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A methodology for performance evaluation and system loss analysis of photovoltaic power plants: case studies in Vietnam

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ABSTRACT

This study presents a methodology for performance evaluation and loss analysis of two photovoltaic (PV) power plants in Vietnam with different geographical locations and climatic conditions. An experimental methodology is utilized to analyze the system losses. Data was collected from the BIM2 (250 MWp) and Buon Ma Thuot (35 MWp) plants. The results show that system losses do not exceed 1.3%, with performance rates ranging from 73-79% for BIM2 and 74-88% for Buon Ma Thuot. Correlation analysis between module operating temperature, solar irradiance, and energy yield reveals an inverse relationship between the temperature-irradiance ratio and energy yield. A considerable decline in power plant efficiency is observed when this ratio exceeds 8. Additionally, vital monitored indices for PV plant operation are investigated, including energy supplied to the grid, PV array temperature, ambient temperature, and loss metrics.

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1. INTRODUCTION

In recent years, Vietnam’s renewable energy industry, including solar energy, has seen strong breakthroughs. According to the statistical data in Table 1 [1], Vietnam's grid-connected solar power capacity in 2017 was negligible at only 8 MW. However, over the next five years, this figure soared to 18,475 MW by 2022, an increase of over 2,000 times compared to 2017. This exponential growth has been fueled by favorable policies from the government to encourage solar development as well as falling prices of PV panels globally, making adoption more affordable. With such rapid growth, solar energy has become Vietnam’s leading renewable power source. Specifically, while in 2017 the share of solar capacity compared to Vietnam’s total renewable energy capacity was almost insignificant (0%), by 2022 this figure reached 27%. Thus, in just five years, solar has gained a significant market share within Vietnam's renewables mix. Moreover, the exponential scale growth of Vietnam's solar industry over the past five years has helped establish the position of this clean energy on the national renewable energy landscape, while opening great opportunities and potential for Vietnam's future green energy sector. Additionally, according to IRENA’s statistics on the top 10 countries globally in electricity generation from renewable sources, Vietnam ranks 7th behind Italy, South Korea, and Spain, as illustrated in Figure 1 [2].

Studies on the performance of photovoltaic (PV) systems have focused on three main research directions to improve the operational efficiency of this renewable energy technology. Firstly, studies have evaluated the actual operational performance of PV systems through monitoring and analyzing electricity generation data from the system during operation [3]-[8]. Typical of this, one study assessed the operational effectiveness of performance assessment of a large-scale 10 MW grid-connected solar photovoltaic power plant located in Andhra Pradesh, India. The plant utilizes monocrystalline silicon solar cell technology with photovoltaic modules installed across a wide area. To evaluate the operational efficiency, the authors monitored and measured key technical indicators over an extended period. The findings showed that annually the plant can generate an average electricity of 17.1 million kWh, exceeding its initial designed capacity.

Table 1. The development of solar photovoltaic in Vietnam's renewable energy

Year	Off-grid solar power		Connected to grid solar power		
	Total renewable capacity (MW)	Solar capacity (GW)	Total renewable capacity (MW)	Solar capacity (MW)	Solar production (GWh)
2017	240490	4490	18217	8	8
2018	336490	4490	18715	105	105
2019	155490	5490	26078	4994	4988
2020	83990	5490	38380	16661	10718
2021	67490	5490	42728	16661	25717
2022	67490	5490	45327	18475	25717

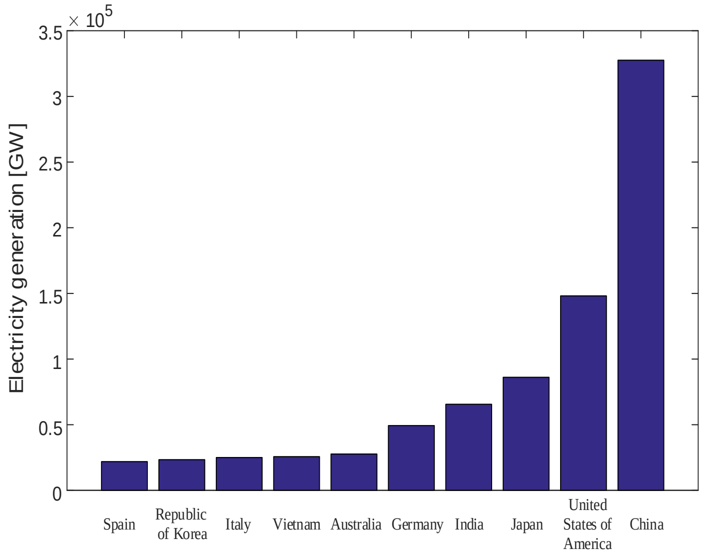


Figure 1. Top 10 countries with the highest electricity generation globally

Secondly, research has focused on studying methods for measuring the power of PV modules, aiming to identify the most accurate measurement method [9]-[11]. Finally, studies have focused on developing mathematical models to predict the final energy yield of the system based on operating parameters such as solar radiation intensity and module temperature [12]-[15]. Moreover, the performance of photovoltaic systems is contingent upon various factors. A comprehensive understanding of the impacts of these factors is essential for improving the design and enhancing the efficiency of solar energy conversion. Photovoltaic cells convert sunlight directly into electrical energy through the photovoltaic effect. The efficiency of photovoltaic conversion is closely tied to the intrinsic and extrinsic parameters of the cell. Intrinsic parameters are related to semiconductor materials and junction properties, including bandgap, carrier mobility-lifetime product, and recombination mechanisms. Conversely, extrinsic factors are associated with external operating conditions such as solar irradiation and temperature. Additionally, other operational considerations, such as system losses, including wiring losses, inverter losses, and transformer losses, need to be considered. Studying the factors affecting photovoltaic systems from extrinsic parameters during the operation period has attracted research interest from many authors. Various methods have been employed, such as DEA + Tobit regression analysis, multivariate regression analysis, and specific experimental methods, as presented in Table 2.

Following Table 2, previous studies have focused on evaluating the operational performance of photovoltaic systems and analyzing the factors affecting their efficiency. Yi *et al.* [16] conducted a case study in China, analyzing factors such as solar irradiation, ambient temperature, wind speed, and humidity influencing the power generation efficiency. Wang *et al.* [17] proposed a method for evaluating the operational performance of solar power plants under actual environmental conditions, comprising three stages: technical efficiency assessment, environmental adjustment, and management efficiency evaluation. Ketjoy *et al.* [18]focused on investigating the factors affecting the efficiency of inverters in grid-connected photovoltaic systems in Thailand. Meanwhile, Pradhan [19] examined ten external factors influencing the efficiency of photovoltaic systems. Finally, Elhamaoui *et al.* [20] evaluated the long-term performance and degradation of a CIS photovoltaic plant under semi-arid climatic conditions. Most studies indicate that the two primary factors affecting the performance of photovoltaic cells are solar irradiation and the operating temperature of the photovoltaic array. However, operational factors in power plant operations, such as system losses, and environmental parameters, also introduce performance variations [21], [22]. The common research methodology of these studies involves collecting and analyzing real-world data from photovoltaic power plants, assessing the impact of environmental and technical factors on system efficiency. However, each study has a different scope and emphasis regarding the factors considered and the specific analysis methods applied.

The main contribution of this study is to analyze the performance and losses of two photovoltaic power plants located in two different locations with different climate conditions under actual operating conditions. Additionally, a formula was developed to express the correlation between solar irradiation and temperature to determine the optimal location for installing solar power plants with the highest performance. The next part of the study presents the proposed method in section 2, a methodology is presented in Section 3, the results and discussion are presented in Section 4, and the conclusion is presented in section 5.

Table 2. Methodologies used to analyze the impact of factors on solar photovoltaic systems

Reference	Methodology	Objective	Result
[16]	Three-stage efficiency analysis (DEA + Tobit regression)	Evaluate operational efficiency of US solar PV plants, remove environmental factor effects	Slight decrease in operational efficiency after removing environmental factor effects
[17]	DEA + Tobit regression analysis	Evaluate solar PV generation efficiency in China, identify influencing factors	Electricity radius, per capita GDP have positive impacts
[18]	Multivariate regression analysis	Study factors affecting solar PV efficiency in Thailand	Temperature and solar irradiation are two main factors
[19]	Experimental analysis	Study 10 factors affecting solar PV system efficiency	Solar irradiance and temperature are two main factors
		Analyze environmental factor impacts on solar PV plant efficiency in China	Temperature is the most significant factor
This study	Experimental analysis	This study analyzes yield performance and investigates factors related to losses, solar radiation, and operating temperatures of two photovoltaic plants in Vietnam	

2. EXPRIMENTAL PHOTOVOLTAIC SYSTEM

The approach of this study is to select two solar power plants at two different locations with distinct natural characteristics, and then analyze to find the relationships between the plant indices and climatic features. The main parameters of the plants, including solar irradiation, operating temperature of the photovoltaic panels, energy output, daily operational hours of the plants, as well as the performance ratio (PR), are collected daily. In this study, data for analyzing the external influencing factors of the photovoltaic system was collected from the BIM2 and Buon Ma Thuot photovoltaic power plants. The BIM2 plant has a designed capacity of 250 MWp, with an actual operating capacity of 203 MWp. The plant is located in Phuoc Ninh commune, Thuan Nam district, Ninh Thuan province, Vietnam, at a latitude of 11.201 degrees and a longitude of 108.98 degrees (see Figure 2). The land area is 650 ha with flat terrain, situated approximately 12 km from the coast. Additionally, the Buon Ma Thuot photovoltaic power plant is located in the Daklak Province, Vietnam. This facility has 86,956 SARAPHIM panels with a rated power of 345Wp each and 7 ABB inverters, each rated at 3.5MWp. The total nominal capacity of this system is 30,718 MWp. The main technical specifications of both photovoltaic plants are shown in Table 3.

Table 3. Specifications of BIM2 power plan

BIM2 photovoltaic plant			
Items	Value	Items	Value
Installed capacity	203 MWp	Items	Value
PV module	330Wp	Installed capacity	30.7 MWp
Number of PV module	615152	PV module	345 Wp
Capacity of inverter	3.5 MW	Number of PV module	8.9037
Number of inverters	58	Capacity of inverter	3.5MW
Buon Ma Thuot photovoltaic plant		Number of inverters	7

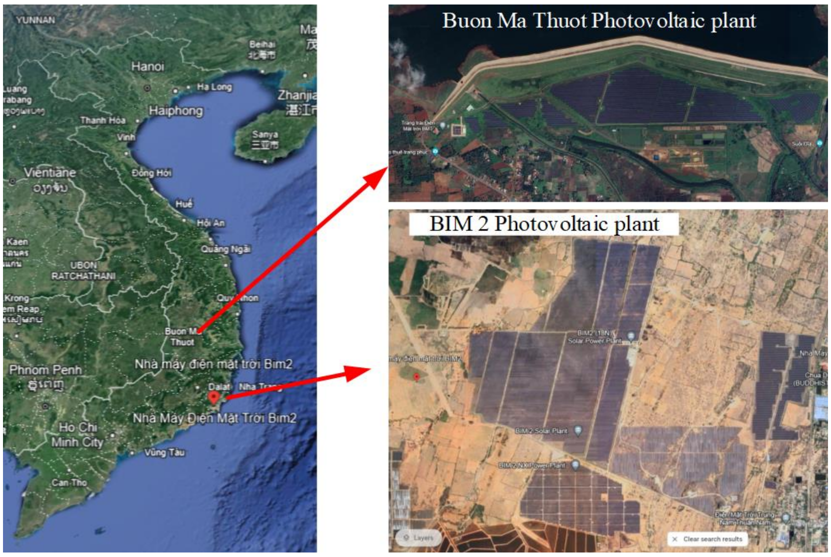


Figure 2. Location and snapshot of BIM2 and Buon Ma Thuot photovoltaic power plant

3. METHODOLOGY

This study takes an empirical approach using actual measured data from the solar power plant. The calculations are based on formulas from the IEC61724 standard to determine the key parameters of the plant [23]-[27]. it is given by these (1)-(5).

$$PR = \frac{Y_f}{Y_r} \tag{1}$$

$$Y_f = \frac{E_{PV}}{P_0} \tag{2}$$

$$Y_A = \frac{E_A}{P_0} \tag{3}$$

$$Y_R = \frac{H_T}{G_{STC}} \tag{4}$$

$$CF = 100 * \frac{E_{PV}}{P_0} \tag{5}$$

Where PR is performance ratio; Y_f is the final yield, Y_R is reference yield; Y_A is array yield; E_A is array output; P_0 is peak power; H_T is mean daily irradiation; E_{PV} is energy to grid; and CF is capacity factor.

Accurately estimating the operating time of a solar power plant is extremely important in the planning and operation process of the plant. The operating time directly affects the productivity and economic efficiency of solar power projects. Therefore, engineers need to accurately estimate this timeframe based on factors such as geographic location, weather, panel technology, and installation system. PVsyst software is a useful simulation tool that allows consideration of all the above factors and accurately predicts the operating time of a solar power plant. In addition, solar power plants collect nominal operating hour data by calculating the difference between the De-synchronization time (hh:mm) and Synchronization time (hh:mm). It is given by (6).

$$H_n = H_d - H_s \tag{6}$$

Additionally, temperature and solar irradiance are two pivotal factors that impact the efficiency of solar power plants. Previous research has elucidated that as the temperature rises, the band gap of semiconductor materials narrows, leading to a decrease in the open-circuit voltage in response to the temperature [28], [29], thereby diminishing the system's efficiency. Consequently, regions with cooler climates tend to exhibit higher solar plant efficiencies. This particular study aims to contrast the efficiency of two power plants situated in areas with significant differences in ambient temperature, namely Buon Ma Thuot province and Ninh Thuan province. Buon Ma Thuot is known for its tropical monsoon climate near the equator, marked by hot and humid conditions throughout the year. The average annual temperature hovers around 23-24 °C.

April is typically the warmest month, averaging 26.5 °C, whereas December and January are the coolest, with temperatures around 21 °C. In contrast, Ninh Thuan experiences a tropical monsoon climate with proximity to the desert, making it prone to relatively higher temperatures year-round. The average annual temperature in Ninh Thuan is between 27-28 °C. May experiences the highest average temperatures, approximately 30 °C, while the coldest month, January, averages at 25 °C.

Another significant optical factor directly affecting the performance of a solar power plant is solar radiation. Regions with high radiation levels often experience elevated environmental temperatures, thereby exerting a considerable impact on the plant's efficiency. The coefficient ε represents the ratio between solar radiation and temperature. The solar power plant's efficiency generally increases as this coefficient decreases, and vice versa. it is given by (7).

$$\varepsilon = \frac{T_m}{G_m} \tag{7}$$

Where: T_m is the operation temperature of PV module; G_m is a measurement of solar radiation.

The (7) plays a crucial role in the design phase of solar power plants. Engineers rely on the index provided by this formula to evaluate the efficacy and optimize the performance of the plant. The efficiency of a solar power installation primarily depends on two factors: temperature and solar irradiance. In tropical regions, despite the high amounts of solar irradiance, the temperature is also elevated, which can negatively impact the efficiency of photovoltaic (PV) panels. This is due to the nature of PV panels, as their energy conversion capabilities decrease in hot environments, leading to a lower electricity production efficiency.

Conversely, in areas with cooler climates, although the level of solar irradiance may not match that of tropical regions, the lower temperatures can help improve the efficiency of the PV panels. Therefore, choosing a location that balances high irradiance with moderate temperatures can create favorable conditions for maximizing the power output of the plant. This index offers a method to assess the combination of temperature and radiation to understand their relationship. This assists engineers in establishing a basis for deciding where to install PV panels to achieve optimal efficiency. It is an important part of establishing an effective and economical solar power plant.

Monitoring and analyzing energy losses during the operational phase is crucial for ensuring efficient system performance. Losses may arise from several factors, including module mismatch, which is estimated to cause about 0.1-0.23% of energy loss [30]. Additionally, it is found that losses due to electric resistance in wires and connections can account for approximately 1.7% when using cables of 1.5 mm^2 [31]. Furthermore, an important factor to consider is the accumulation of dirt and dust on solar panels, which is known to potentially lead to a 2-5% decrease in efficiency [32]. This study has conducted a detailed collection and analysis of data regarding losses from inverters to the main Switchgear and from the main Switchgear to the transformer, offering insight into the optimization of energy production

4. RESULTS AND DISCUSSION

4.1. Performance of BIM2 photovoltaic power plant

The main indices that need to be monitored daily for a PV power plant include several crucial parameters. Firstly, the energy output generated by the plant, measuring the system's efficiency. The electricity delivered to the grid is also a vital indicator, indicating the plant's contribution to the overall power supply, and this metric is often used to analyze the revenue generated by the facility.

Furthermore, tracking indices related to losses helps determine the system's efficiency and implement necessary measures to minimize these losses. The production time of electricity is a significant parameter for monitoring the real-time performance of the plant. Weather indices such as solar radiation, temperature, and cloud cover also need to be monitored to understand the impact of weather conditions on the plant's performance. Specifically, Table 4 provides detailed information on the daily-monitored indices.

According to Table 4, the system losses consist of energy loss from inverters up to the main switchgear and energy lost from the substation, totaling 12.96 MWh, accounting for 0.93%. The electricity production is 1393.21 MWh, with a solar radiation of 7.27 kWh/m^2

and an average module temperature of 37.79 °C. Let's delve into how the operating temperature affects a photovoltaic system's electricity production, using the BIM2 PV power plant as an example. According to the findings depicted in Figure 2, the data from April 2019 show a variation in the average ambient temperature from 28.52 to 31.70 °C. Now, when we look at the photovoltaic panels themselves, their operational temperature was recorded to fluctuate between 31.1 to 40.85 °C alongside solar radiation levels that span from 4.5 to 7.6 kWh/m^2, as illustrated in Figure 3(a). Digging into Figure 3(b), the empirical data reveal that the PR, a key indicator of a plant's efficiency, oscillated between 73 to 80% and the annual yield between

800-1400 MWh. An interesting note from these observations is the pronounced dip in efficiency on the 6th and 7th days, attributed to energy losses from external factors.

Understanding these fluctuations is crucial because maintaining a consistent PR is critical for solar facilities once they're connected to the grid. This is where daily collection and analysis of historical data come into play, enabling energy managers to quickly tweak the PR of the plant to align with the predefined requirements. Shifting our focus to the operational factors influencing a PV plant, the operational hours are immensely significant. Generally, these hours are mostly dictated by the natural cycle of sunrise and sunset, detailed in Figure 3(c). Yet, for a solar power plant, the operational timing goes beyond simply daylight availability. To round up our insight into the power plant's performance over time, Figure 3(d) illustrates the energy output over the span from June 2019 to April 2020, showcasing how it correlates with varying degrees of solar radiation. This visual representation helps us to connect the dots between solar irradiance and the power output, thus shedding light on the plant's operational effectiveness throughout the year.

Table 4. Daily monitored indices of BIM2 photovoltaic power plant @ 30/04/2019

Plant-energy		Plant-hours		Plant weather	
Daily peak AC power (entire plant) (MW)	190.57	Nominal operational hours (h)	12	Plant irradiance	7.270
Energy output (inverter) MWh	1393.21	External grid outage (h)	0	Average ambient temperature	31.70
Energy output (main switchgear in MCB) (MWh)	1382.44	Curtailment outage (h)	0	Weather condition 6AM to 9AM	Sunny
Plant energy delivered to grid EVN (@ 220kV - meter reading) MWh	1376.20	HV contractor or owner failure outage (h)	0	Weather condition 9AM to 12PM	Sunny and cloudy
Reactive energy output (main switchgear in MCB) (MVArh)	26.737	System operational hours (for PR) (h)	12.62 h	Weather condition 9AM to 12PM	Sunny and cloudy
Energy loss from inverters up to main switchgear (MWh)	10.77	Preventive maintenance outage (h)	0	Weather condition 3PM to 6PM	Sunny
Energy loss in HV substation (MWh)	2.19	PV plant component outage (h)		Wind speed (m/s)	5.04
E consumed (self consumed energy from grid) (MWh)	2.070	System operational hours(h)	12.62 h	Average module temperature (ºC)	37.79
Energy loss (self consumption) (%)	0.15%			Rain	
Net power plant energy production (MWh)	1384.51			Maximum module temperature 11:44:03 AM (ºC)	49.76
Energy consumption @ night (9pm-4am) MWh	2.15			Maximum ambient temperature 1:31:36 PM (ºC)	35.50

4.2. Performance of Buon Ma Thuot photovoltaic power plant

Similar to the BIM2 solar installation, data for the Buon Ma Thuot plant is presented in Figure 4. Figure 4(a) displays the ambient temperature, panel temperature, and solar radiation measurements recorded at the Buon Ma Thuot solar plant throughout the month. An increasing trend in both temperature and irradiation can be noticed as the summer approaches. This reflects the inherent correlation between weather conditions, ambient factors, and the solar panel system's performance. Figure 4(b) shows the yield and PR coefficient of the Buon Ma Thuot PV plant. Significant daily fluctuations can be observed within the month through the curve.

Specifically, the yield ranges from about 3.5 to over 5.5 MWh, while the PR stays between 73% to 88%. Additionally, Figure 4(c) shows the operating time of the plant. Monitoring the operating time of the plant is critical for developing an effective management strategy. Finally, Figure 4(d) presents the yield for the first 6 months of the year. These metrics are for comparing the yield over the years to calculate degradation, as well as to plan cleaning of the electrical system to avoid losses due to soiling.

4.3. System loss analysis

Figure 5(a) illustrates the factors leading to energy losses in the Buon Ma Thuot solar power plant system. It can be seen that the load resistance, contact resistance, and other losses account for a total of about 1.34% energy loss. Meanwhile, Figure 5(b) shows a higher ratio of losses at the BIM2 plant, with total system losses of approximately 1%. The general trend is that these losses will reduce electricity production efficiency.

To minimize the negative impact of these losses, some solutions that could be applied are using better conductive materials to reduce resistance, improving the efficiency of the power electronic converters through more advanced design, optimizing operational parameters and maintenance schedules to reduce factors leading to system fault losses, and upgrading older equipment. A comprehensive strategy considering both technology upgrades and improved operations and maintenance will be key to driving down system losses.

4.4. Effect of solar radiation and temperature on yield

Figure 6 illustrates the correlation ε between the temperature coefficient, solar radiation, and the yield of the Buon Ma Thuot and BIM2 photovoltaic power plants. Specifically, ε in Figure 6(a), based on empirical measurements conducted on April 7th, 8th, and 29th, the ε coefficient attained superior values relative to the remaining days of the month, while the electrical production was at its nadir within the same period. Furthermore, the illustration enables the deduction that elevated magnitudes of the temperature ε coefficient corresponds to diminished electricity generation, or in other words, an inverse proportionality exists between electrical output and the ε coefficient. Additionally, the chart in Figure 6(b) demonstrates that optimal photovoltaic power plant performance occurs for values of the temperature ε coefficient below 8. This quantitative parameter constitutes a critical determinant in the analytical forecasting of plant electricity yield preceding geographical site selection for construction.

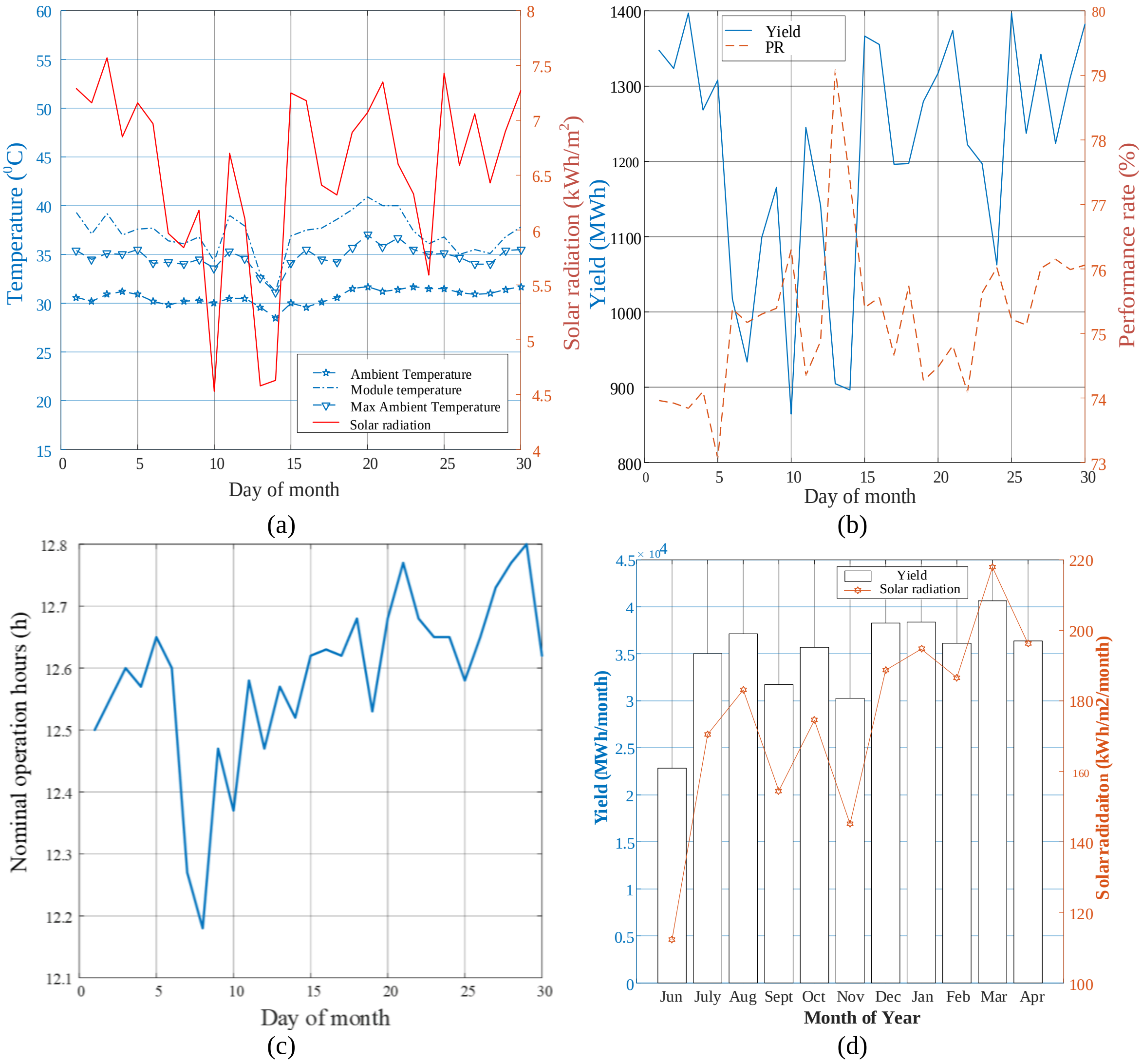


Figure 3. Performance of BIM2 photovoltaic power plant for (a) temperature and solar radiation recorded @ April 2019, (b) yield and PR @april 2019, (c) nominal operation hours @ April 2019, and (d) the total yield @2019-2020

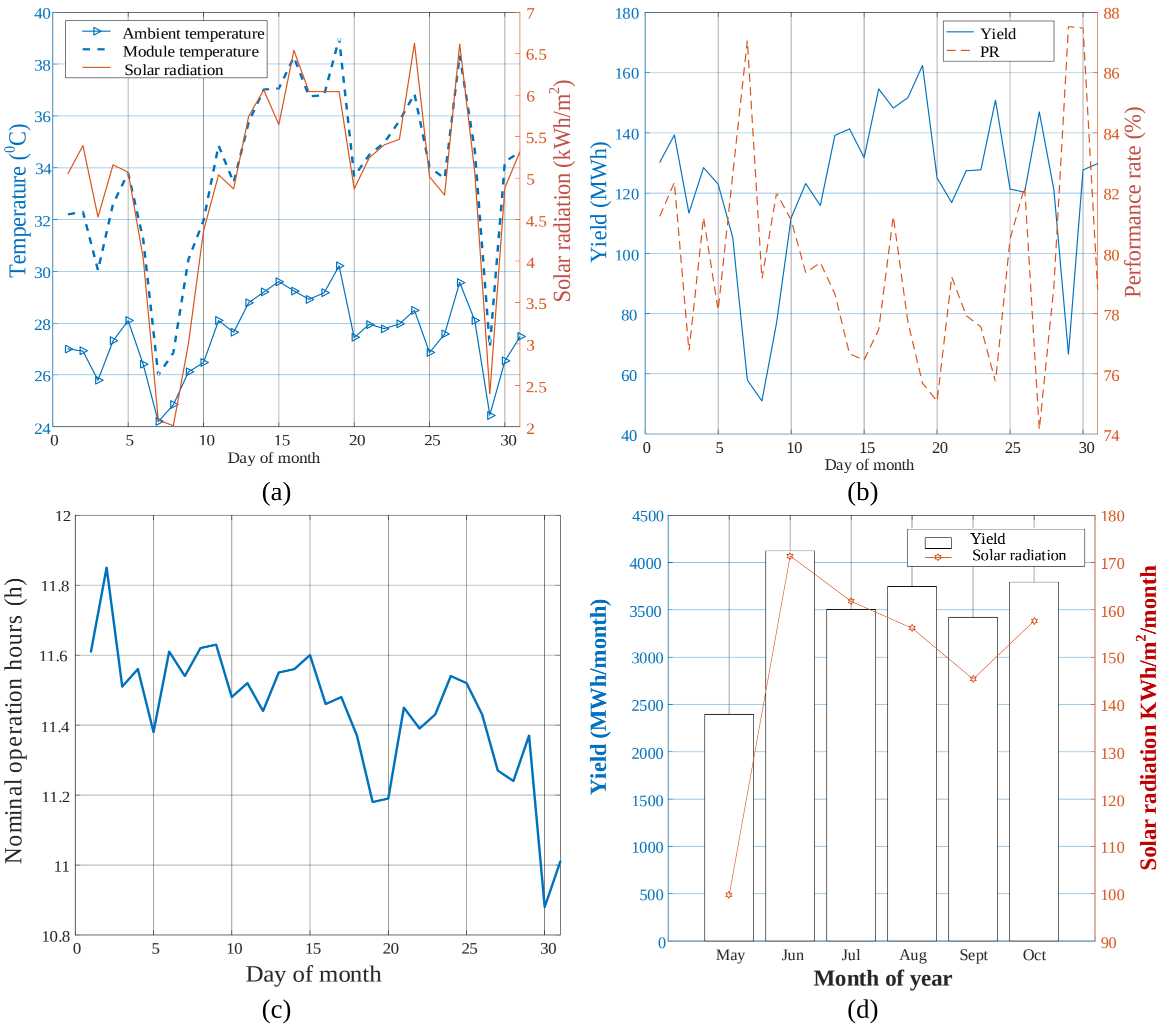


Figure 4. Performance of Buon Ma Thuot photovoltaic power plant for (a) total yield and PR @ June 2019; (b) temperature and solar radiation recorded @ June 2019; (c) nominal operation hours @ June 2019 and (d) the total yield for six months @ 2019

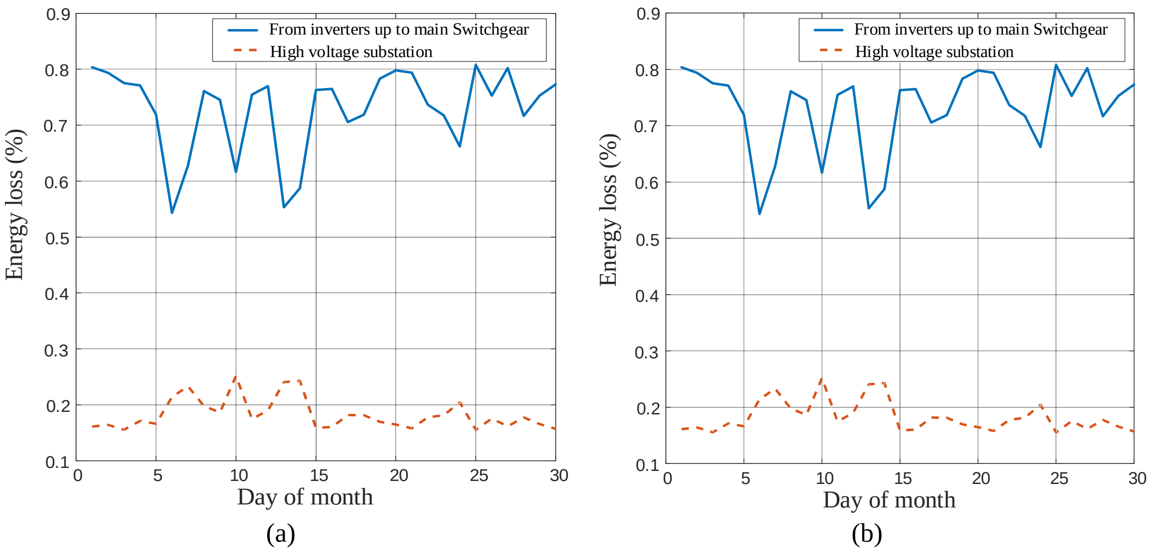
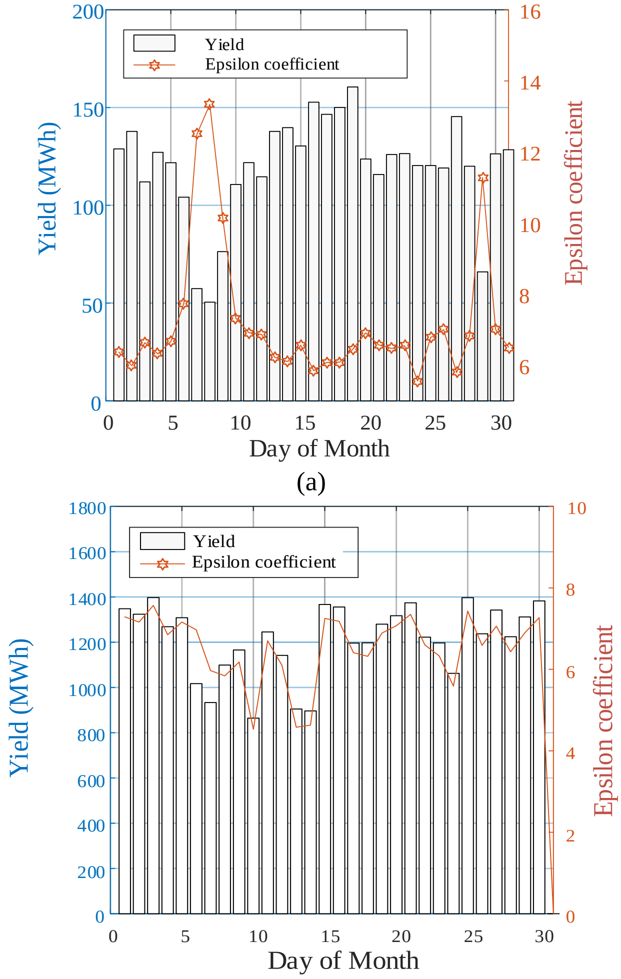


Figure 5. Energy loss for (a) Buon Ma Thuot photovoltaic plant and (b) BIM2 photovoltaic plant



(a)

(b)

Figure 6. The relationship of solar radiation, and temperature to yield for (a) Buon Ma Thuot plant and (b) BIM2 plant

5. CONCLUSION

This paper presents a performance analysis of two photovoltaic power plants located in distinct geographical regions with different climatic conditions. The results indicate that the system losses for both plants did not exceed 1.3%. The efficiency of BIM2 plant ranged from 73% to 79%, while the photovoltaic power plant in Buon Ma Thuot demonstrated a higher efficiency, fluctuating between 74% and 88%. Furthermore, correlation analysis between the operating temperature of the photovoltaic modules, solar irradiance, and energy yield reveals an inverse relationship between the temperature-irradiance ratio and power output. This ratio reaches 8 when the plant efficiency decreases significantly. From a practical viewpoint, the research findings presented in this paper serve as a valuable reference for the feasibility analysis and loss calculation stages of photovoltaic power plant development in Vietnam.

To enhance the generalizability and applicability of the study, subsequent research endeavors should be conducted across a broader spectrum of geographical regions with diverse climatic conditions. This approach will facilitate the determination of an appropriate range of efficiency values specific to each climatic zone and elucidate the intricate relationship between the performance of photovoltaic power plants and their geographical locations. By expanding the scope of the research, a more robust and accurate performance prediction model can be achieved, enabling wider adoption and implementation within the renewable energy industry.

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