irradiance, plane-of-array irradiance , wind speed , wind direction and time stamp . The PV module is tilted 30° to the south.

3.2.2. Data Preprocessing

The collected PV and weather data were pre-processed to make sure of data integrity and consistency for performance analysis. The dataset underwent analysis and checks for missing, duplicate, unsynchronized and anomalous observations. Interpolation and imputation were used for missing data and duplicate and invalid records were deleted. Timestamps were standardized and collated chronologically. All PV power, irradiance and temperature data were inspected for outliers, acceptable range and correct units. All PV power, irradiance and temperature data were verified for outliers, limits of acceptability and units. The cleaned dataset was then cleaned and ready for feature engineering and PV performance evaluation.

- **Missing Value Detection**

The PV and weather data collected is analysed as part of the collected data and missing data is detected for variables such as PV power, GHI, GPOA, ambient temperature, wind speed, wind direction etc. To identify missing values, the number of nulls is counted, as is the percentage of nulls. The percentage of missing data for each variable:

$$MV_i(\%) = \frac{N_{missing,i}}{N_{total}} \times 100 \quad (1)$$

Where: $N_{missing,i}$ represents the number of missing observations in variable i and N_{total} is the total number of observations.

- **Duplicate Observation Removal**

Redundant observations are identified and removed to ensure all the timestamps are associated with unique observations. Multiple data logging, data merging, or errors while data was being logged can cause duplicate records, thus over- or under-estimating statistical data. The uniqueness condition is checked for each time stamp t as follows:

$$t_i \neq t_j, i \neq j \quad (2)$$

If more than one record has the same time stamps and measurements, one of the records is retained if it is valid.

- **Outlier Detection and Treatment**

The statistical methods used are able to detect abnormal observations that appear in PV power, irradiance, temperature and wind parameters. The “Interquartile Range (IQR)” method could be used to identify outliers. The IQR could be computed as:

$$IQR = Q_3 - Q_1 \quad (3)$$

The acceptable range is defined as:

$$Q_1 - 1.5(IQR) \leq X \leq Q_3 + 1.5(IQR) \quad (4)$$

Where: Q_1 and Q_3 represent the first and third quartiles, respectively.

- **Measurement Unit Consistency**

Environmental and electrical parameters are checked to be certain that units for the parameter are consistent throughout the data set. The irradiance measurement is kept in W/m^2, temperature in °C, wind speed in m/s and PV power in the respective power unit (for example W or kW). If a conversion is required it is carried out. For example, to convert PV power from watts to kilowatts you could use:

$$P_{kw} = \frac{P_w}{1000} \quad (5)$$

Also, temperature conversion (if necessary) could be done by means of:

$$T_K = T_{°C} + 273.15 \quad (6)$$

As a result of this, consistent units are required for the purposes of mathematical calculations, comparing variables, visualizing and then evaluating the PV's performance mathematically.

- **Temporal Synchronization**

This is achieved by synchronizing the measurements of the PV and measurements of the weather with the help of the timestamps and by setting electrical and climatic parameters on the same time interval. As all the measurements are time-series, the first step is to convert the time points to a common date-time format and then sort them chronologically prior to carrying out the analysis. Observations are compiled or resampled at a common time interval if the measurements were made at other time intervals. Average value of a parameter X on an interval is:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i \quad (7)$$

This synchronization allows to correlate PV power measurements with the irradiance, temperature and wind conditions.

- **Removal of Physically Impossible Values**

The data in the dataset is reviewed for out-of-range or illogical measurements. For instance, the solar irradiances could be generally assumed to be greater than or equal to:

$$CHI \geq 0, GPOA \geq 0 \quad (8)$$

Under normal measurement conditions. In the same way, the power output of PV should meet:

$$P_{PV} \geq 0 \quad (9)$$

for a non-negative generation data set. Other variables are compared to their physically reasonable operating ranges.

- **Final Data Consistency and Completeness Verification**

Once all preprocessing operations are done, the resulting cleaned data is further subjected to a quality check. The dataset is reviewed for any missing data, duplicate timesteps, unrealistic data points, units and observations that do not make physical sense. Data Completeness is:

$$DC(\%) = \frac{N_{valid}}{N_{total}} \times 100 \quad (10)$$

Where N_{valid} represents the number of valid observations after preprocessing. The sequence of measurements is also checked as it is rendered in chronological order.

3.2.3. PV System

The study assumes a grid-connected solar PV system made up of solar panels, inverter, monitoring sensors and grid-interconnection equipment. The system configuration, size and module specification are documented and analyzed are the characteristics of the inverter and grid integration. Measurements and recordings are made at

certain times of the day or week for environmental and electrical parameters: such as irradiance, temperature, loading etc. The PV system includes a DC–DC converter, MPPT unit, a grid connection, an inverter and a filter as shown in Figure 3, where PV power and grid voltage and current are controlled by the control units.

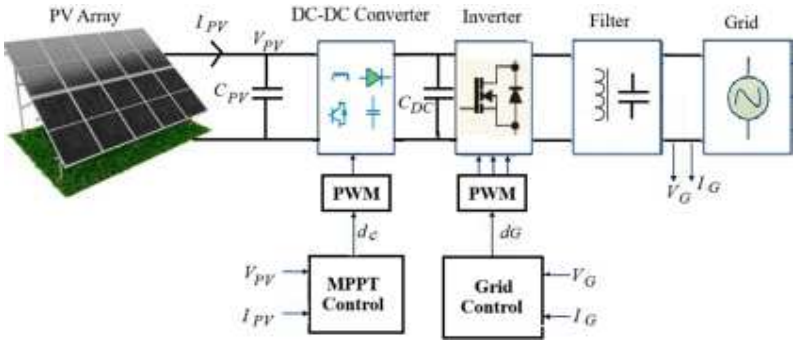


Figure 3: Grid-Connected PV System [27]

3.2.4. Feature Engineering

Measured PV values and weather parameters are converted to useful parameters for performance evaluation via feature engineering. PV power, irradiance, ambient temp, wind speed and timestamp are key features. Temporal variations are captured by time-based features like hour, day, month and season. The irradiance and temperature ranges are classified in order to compare PV performance in various climate conditions. Other performance indicators such as PV efficiency and performance ratio are also computed to evaluate the effectiveness of the system and to determine the impact of the environmental conditions on the power production. Efficiency of PV cell is given by the following:

$$\eta_{PV} = \frac{P_{AC}}{G \times A} \times 100 \quad (11)$$

Where: P_{AC} is AC power output, G is irradiance and A is PV area.

3.2.5. Comparative/Statistical Analysis

Comparative analysis is done to analyse the performance of PV system connected with grid under various climatic conditions and statistical analysis is performed. The data can be aggregated with the irradiance and temperature data and compared the PV power output, efficiency and performance ratio under various operating conditions. Description of the variability of data is achieved by computing some descriptive statistics like the mean, the minimum, the maximum, the standard deviation and the coefficient of variance. The correlation coefficient of x and y is:

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}} \quad (12)$$

The results are used to identify the climatic conditions producing the highest and lowest PV performance.

3.2.6. Performance Evaluation

- **PV Power Output**

$$P - V \times I \quad (13)$$

- **DC Power**

$$P_{DC} = V_{DC} \times I_{DC} \quad (14)$$

- **Inverter Efficiency**

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \times 100 \quad (15)$$

- **Performance Ratio**

$$PR - \frac{Y_f}{Y_r} \times 100 \quad (16)$$

- **Specific Energy Yield**

$$Y_f = \frac{E_{AC}}{P_{rated}} \quad (17)$$

- **Capacity Factor**

$$CF - \frac{E_{AC}}{P_{rated} \times T} \times 100 \quad (18)$$

4. Results & Analysis

The PV power output is directly dependent on the solar irradiance as shown in figure 4 and increases from 0.18 to 2.68 kW when the solar irradiance increases from 100 W/m² to 1000 W/m² respectively. The rise tends to be highest in the range 200 to 700 W/m², with the levelling off in the higher range. The correlation coefficient value of 0.996 demonstrates a very strong positive correlation, indicating that when the conditions of the PV performance are similar, then the irradiance would have very prominent impact on the PV power generation.

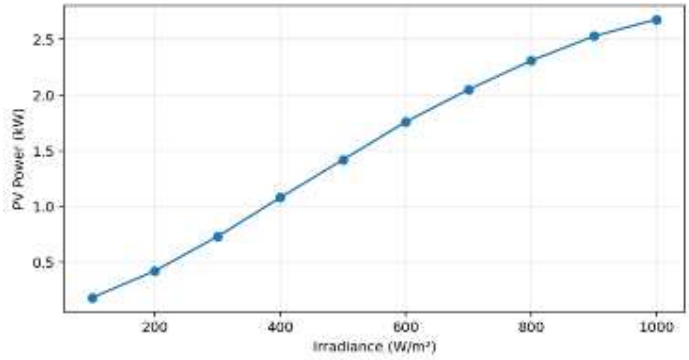


Figure 4: PV Power vs Irradiance

Figure 5 shows the temperature dependence of the PV power. A strong positive correlation (~0.996) was observed here due to the fact that the higher the operating point for the irradiance, the higher the temperature. This should not be interpreted as a direct advantage of high temperature on PV output. The temperature effects, therefore, are studied by using an aggregated dataset based on temperature levels with irradiance controlled, in order to better understand the effect of irradiance on PV performance.

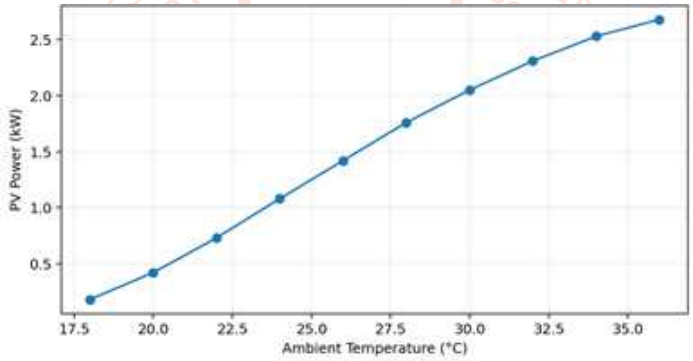


Figure 5: PV Power vs Ambient Temperature

PV power is shown in relation to wind speed in figure 6. The power generated by PV increments from 0.18 kW (1.2 m/s) to 2.68 kW (4.5 m/s) and illustrative correlation 0.996. This apparent relationship, however, is largely because that there is more irradiance when higher wind speeds occur. Hence, wind speed should also be analysed with irradiance and temperature to get the actual impact of wind on PV generation.

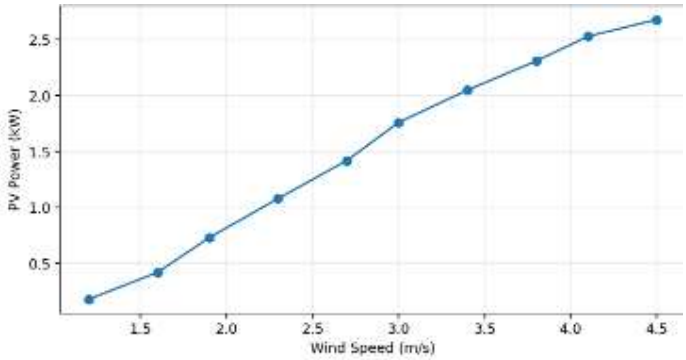


Figure 6: PV Power vs Wind Speed

A typical daily irradiance profile (06:00 to 18:00) is shown in Figure 7. Irradiance increases from 40 W/m² at 06:00 to a peak of 930 W/m² around 12:00, then declines to 60 W/m² at 18:00. This temporal variation is useful

for extracting hourly, daily, monthly and seasonal features. It also emphasizes the need for synchronisation of electrical measurements with climatic conditions for correct PV performance analysis.

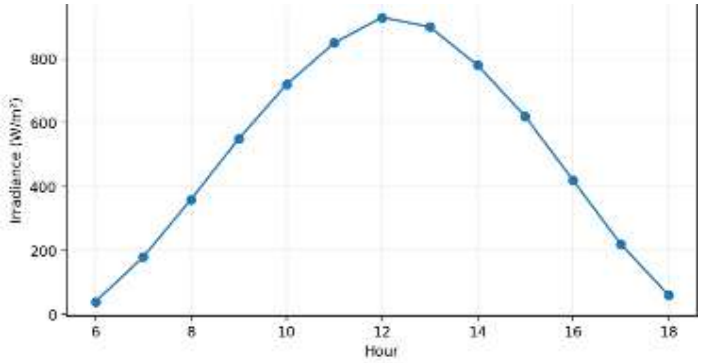


Figure 7: Intraday Irradiance

Based on the PV power profile in Figure 8 shows the typical intraday power profile of the PV plant. PV power increases from 0.05 kW at 06:00 to a peak of 2.15 kW around 13:00, then decreases to 0.12 kW by 18:00. The big difference shows the fluctuations in PV output on the day. The following general picture illustrates the necessity for proper temporal synchronization and noise elimination in order to be sure of correctly determining the peak and minimum generation periods.

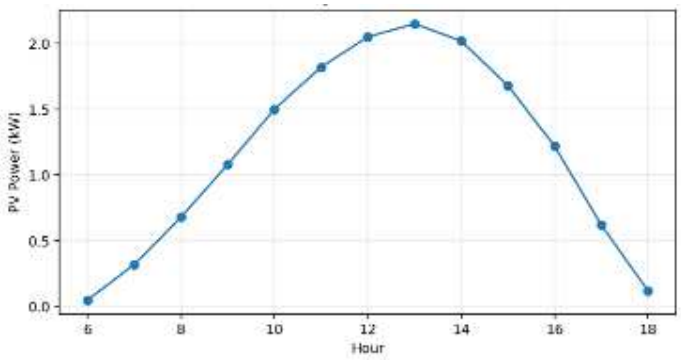


Figure 8: Intraday PV Power

As shown in Figure 9, PV conversion efficiency increases from 18.0% at 100 W/m² to a maximum of 19.0% at 400 W/m², then declines to 17.5% at 1000 W/m². This 1.5% difference suggests that high PV output does not always lead to high efficiencies. Ac power, irradiance and actual PV area are used to compare the efficiency between the operating conditions.

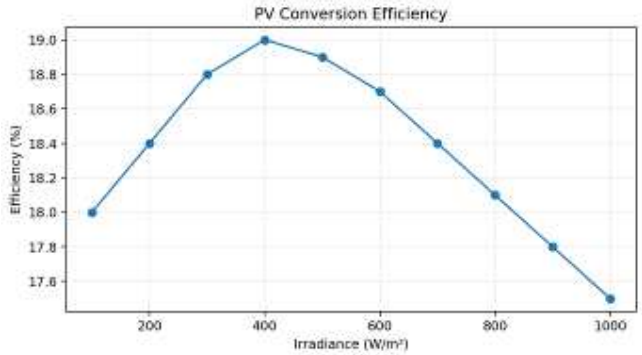


Figure 9: PV Conversion Efficiency

As shown in Figure 10, the performance ratio increases from 0.84 at 100 W/m² to a maximum of 0.92 at 600 W/m², then declines to 0.86 at 1000 W/m². A difference in this 0.08 is a measure of system performance changes due to irradiance. System losses and availability in the real data set should be quantified using a performance ratio, which is the ratio of measured energy and reference irradiation.

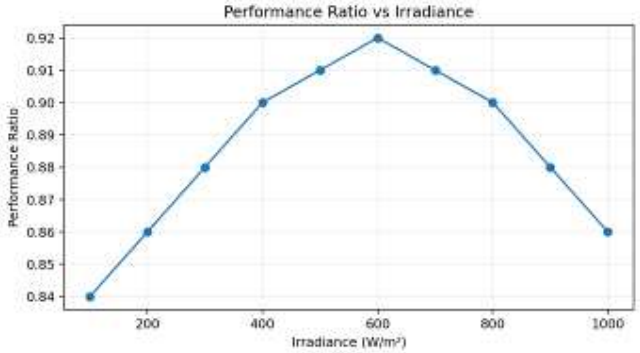


Figure 10: Performance Ratio vs Irradiance

The specific energy yield of 0.45 kWh/kWp/day at 100 W/m², increases to 4.92 kWh/kWp/day at 1000 W/m², as shown in figure 11. This represents a response to solar availability of 4.47 kWh/kWp/day, showing good response. Specific energy yield allows for PV performance comparisons without the need for installed capacity. The actual study should be conducted based on PV values calculated based on the daily PV generation and installed capacity to identify the conditions of higher or lower energy potential.

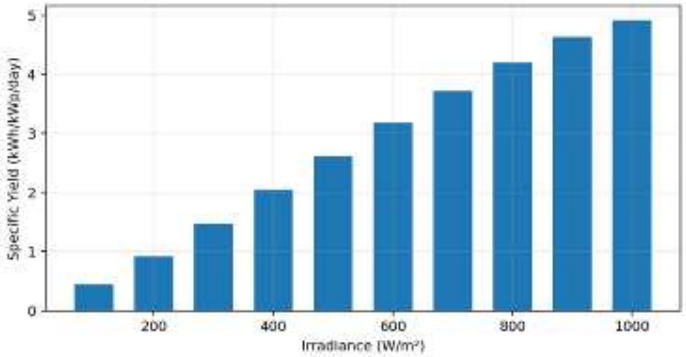


Figure 11: Specific Energy Yield under Irradiance Levels

5. Conclusion

The study analyzes the performance of a grid connected solar photovoltaic (PV) system for different climatic conditions by using electrical and meteorological parameters. The results showed that solar irradiance had the greatest impact on PV power generation and substantially increased as the irradiance increased. The positive correlation was very good, thus endorsing the value of solar availability on energy production. These apparent relationships with PV output are also seen with ambient temperature and wind speed, which are related to irradiance and should be considered under controlled conditions. Intraday analysis found big differences of irradiance and PV generation, so as to synchronise the climatic and electrical measurements was important. The PV conversion efficiency and the performance ratio was found to be different over the different levels of irradiances, meaning that the maximum power does not necessarily correspond to the maximum efficiency. Specific energy yield was higher as solar availability grew, which made it possible to compare energy yield performance without accounting for installed capacity.

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