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Performance and Techno-economic Analysis of a 1.82 kWp Rooftop PV System in the Tropical Climate of Indonesia: A Simulation vs Reality Approach

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ABSTRACT

The utilization of renewable energy through rooftop photovoltaic (PV) systems serves as a strategic solution for mitigating climate change; however, their performance in tropical climates often exhibits a deviation between theoretical predictions and field reality. This study aims to evaluate the technical performance and economic viability of an on-grid 1.82 kWp rooftop PV system in Indonesia. The research employs a comparative quantitative approach by validating PVsyst simulation results against actual measurement data recorded from April to July 2024. The findings indicate a simulation overestimation, where actual energy production was 30.3% to 40.5% lower than PVsyst projections. A significant discrepancy was also observed in the Performance Ratio (PR), with the actual PR reaching only 55-59%, substantially lower than the simulated 81-82%. Despite these technical inconsistencies, the economic analysis confirms the project's financial feasibility. Under a 5.25% interest rate scenario, the study yielded a Net Present Value (NPV) of IDR 15.88 million, a Benefit-Cost Ratio (BCR) of 1.50, a Payback Period of 9.8 years, and a Levelized Cost of Electricity (LCOE) of IDR 974.88/kWh, more competitive than the national utility (PLN) tariffs. In conclusion, although tropical environmental factors such as high temperatures and dust accumulation reduce technical efficiency, rooftop PV investment in Indonesia maintains strong profitability and remains viable for implementation.

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INTRODUCTION

The escalation of carbon dioxide (CO_2) emissions resulting from fossil fuel consumption has emerged as a primary concern in global climate change mitigation efforts, necessitating a critical transition toward renewable energy. Empirical studies demonstrate that the deployment of renewable energy sources directly and significantly reduces carbon footprints [1],[2]. Furthermore, renewable energy is identified as the primary alternative to replace carbon-intensive energy sources [2]. Other studies corroborate that an increase in renewable energy consumption can alleviate environmental pressure, including per capita carbon emissions [3].

One of the most rapidly advancing forms of renewable energy is photovoltaic (PV) technology, which serves as a critical solution for addressing the consequences of global warming and enhancing the efficiency of direct solar to electrical energy conversion through the photovoltaic effect [4],[5]. Advancements in PV technology have yielded significant progress in both material properties and system performance [6]. Based on cell type, PV technology can be categorized into three distinct classifications. Monocrystalline silicon offers high efficiency through a single-crystal structure, whereas polycrystalline silicon is more cost-effective but exhibits slightly lower efficiency. Additionally, thin-film technology provides enhanced flexibility, although it typically demonstrates the lowest efficiency among the three. [7], [8], [9], [10].

In recent years, Passivated Emitter and Rear Cell (PERC) technology has revolutionized silicon cell design by incorporating a rear passivation layer to minimize charge recombination and enhance light reflection, thereby significantly increasing conversion efficiency [11], [12]. Compared to conventional cells, PERC cells can achieve conversion efficiencies of up to 22.8% while maintaining compatibility with existing production lines, thereby providing a high-efficiency solution that remains cost-effective [13]. Consequently, PERC technology has rapidly secured a substantial market share and emerged as the new benchmark for silicon-based PV modules

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[14]. Beyond material innovations, PV technology has also advanced in physical configurations through the transition from full-cell designs, where entire cells are connected in series, toward designs that are more adaptive to field operational conditions [15], [16]. However, this design has limitations regarding thermal efficiency and susceptibility to partial shading. To address these weaknesses, modules featuring a half-cut cell design were developed, in which each cell is divided into two identical sections. This configuration enables lower electrical current in each path, thereby reducing internal resistance and resulting in decreased thermal losses [17],[18].

PV systems are deployed in various configurations depending on grid availability and user requirements, typically categorized into off-grid and on-grid systems, each characterized by distinct operational parameters [19]. An off-grid system is a standalone configuration that utilizes energy storage systems to maintain continuity of power supply without reliance on the primary utility grid [20]. The off-grid concept is highly relevant for remote areas lacking access to conventional power grids, offering the advantages of energy independence and installation flexibility [21]. In contrast, on-grid systems are directly interfaced with the primary utility grid, enabling energy injection into the network and power withdrawal when PV production is insufficient [22]. The advantages of on-grid systems include the elimination of costly energy storage requirements, the optimization of energy utilization through net metering, and a higher overall system efficiency level [23]. Other studies corroborate that grid-connected PV systems provide a surplus of energy to the utility grid once daytime demand has been met [24]. "However, on-grid systems possess certain limitations, such as dependence on utility grid stability and the requirement for specialized inverters capable of synchronizing with the grid [25] . Although off-grid systems offer energy independence, they are constrained by high initial investment costs for storage systems and the complexity of energy management systems [26].

Notwithstanding significant technological progress, PV systems are inherently subject to various energy losses that impact their cumulative performance [27]. These losses can be classified into optical losses, thermal losses, mismatch losses, shading losses, and ohmic losses, all of which can significantly reduce the system's actual energy output if not properly addressed [28]. Furthermore, environmental conditions such as high ambient temperatures, soiling, and partial shading can lead to a significant degradation in PV system performance relative to its nominal capacity [29]. Previous studies have demonstrated that solar irradiance is the most dominant factor determining power output, whereas increases in module temperature result in an efficiency decline of approximately 0.4 - 0.5% per °C [30]. Therefore, the identification and mitigation of various energy losses are crucial for optimizing system performance and enhancing the Performance Ratio (PR) value.

In the solar energy industry, the Performance Ratio (PR) is a crucial metric for investors and developers to evaluate the feasibility and performance of PV systems, as its value is significantly influenced by the meteorological conditions of the study site [31]. The Performance Ratio (PR) is defined as the ratio of the system's actual energy output to its theoretical output under ideal conditions. This value provides essential information regarding how closely the actual performance aligns with the system's maximum potential. In global practice, PR values typically range from 10–20% for systems with significant losses to as high as 95% for optimally performing systems. [32].

Given the complexity of factors influencing system performance, the use of simulation tools is crucial for PV design and feasibility analysis. One of the most widely utilized applications is PVsyst, an industry-standard software that offers comprehensive simulations for system design and performance evaluation with high accuracy across various climatic conditions [33]. This software is specifically designed to predict PV system efficiency by integrating meteorological variables, component specifications, and the technical configuration of the installation [34]. In the PV system design and evaluation process, PVsyst software is essential due to its capability to perform detailed simulations, performance analyses, and economic evaluations of photovoltaic systems [35]. Previous research has demonstrated high accuracy in approximating actual performance (actual PR of 81.02% vs. 80.42% in simulation), and this study reinforces the use of PVsyst as a reliable tool for system planning and evaluation [36]. PVsyst demonstrates simulation results that closely approximate actual data, with a deviation of 1-10% for energy yield and 0-7% for the PR [37]

This reliability makes PVsyst highly effective for designing rooftop PV systems, which face constraints such as limited space, specific tilt angles, shading from surrounding structures, and building-specific electricity consumption patterns [38]. By incorporating site-specific data and module parameters, researchers and system designers can optimize the design to maximize energy production, shorten the payback period, and improve the return on investment (ROI) [39]. In tropical regions such as Southeast Asia, PVsyst is widely applied to evaluate rooftop PV performance under extreme temperature conditions and high cloud cover. These simulations provide crucial insights into seasonal energy fluctuations and efficiency degradation caused by thermal effects [30], [40].

Beyond the technical aspects, the simulation results also serve as a fundamental basis for assessing the economic feasibility of the PV system. Several key financial indicators commonly used to evaluate the investment viability of PV systems include the Levelized Cost of Electricity (LCOE), Benefit-Cost Ratio (BCR), Net Present Value (NPV), and Payback Period [41]. LCOE represents the average cost of electricity production per kilowatt-hour over the system's lifetime, covering initial investment, operational costs, maintenance, and degradation. BCR shows the ratio of total economic benefits to total project costs, where a value of BCR > 1 indicates a financially viable project. NPV calculates the difference between the present value of cash inflows and the total investment and is considered profitable if the value is positive. Meanwhile, the Payback Period indicates how long it takes to recover the initial capital from the savings or revenue generated; the shorter this period, the faster the project yields a profit [41], [42].

Unlike previous studies that only focused on simulating rooftop PV systems without validating field conditions [43], [44], [45], [46], [47]. This research integrates four months of actual data with PVsyst simulation results to analyze the impact of tropical temperature, irradiance, and wind speed on system efficiency and PR. Another novelty of this study lies in its techno-economic analysis, which is based on two discount rate scenarios (national and international) and calculates the Levelized Cost of Electricity (LCOE), Benefit-Cost Ratio (BCR), Net Present Value (NPV), and Payback Period. This comprehensive evaluation is expected to contribute to the optimization of planning and implementation of rooftop PV systems in Indonesia and serve as a reference for sustainable renewable energy development in tropical regions through a contextual approach based on technical validation and economic feasibility

METHODS

This study employs a quantitative approach with a comparative method to evaluate the performance and techno-economic feasibility of a 1.82 kWp on-grid rooftop PV system in Indonesia's tropical climate. The analysis is conducted by comparing actual field measurement data with simulation results from PVsyst software to assess the accuracy of the simulation model against real-world operational conditions. The study was carried out on a PV system installed on the rooftop of the BRIN Energy Building in Serpong, consisting of four monocrystalline Mono PERC modules with half-cut technology and a capacity of 455 Wp each. These modules are installed facing north with a tilt angle of 16.3° and have been tested under Standard Test Conditions (STC).

Table 1 System Specifications

Item	Value
Maximum power	455 Wp
Tolerance	0-3%
Voltage at Pmax	41.70 V
Current at Pmax	10.92 A
Open circuit voltage	49.50 V
Short circuit current	11.66 A
Voc and Isc Tolerance	±3%
Maximum system voltage	1500 V
Maximum series fuse rating	20 A
Temperature operation	-40 °C~+ 85°C
Protection class	Class II

STC: 1000 W/m^2 25 °C

Operational data, including energy production, irradiance, temperature, and wind speed, were collected over the period of April to July 2024. This data was then analyzed using the Performance Ratio (PR), Capacity Factor (CF), and system efficiency, while the simulation accuracy was evaluated using MAPE and RMSE. Furthermore, the system's economic feasibility was analyzed through several indicators, namely the Levelized Cost of Electricity (LCOE), Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Payback Period. These were assessed under two discount rate scenarios to obtain a comprehensive overview of the performance and viability of the rooftop PV system in a tropical environment.

2.1 Performance Ratio (PR)

The Performance Ratio (PR) is a key indicator used to measure the actual performance of a solar power system compared to its theoretical performance under ideal conditions [48].

$$PR = \frac{Actual\ energy\ output\ (kWh/year)}{Theoretical\ maximum\ energy\ output\ (kWh/year)} \times 100\% \qquad (1)$$

The actual energy output is the energy (kWh) recorded by the PV system's output kWh meter. The theoretical maximum energy output is the total annual solar radiation received on the surface of the installed PV module, multiplied by the module's ability to convert sunlight into electricity under real-world field conditions. This can be calculated using the following equation [48],

$$PR = \frac{kWh\ meter\ (kWh)}{solar\ iradiation\left(\frac{kWh}{m2}\right) \times PeakPower\left(\frac{w}{1000w}/m2\right)} \times 100\% \qquad (2)$$

The Performance Ratio (PR) is calculated with the following equation [49]:

$$PR\ (\%) = \frac{Y_f}{Y_r} \times 100\% \qquad (3)$$

Where the value of Y_r reference yield of the DC Performance Ratio, Y_f Final yield :

$$PR_{DC}(\%) = \frac{Y_{DC}}{y_r} \times 100 \qquad (4)$$

AC Performance Ratio :

$$PR_{AC}(\%) = \frac{Y_{AC}}{y_r} \times 100 \qquad (5)$$

The overall efficiency of a system in a given year can be evaluated through the reference yield (Y_r), which represents the total operating hours of the system under standard radiation conditions. The value of Yr is calculated by comparing the total global radiation on the tilted plane (G_t in kWh/m^2) with the standard PV module radiation value, which is 1 kW/m^2. This parameter can be presented on an annual, monthly, or daily scale, depending on the G_t data used [49],

$$Y_r = \frac{G_t(kWh/m2)}{G_0(kWh/m2)} \qquad (6)$$

The final yield (Y_f) indicates the energy generated in relation to the system's size. It can be calculated by dividing the measured energy output of the installed PV array (E_{AC}) by its rated power at STC, which is denoted as ($P_{PV,rated}$). Similar to the Y_r, Y_f can also be represented on an annual, monthly, or daily basis, depending on the value of the actual energy output (E_{AC}) used [49].

$$Y_f = \frac{E_{AC}}{P_{PV,rated}} \qquad (7)$$

The total energy losses in a PV system are the difference between the solar energy received and the electrical energy produced. These losses occur due to the imperfect efficiency of the PV modules and the inverter. They are calculated using the following equation [49] :

$$L_T = Y_r - Y_f \tag{8}$$

Where, L_T total losses, Y_r reference yield, Y_f final yield

2.2 Capacity Factor

The Capacity Factor (CF) is the ratio of the total electrical energy a system generates in one year to the maximum energy it could produce if it operated continuously at its installed capacity for 24 hours a day, all year long. It is therefore expressed as follows [49]:

$$CF_A = \frac{E_{AC}}{P_{PV,rated} \times 365 \times 24} \times 100\% \tag{9}$$

Where, E_{AC} energy output, $P_{PV,rated}$ PV power

2.3 Measurement of Accuracy

The accuracy of this energy model was evaluated by comparing the energy simulation results from PVsyst software with actual measured energy data over a four-month period. Subsequently, the Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE) of the simulation model were calculated based on the absolute difference between the actual energy output of the PV system and the simulation results generated by PVsyst for that period, using the following equations [48] :

$$MAPE = \frac{1}{n}\sum_{actual=1}^{n}\left|\frac{E_{actual} - E_{calculated}}{E_{actual}}\right| \times 100\% \tag{10}$$

$$\text{RMSE} = \sqrt{\frac{\sum(Actual\ Value - Prediction\ Value)^2}{n}} \tag{11}$$

2.3 Photovoltaic conversion efficiency

The conversion efficiency of a solar cell, is the percentage of solar energy that illuminates the PV device and is converted into usable electricity [48].

$$\eta = \frac{V \times I}{E_{sun} \times A_{pv}} \tag{12}$$

Where, V voltage PV, I current PV, E_{sun} solar irradiation and PV surface area A_{pv}.

2.4 Economic Analysis

Economic analysis plays a crucial role in encouraging people to invest in grid-connected PV systems. The LCOE represents the average cost of producing electrical energy per kWh from the system and is expressed in Rupiah per kWh (Rp/kWh).

2.4.1 Levelized Cost of Electricity (LCOE)

To evaluate the cost of energy per unit (Rp/kWh) over a project's lifetime, the LCOE can be calculated using the following equation [49]:

$$LCOE = \frac{C_t(Rp/year)}{E_t(kWh/year)} \tag{13}$$

The value of C_t refers to the total annual cost after economic adjustments, while E_t indicates the total annual electrical energy production, which includes both internal consumption and energy fed into the grid. This metric is a crucial indicator for assessing the efficiency of a power generation system in producing energy at a given cost. The primary objective of this calculation is to achieve the lowest possible cost of electricity production per kilowatt-hour (kWh). The calculation process involves several key parameters, such as the system's operational lifespan (PL), the discount rate (r), and the Capital Recovery Factor (CRF) as well as the Net Present Cost (NPC), or the total present cost calculated over the project's lifetime.

$$C_t = CRF\ (r, PL).NPV \tag{14}$$

$$CRF\ (r, PL) = \frac{r(1+r)^{PL}}{(1-r)^{PL} - 1} \tag{15}$$

2.4.2 Net Present Value (NPV)

NPV reflects the difference between the present value of a project's cash inflows and cash outflows. If NPV > 0, the project is considered financially viable. If NPV = 0, the project results in neither profit nor loss. However, the project may incur a loss if NPV < 0. The NPV value for a project is calculated using the following equation [50]:

$$NPV = \sum_{n=0}^{N}\frac{B_n}{(1+i)^n} - \sum_{n=0}^{N}\frac{C_n}{(1+i)^n} \tag{16}$$

2.4.3 Payback Period (PB)

The PB represents the shortest time required until the accumulated economic savings equal the total initial investment cost I_t. This value can be calculated using a specific equation, where the C_{ES} refers to the savings obtained from using electricity generated by the PV system to replace electricity from the conventional grid. The simple payback period is often calculated with the following equation [49]:

$$PB = \frac{I_t}{C_{ES}} \tag{17}$$

2.4.4 Benefit-Cost Ratio (BCR)

The Benefit-Cost Ratio (BCR) is an economic measure that compares the total present value of benefits with the total present value of costs. If the BCR is > 1, it indicates that the PV system project is financially viable and profitable. This value is typically calculated using a specific equation [50]:

$$BCR = \frac{\sum_{n=0}^{N}\frac{B_n}{(1+i)^n}}{\sum_{n=0}^{N}\frac{C_n}{(1+i)^n}} \tag{18}$$

2.5 Simulasi Software PVsyst

The simulation of the PV system in this study was performed using PVsyst software version 7.4. There are several stages in the data acquisition process, as shown in Figure 1. The first step in this process was to set the Geographical Site to define the research location. The project was set in Rawapicung, Indonesia, which is geographically located at a latitude of 6°21′33″ S and a longitude of 106°39′58″ E, with an altitude of 64 meters above sea level. This location is in the GMT+7 time zone, corresponding to Western Indonesian Time (WIB), with a legal time offset from solar time of -6 minutes. To ensure the accuracy of the simulation,

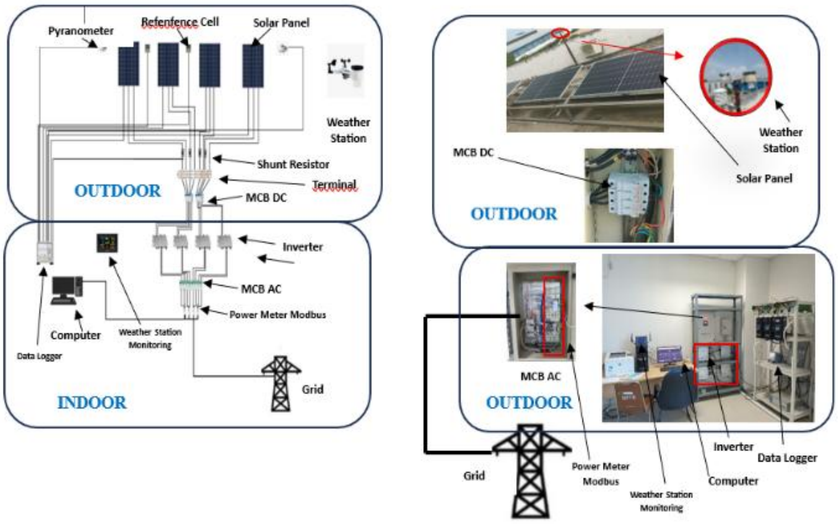


Figure 2. On-Grid Rooftop PV System Configuration

the annual climate data in the Geographical Site settings was obtained from the Meteonorm version 8.1 database, which is one of the global climate data sources integrated into PVsyst. Meteonorm data includes global radiation, diffuse radiation, air temperature, and other meteorological parameters used to calculate the energy potential and performance of a PV system. The selection of this source was based on its consistency and availability in providing representative data for tropical regions like Indonesia. These coordinates and climate data form the basis for modeling radiation, estimating energy production, and performing the technical and economic evaluation of the On-Grid PV system.

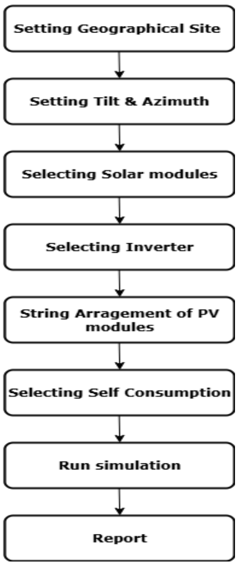


Figure 1. PVsyst Simulation Workflow for a PV System

The determination of the modules' tilt and orientation was performed using the Orientation menu in PVsyst. The system uses a fixed-tilt configuration with a tilt of 16.3° and an azimuth of 0°, facing north, which is appropriate for the location in Indonesia. A quick optimization analysis showed an annual global radiation of 1780 kWh/m², which is only -0.1% lower than the optimal position, indicating that this orientation is very close to ideal. A Transposition Factor (FT) value of 1.01 indicates that this configuration increases radiation absorption compared to a horizontal surface.

2.6 Field-Measured Conditions

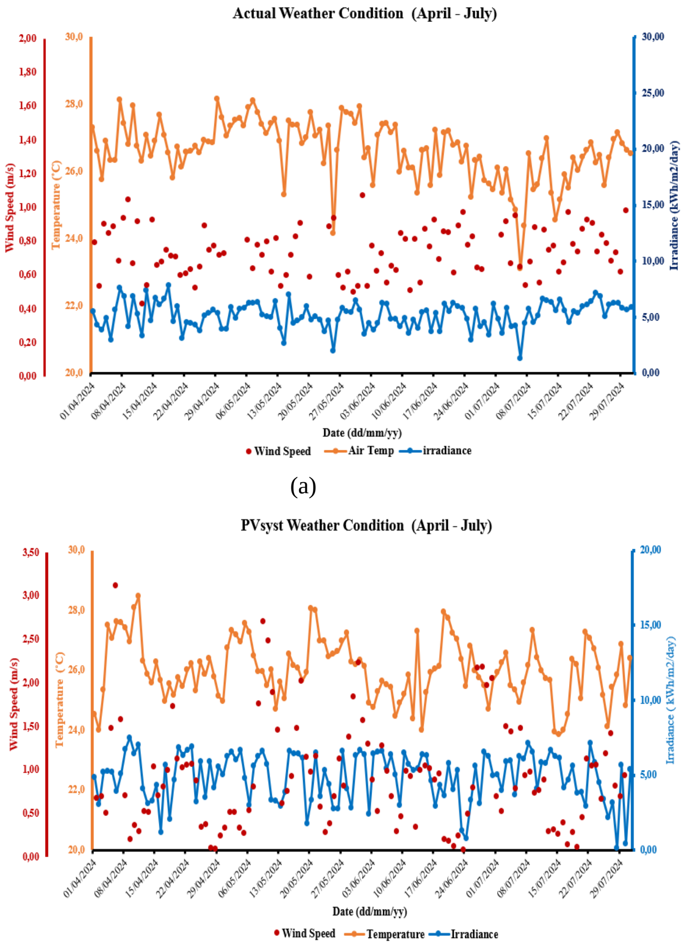
To support the PV system configuration used in the field, as shown in Figure 2, the system consists of a monocrystalline (Si-mono) module with a peak power of 455 Wp. This module has an operating voltage of 36.8 V at a temperature of 60°C and a maximum open-circuit voltage of 54.4 V at a temperature of -10°C. The inverter used has an output power of 2.2 kW, with an operating voltage range of 25-55 V and a maximum input of 60 V. This inverter supports 4 MPPT inputs, which allows for a multi-string configuration to minimize mismatch and optimize power output. The system design uses 1 module per string in 4 parallel strings, for a total of 4 modules with an area of ±9 m². The nominal array power is 1.8 kWp, and the inverter power is 2.2 kWac, resulting in a Pnom ratio of 0.83, which indicates an efficient and not oversized configuration. This setup is designed to optimize power and area utilization in accordance with the climate and radiation characteristics at the study site. One of the important configurations that must be determined is the user's energy load profile. In this scenario, the user selected the 'No self-consumption' option, which means the modeled PV system does not account for any electrical load being supplied directly from the energy generated by the system. In other words, all energy generated by the system is assumed to be fed into the grid, without being consumed directly by the user.

This approach is commonly used in preliminary studies or technical system evaluation scenarios, where the analysis focuses on the energy production performance of the PV system itself, without considering direct interaction with the load. In this scenario, the nominal system power is 1.820 Wp with an estimated annual production of 2.567 kWh. Since there is no load definition, the Pnom ratio to the average and maximum load is not calculated. This configuration is used as a baseline for comparison against a scenario with an actual load, in order to evaluate local energy utilization and its impact on the system's performance and techno-economic aspects.

RESULT & DISCUSSION

This discussion is divided into four main sections. The first section analyzes Weather Conditions by comparing the irradiance, temperature, and wind speed of the PV system. The second section analyzes the Energy Performance of the system by reviewing the total actual energy and simulation results over a four-month period (April - July 2024). The third section focuses on PR Evaluation, based on both simulation data and actual measurements. The final section presents a Techno-Economic Analysis of the rooftop PV.

3.1 Weather Condition



(a)

(b)

Figure 3. (a) Actual Weather Conditions, (b) PVsyst Weather Conditions

Based on the actual data in Figure 3(a), the peak daily irradiance was recorded on April 18, 2024, at 7.81 kWh/m²/day, while the lowest value occurred on July 6, 2024, at 1.3 kWh/m²/day. Monthly, the highest accumulated radiation was in July, at 170.1 kWh/m², and the lowest was in June, at 145.6 kWh/m². The higher the irradiance, the greater the energy potential that can be converted into electricity, although this is highly dependent on the system's temperature and thermal ventilation.

Based on the actual data, the highest temperature reached 28.1°C on April 7, while the lowest was 23.1°C on July 6. Monthly averages show the highest temperature was in April at around 26.9°C, and the lowest was in July at 25.1°C. Temperatures exceeding the standard threshold of 25°C can potentially decrease PV module efficiency by up to 0.5% per °C. This means that even with abundant solar energy, the system's efficiency can still be reduced. Wind speed, which affects the cooling of the panel surfaces, was recorded at its highest on June 6 at 1.07 m/s, and at its lowest on April 21 at 0.43 m/s. Wind plays a crucial role in keeping the panel's operating temperature stable

Meanwhile, the PVsyst simulation results for the same period showed a similar trend but with quantitative differences. As shown in Figure 3(b), the highest daily irradiance occurred on April 9, 2024, at 7.51 kWh/m², and the lowest on July 28, at 0.12 kWh/m². The highest monthly total was recorded in May at 153.4 kWh/m², with the lowest in July at 148.4 kWh/m². The simulated temperature showed a maximum value of 28.5°C on April 11 and a minimum of 23.8°C on July 15, with the highest monthly average in May at 26.4°C and the lowest in July at 25.6°C. Meanwhile, the highest wind speed in the simulation reached 3.12 m/s on April 15, and the lowest was 0.08 m/s on June 27, indicating a more significant cooling effect compared to actual conditions.Both the actual data and the PVsyst simulation show that the highest irradiance occurred in April, but this was accompanied by high temperatures (>28°C) that can decrease panel efficiency by up to 0.5% per °C. This means that despite high energy potential, PV performance can be hindered by high temperatures. A notable difference is seen in wind speed the simulation shows a higher wind speed of 3.12 m/s compared to the 1.07 m/s in the actual conditions, which impacts panel cooling. Overall, optimal rooftop PV performance is achieved when high irradiance is supported by low temperatures and sufficient wind.

3.2 Energy Performance

This section presents a comparison between the actual energy yield and the PVsyst simulation results over a four-month period from April to July. As shown in Table 1, the discrepancy serves as an indicator of the alignment between field data and estimated results. In April, the actual energy was recorded at 159.3 kWh, while the PVsyst simulation projected 221.6 kWh, resulting in a discrepancy (MAPE and RMSE) of 39.1% and 15.6 kWh, respectively. In May, the actual energy increased to 166.0 kWh compared to the PVsyst projection of 229 kWh, yielding a difference of 38.0% and 15.8 kWh. A slight decline in actual energy to 156.8 kWh occurred in June, while PVsyst projected 220.2 kWh, leading to the highest observed discrepancy of 40.5% and 15.9 kWh. By July, although the actual energy rose to 177.6 kWh, the PVsyst estimate of 231.4 kWh caused the deviation to decrease to 30.3% and 13.5 kWh, the lowest values during the observation period.

Table 1.

Discrepancy

Month	MAPE (%)	RMSE (kWh)
April	39,1%	15,6
May	38,0%	15,8
June	40,5%	15,9
July	30,3%	13,5

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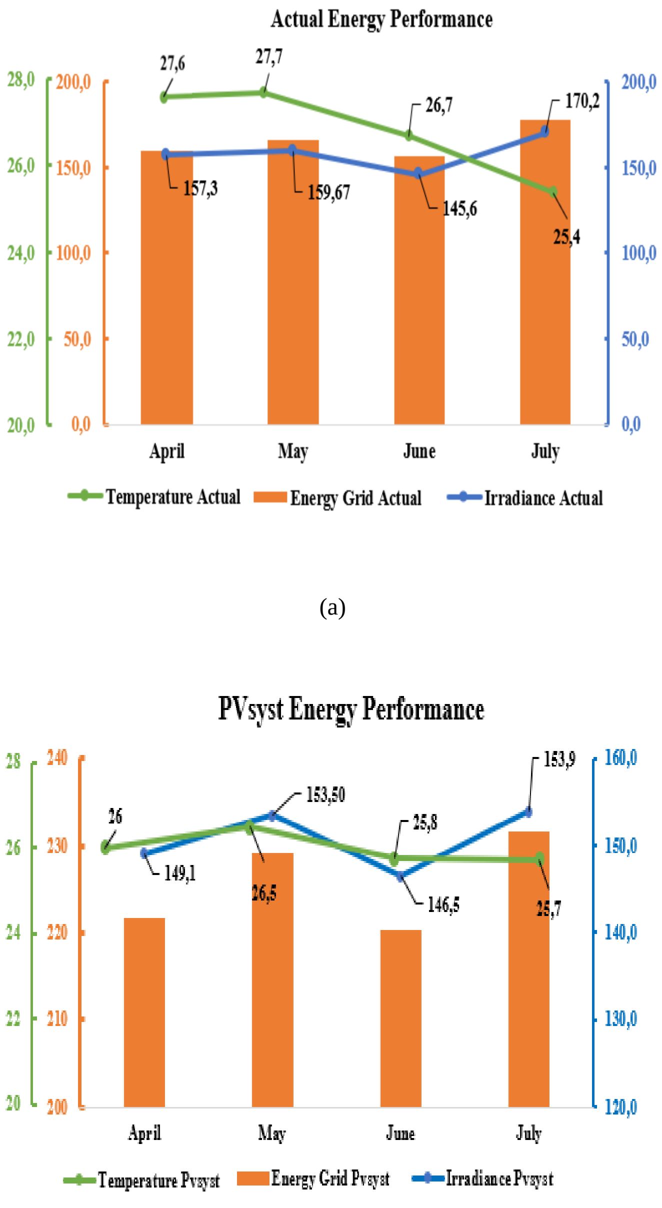

(a)

(b)

Figure 4. (a) The Influence of Irradiance and Temperature on Actual Grid Energy (EAC), (b) The Influence of Irradiance and Temperature on PVsyst Grid Energy (EAC)

Overall, the results indicate that PVsyst simulations consistently provide higher estimations than the actual energy measured in the field, with deviations ranging from 30.3% to 40.5% for MAPE and 13.5 kWh to 15.9 kWh for RMSE. This suggests a significant overestimation by the simulation software, likely due to idealized assumptions regarding parameters such as solar irradiance, system efficiency, and local weather factors that are not fully captured in the model. Consequently, these substantial discrepancies highlight the critical importance of calibrating and adjusting local parameters within the PVsyst model to enhance the predictive accuracy of energy generation, particularly in tropical environments. This emphasizes that site-specific adjustments, including temperature coefficients, derating factors, and shading losses, must be meticulously considered in the simulation input.

Figure 4(a) illustrates the close relationship between solar irradiance, ambient temperature, and the energy generated by the rooftop PV system from April to July. In April, the energy output was recorded at 159.3 kWh, with a corresponding solar irradiance of 157.3 kWh/m² and an average temperature of 27.6°C. This figure rose in May to 166.0 kWh as irradiance increased to 159.67 kWh/m² and the temperature reached 27.7°C. However, in June, the energy yield declined to 156.8 kWh, following a decrease in irradiance to 145.6 kWh/m², despite a slight drop in temperature to 26.7°C. The peak performance occurred in July, reaching the highest energy output of 177.6 kWh when irradiance peaked at 170.2 kWh/m² and the temperature was at its lowest at 25.4°C. This pattern demonstrates that solar irradiance plays a dominant role in determining energy output, while temperature acts as a secondary factor affecting thermal efficiency.

The simulation results from PVsyst further reinforce these findings. As depicted in Figure 4(b), the electrical energy generation from April to July follows a pattern consistent with irradiance fluctuations. In April, with a simulated irradiance of 149.1 kWh/m² and a temperature of 26°C, the energy output reached 221.6 kWh. This value increased in May to 229 kWh as the irradiance rose to 153.5 kWh/m², despite a concurrent temperature increase to 26.5°C. A decrease in irradiance to 146.5 kWh/m² in June, accompanied by a temperature of 25.8°C, caused a marginal decline in energy output to 220.2 kWh. However, in July, the irradiance rose again to 153.9 kWh/m² while the temperature slightly decreased to 25.7°C, resulting in the peak energy yield of 231.4 kWh. Notably, despite the lower simulated irradiance levels compared to field data, the resulting energy output remains higher because the simulation assumes idealized conditions, excluding factors such as shading, soiling, and other systemic losses.

Overall, both data sources demonstrate that an increase in solar irradiance directly enhances energy output, while lower temperatures improve the energy conversion efficiency of the solar panels. This evaluation underscores the importance of optimizing both environmental and system conditions to achieve maximum performance in rooftop PV systems. Furthermore, it indicates that while PVsyst simulations provide valuable estimations, they may not always fully represent comprehensive field conditions. The discrepancy between actual energy values and simulation results serves as a critical basis for evaluating the efficiency of the installed system, potential degradation, and the influence of external factors on the real-world performance of PV systems.

Based on the data shown, the total energy loss from actual measurements consistently shows a higher value compared to the PVsyst simulation results, as shown in Figure 5. The highest actual daily loss was recorded at 2.34 kWh/kWp/day, while the lowest value was 1.98 kWh/kWp/day. Meanwhile, the PVsyst simulation results showed a significantly lower daily loss, ranging from 0.85 to 0.91 kWh/kWp/day. On average, the actual energy loss was around 2.16 kWh/kWp/day, whereas the simulation average was only about 0.88 kWh/kWp/day. The average difference of 1.28 kWh/kWp/day between the actual and simulation results indicates that the software's estimation is inconsistent with real-world field conditions.

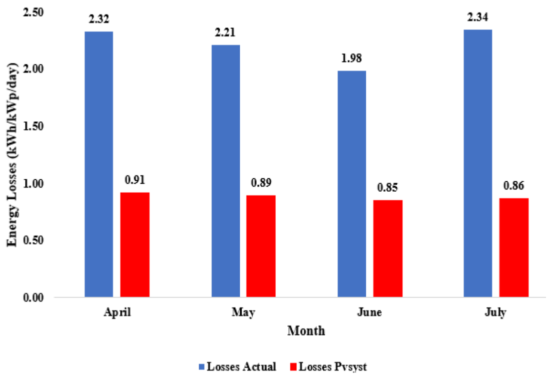

Figure 5. Comparison of grid energy losses from April to July

3.3 Photovoltaic conversion efficiency

Table 2. PV System Efficiency

Month	Efisiensi Actual (%)	PVsyst Efficiency (%)
April	46,6	68,4
May	47,8	68,6
June	49,5	69,2
July	48,0	69,2

To determine the efficiency of the rooftop PV system based on actual and simulation data, see Table 2. In April, the actual efficiency was recorded at 46.6%, while the PVsyst simulation result showed a much higher value of 68.4%. Next, in May, the actual efficiency increased to 47.8%, while the simulated efficiency also rose slightly to 68.6%. The most significant increase in actual efficiency occurred in June, reaching 49.5%, while the simulated efficiency also rose to 69.2%. In July, the actual efficiency slightly decreased to 48.0%, but the simulated efficiency remained stable at 69.2%. This significant difference indicates that the simulation results tend to be more optimistic compared to the actual realization in the field, which is caused by external factors such as weather conditions, shading, or system performance that are not entirely ideal in a real-world environment.

3.4 Capacity Factor

The Capacity Factor (CF) is an important parameter in the evaluation of a PV system's performance, as shown in Table 3, which presents the capacity factor data. In April, the actual CF was recorded at 3.04%, while the PVsyst result was higher, at 4.23%. In May, there was a slight increase in the actual data to 3.17%, while the PVsyst data also rose to 4.37%. However, in June, the actual CF experienced a decrease to 2.99%, while the PVsyst result also slightly declined to 4.20%. In July, the actual CF increased quite significantly to 3.39%, and the PVsyst data also rose to 4.41%.

Table 3. PV System Capacity Factor

Month	Actual Capacity Factor (%)	PVsyst Capacity Factor (%)
April	3,04	4,23
May	3,17	4,37
June	2,99	4,20
July	3,39	4,41

This data shows that the CF value from the PVsyst simulation is consistently higher compared to the actual measurements for each month of observation. This difference between the actual and simulated CF values indicates a deviation between the system's performance in the field and the simulation software's prediction.

3.5 Performance Ratio (PR)

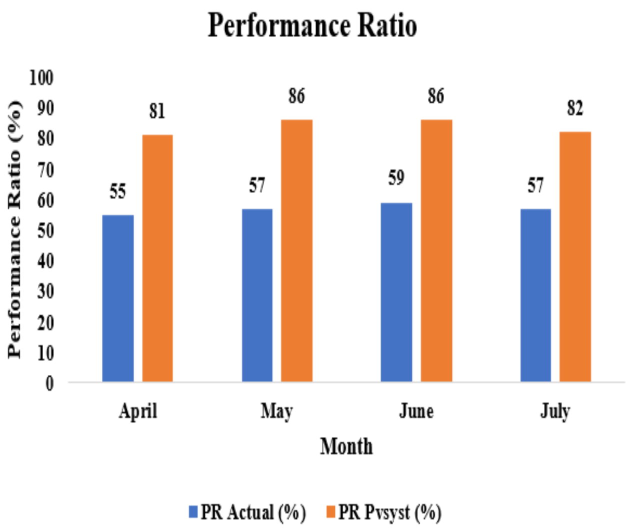

Figure 6. Comparison of actual and PVsyst Performance Ratio (PR)

The discussion regarding the PR is vital for assessing the extent to which the PV system operates near its optimal performance, as it represents the ratio between the actual energy generated and the theoretical energy that should be produced under ideal conditions. Based on the data presented in Figure 6, there is a significant discrepancy between the actual PR values and the simulated PR values across all observed months. In April, the actual Performance Ratio (PR) was recorded at 55%, whereas the simulation results yielded a PR of 81.7%. This discrepancy persisted through May, with actual and simulated values of 57% and 82%, respectively. In June, the values were 59% compared to 82.6%, and in July, 57% compared to 82.6%. The average deviation between these two datasets ranges from 23% to 27%, indicating a tendency for PVsyst software to overestimate the performance of the PV system relative to real-world field realization. These findings contrast with previous research involving a 1.5 MWp on-grid PV system, which reported an average simulated PR of 82.7% against an actual PR of 88.05%. That study observed a performance enhancement of approximately 5.35% under real operating conditions [51].

This disparity may be attributed to various factors, including the accumulation of dust on the solar modules (soiling), partial shading from surrounding vegetation or structures, module degradation due to aging, and component efficiencies that deviate from ideal assumptions. Conversely, PVsyst typically conducts simulations based on Standard Test Conditions (STC) and idealized environmental parameters, which often fail to account for field-level imperfections. Furthermore, the divergence between actual temperature and irradiance data compared to the simulation input parameters significantly contributes to the PR discrepancy. With an actual PR ranging between 55% and 59%, these figures remain significantly below the optimal target of 70% to 80% for modern rooftop PV systems.

Table 4. Previous Research Findings

Energy Grid (MWh)		**Performance Ratio (%)**		**Capacity Factor (%)**		**Ref**
Real	**PVsyst**	**Real**	**PVsyst**	**Real**	**PVsyst**	
0.196	0.142	-	-	13.6	10.3	[52]
14.5	11.2	70.7	52.5	18.4	13.6	[53]
99.04	99.04	77	70.4	15.7	15.7	[54]
36.3	39.2	71.67	76.92	20.7	22.3	[55]
0.523	0.535	72.23	71.30	32.31	33.07	[56]

Table 4 presents a comparative analysis of PV system performance between actual field data and PVsyst simulation results derived from several previous studies. In general, the actual energy delivered to the grid closely aligns with the simulated outputs, despite minor deviations observed in specific cases. PR typically ranges from 70% to 77%, exhibiting a discernible discrepancy compared to PVsyst projections due to the influence of real-world operating conditions. Meanwhile, the actual CF is generally comparable to or slightly lower than the simulation results. This comparative study offers strategic contributions for stakeholders in mapping PV system performance within specific climatic conditions and serves as a critical parameter for regional solar energy optimization. Nevertheless, this research constitutes a preliminary foundation that warrants further development. The integration of higher-resolution datasets and in-depth empirical investigations are essential to minimize data anomalies and yield more precise, comprehensive performance assessments.

3.6 Techno-Economi

Based on the results of the economic evaluation of the 1.82 kWp on-grid PV system, with a 5.25% discount rate that refers to the Bank Indonesia benchmark interest rate [57]. and 10,4% based on the National Renewable Energy Laboratory (NREL): Exploring Renewable Energy Opportunities In Select Southeast Asian Countries [58]. This study was analyzed using a life-cycle cost analysis approach based on the NREL method

This evaluation includes key indicators such as Net Present Value (NPV), Benefit-Cost Ratio (BCR), Payback Period, and Levelized Cost of Energy (LCOE). Investment costs were calculated based on the actual costs of physical system elements included in the Engineering, Procurement, and Construction (EPC) scope. This includes photovoltaic panels, inverters, mounting systems, electrical installations, cables, operational and maintenance (O&M) costs, and protection equipment. As explained in the Indonesian Electricity Sector Technology Catalogue from the Directorate General of Electricity [53], the investment cost for a rooftop PV system in Indonesia tends to be higher than that of a ground-mounted PV system. Based on data from several providers, these costs range from 1.07-1.72 million USD/MWp for capacities between 1-5.5 kWp. The economic analysis is projected over a 25-year period..

Table 5. Economic Indicator

Economic Evaluation Area	**Discount rate = 5,25%**	**Discount rate = 10,4%**
Payback Period (years)	9,8	9,5
Net Present Value (NPV)	Rp 15.878.111	Rp 10.507.303
Benefit-Cost Ratio (BCR)	1,50	1,33
Levelized Cost of Electricity (LCOE)	Rp 974,88	Rp 1.454,10
25 years		

The evaluation results show economic feasibility with two discount rate scenarios, namely 5.25% and 10.4%, indicating a significant difference in several key indicators. In the scenario with a 5.25% discount rate, the NPV was recorded at Rp 15,878,111. This value indicates that the investment in the rooftop PV system provides a substantial net economic benefit when calculated based on the current value of money. Meanwhile, in the 10.4% discount scenario, the NPV decreased to Rp 10,507,303. This decrease reflects that the higher the discount rate used, the smaller the value of future economic benefits when calculated at the present value, thereby reducing the project's profitability.

From the BCR side, the 5.25% discount scenario yielded a value of 1.50, which means that every Rp 1 of investment cost will generate a benefit of Rp 1.50. This shows that the project is very financially viable. However, when the discount rate was raised to 10.4%, the BCR value decreased to 1.33, indicating that although the project is still viable because BCR > 1, the profit margin becomes narrower. In terms of the Payback Period, there was a very small difference between the two scenarios: 9.8 years for the 5.25% discount and 9.5 years for the 10.4% discount. This shows that the investment recovery time is relatively stable against changes in the discount rate, because the annual return value is still sufficient to cover the initial costs in a similar.

The LCOE for a rooftop PV system is dependent on the discount rate. At a 5.25% discount rate, the LCOE was Rp 974.88/kWh, which is well below the tariff of the National Electricity Company (PLN) at Rp 1,444/kWh, offering potential savings of around Rp 469.12/kWh.nHowever, at a 10.4% discount rate, the LCOE increased to Rp 1,454.10/kWh, making it slightly more expensive by Rp 10.10/kWh than the PLN tariff. This demonstrates that an increase in the discount rate can reduce the economic competitiveness of a rooftop PV system. Therefore, low-cost financing is a crucial component to ensure a project remains profitable and financially sustainable.

Overall, it can be concluded that a change in the discount rate from 5.25% to 10.4% has a direct impact on the economic feasibility indicators of a rooftop PV system. The higher the discount rate, the more the project's economic value decreases in terms of NPV, BCR, and LCOE. Nevertheless, the project is still considered viable in both scenarios, given that all indicators remain within an acceptable range: a positive NPV, a BCR > 1, and a Payback Period that is still below the project's technical lifespan. This shows that investing in a rooftop PV system remains promising in the long run, although its net profit will be more optimal at a lower discount rate.

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CONCLUSIONS

This study systematically examines the gap between the theoretical and actual performance of a 1.82 kWp on-grid rooftop PV system operating in Indonesia's tropical climate. Measurement results for the period of April to July 2024 indicate that the actual energy production ranged from 156.8 to 177.6 kWh per month, whereas PVsyst simulations predicted a higher output of 220.2 to 231.4 kWh per month. This disparity resulted in an energy deviation of 30.3% to 40.5%, with MAPE and RMSE values ranging between 13.5 and 15.9 kWh, respectively indicating a significant overestimation by the simulation model relative to field conditions. In terms of performance metrics, the actual Performance Ratio (PR) reached only 55-59%, considerably lower than the simulated PR of 81-82%. This low PR aligns with the high actual energy losses, which averaged 2.16 kWh/kWp/day, nearly 2.5 times greater than the simulated loss of 0.88 kWh/kWp/day. Furthermore, the actual system efficiency was significantly lower at 46.6-49.5% compared to the PVsyst estimate of 68.4-69.2%. The actual Capacity Factor (CF) ranged from 2.99% to 3.39%, which is lower than the simulated range of 4.20-4.41%. These findings confirm that tropical environmental conditions such as elevated module temperatures, low wind speeds, shading, and dust accumulation contribute significantly to the performance degradation of rooftop PV systems in the field.

Despite the actual technical performance falling below simulated estimates, the techno-economic analysis demonstrates that the rooftop PV system remains feasible and financially profitable. Under a discount rate scenario of 5.25%, the system yielded a positive Net Present Value (NPV) of IDR 15,878,111, a Benefit-Cost Ratio (BCR) of 1.50, and a Payback Period of 9.8 years. Furthermore, the Levelized Cost of Energy (LCOE) was calculated at IDR 974.88/kWh, which is significantly lower than the current PLN (utility) tariff of IDR 1,444/kWh. In a higher discount rate scenario of 10.4%, the NPV remained positive at IDR 10,507,303, with a BCR of 1.33 and a relatively stable Payback Period of 9.5 years. However, the LCOE increased to IDR 1,454.10/kWh, slightly exceeding the utility tariff. These results underscore that financing structures and discount rates play a pivotal role in determining the economic competitiveness of rooftop PV systems.

Overall, this research underscores that the validation of simulation data through field measurements is a crucial step in the planning and evaluation of rooftop PV systems in tropical climates. The integration of actual operational data in this study provides a practical solution for identifying energy loss sources and enhancing the realism of system performance predictions. Moving forward, further studies based on long-term datasets are required, alongside the development of tropical-specific correction factors within simulation software such as PVsyst. Additionally, evaluating operational mitigation strategies including design optimization, enhanced thermal ventilation, and scheduled module cleaning is essential to improve the Performance Ratio and support the accelerated implementation of reliable and sustainable rooftop PV systems in Indonesia.

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NOMENCLATURE

PV	Photovoltaic
PR	Performance Ratio
CF	Capacity Factor
NPV	Net Present Value
BCR	*Benefit-Cost Ratio*
LCOE	*Levelized Cost of Electricity*
STC	Standard Test Conditions
E_{AC}	Energy delivered to the grid
Y_f	final yield
Y_r	reference yield
G_t	Global irradiance on tilted plane
P_{Pv}	Photovoltaic Power
MAPE	Mean Absolute Percentage Error
RMSE	Root Mean Square Error

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