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Analysis of Performance Decline in 415.15 kWp On-Grid Solar Based on Dust Soiling Factors and Inverter Temperature in the Solar Power System

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ABSTRACT

This study aims to analyze the influence of soiling factors and inverter temperature on the performance degradation of solar panels, using real-time data captured through sensors. Soiling, which includes the accumulation of dust and dirt on the surface of solar panels, as well as fluctuating inverter temperatures, is known to affect energy conversion efficiency. Tests were conducted by monitoring the performance of solar panels under different soiling conditions and varying inverter temperatures. To solve the soiling problem, cleaning was carried out on the solar panels, while the high inverter temperature was handled by adding a fan to the room to increase air circulation and cool down the inverter temperature. The results show that soiling can reduce energy conversion efficiency, while high inverter temperatures worsen system performance. Periodic cleaning of the solar panels was found to be effective in improving efficiency, while the addition of a fan in the room can reduce energy losses caused by high inverter temperatures. These findings provide important insights for performance optimization of solar panels and inverter systems under field conditions.

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INTRODUCTION

The need for electrical energy continues to increase along with population growth, urbanization, and industrialization. However, the dependence on fossil fuels such as petroleum, gas, and coal poses a serious challenge, given the depletion of these resource reserves (Afifudin & Hananto, 2012; Norbury et al., 2017; Prettner, 2013). To overcome the potential energy crisis in the future, renewable energy such as solar power plants is a strategic solution. Indonesia, as a tropical country that gets sunlight for 10-12 hours per day, has great potential for the development of solar power (Han & Li, 2024; Li & Han, 2022; Samsu et al., 2020).

Solar PV converts solar energy into electricity through solar panels connected to inverters. Inverters function to convert direct current (DC) into alternating current (AC), which can be used for industrial and household needs (Ahmadi et al., 2018; Al-Ezzi & Ansari, 2022; Moore & Wei, 2021; Prasetyo et al., 2023; Terashima et al., 2023). The performance of the inverter greatly determines the efficiency of the solar PV system. However, research shows that the performance of inverters often occurs due to various factors, including the accumulation of dust in the solar panels (soiling), which has an impact on the output power [2][3]. At PT PIM Pharmaceuticals, the decrease in inverter performance caused system efficiency to decrease and operational costs to increase.

Therefore, this study aims to identify the causes of the decline in performance in the solar PV system, analyze the effect of dust soiling on energy production efficiency, and provide

effective solutions to maintain the stability and productivity of solar PV. This study uses a simulation approach with PVsyst software to examine the performance of the system in detail, with the hope of providing applicable and sustainable recommendations for the development of renewable energy.

Previous studies have primarily focused on general factors affecting solar panel performance, such as shading, tilt angle, and module temperature. Research by Samsu et al. (2020) and Bactiar (2006) emphasized output power losses due to environmental conditions, while Hartono (2021) discussed the resilience of inverters in tropical climates. Studies on soiling, such as those by Adi & Widodo (2021), show that accumulated dust significantly reduces PV efficiency, and Rahmawati (2020) suggested coatings as preventive measures. However, these studies often analyze factors in isolation or under off-grid systems, without examining integrated effects in real-time on operational on-grid PV systems.

This study addresses that gap by offering a novel contribution: a simultaneous investigation into dust soiling and inverter temperature as two critical and interrelated factors contributing to PV performance degradation in a real-world on-grid solar plant. Soiling reduces light absorption on the panel surface, while high inverter room temperatures lead to efficiency losses through derating or automatic shutdown. The uniqueness of this research lies in its field-based monitoring using sensors to collect real-time data before and after maintenance interventions—namely, panel cleaning and installation of ventilation systems—to quantify their effects on performance ratio (PR). These aspects are especially relevant for tropical countries with high dust exposure and poor thermal regulation.

Therefore, this research aims to analyze the influence of soiling and inverter temperature on the energy performance of a 415.15 kWp on-grid PV system at PT PIM Pharmaceuticals. The results are expected to provide evidence-based recommendations for maintaining optimal PV performance, reducing operational costs, and extending the service life of solar infrastructure. The findings can also serve as a reference for industrial-scale solar energy management in similar climates, emphasizing preventive maintenance strategies and environmental monitoring as essential elements for energy efficiency.

METHOD

This research adopts a field-based quantitative approach supported by real-time sensor data to analyze the influence of soiling and inverter temperature on solar panel performance. To examine the effect of soiling, solar panels were monitored under two different surface conditions: uncleaned (dust-exposed) and cleaned. Temperature sensors, irradiation sensors, and energy meters were installed directly on the panel surfaces and inverter units to capture accurate, real-time data including Global Irradiation (kWh/m²), Theoretical Yield (kWh), Inverter Yield (kWh), and Performance Ratio (PR). PR was calculated using the formula PR = (Inverter Yield / Theoretical Yield) × 100%. Panel cleaning was performed manually and scheduled to assess the correlation between dust removal and recovery in efficiency. The panel surface temperature was also indirectly measured through irradiation changes and verified using environmental data to ensure accurate contextual analysis.

For temperature analysis of the inverter system, a Seaward PV200 multifunction instrument was employed. This device integrates an external temperature probe to measure both the inverter surface temperature and ambient room temperature with high precision.

Measurements were taken before and after the installation of a cooling system (Hexos) to assess its effect on inverter operating conditions. Prior to installation, inverter temperatures ranged from 56°C to 61°C, while room temperature ranged from 40°C to 41°C—indicating a high thermal load. After Hexos implementation, the temperatures decreased significantly to between 38°C and 40°C, showing improved cooling performance. These measurements provided critical insights into thermal derating effects and informed mitigation strategies such as fan installation and improved ventilation to enhance long-term system stability and efficiency.

Soiling Factors

One of the factors that can affect the performance of solar panels is the accumulation of dust and dirt on the panel surface (soiling). In this study, the test was carried out by comparing the performance of solar panels under two different conditions, namely panels that were exposed to dust and panels that had been cleaned. Energy efficiency is measured using sensors mounted directly on the panel to obtain real-time data. Panel cleaning is carried out periodically to see any changes in the system's performance after dust and dirt have been cleaned. The aim of this study was to find out the extent to which soiling affects the efficiency of solar panels and whether cleaning can restore the panel's performance to its original condition.

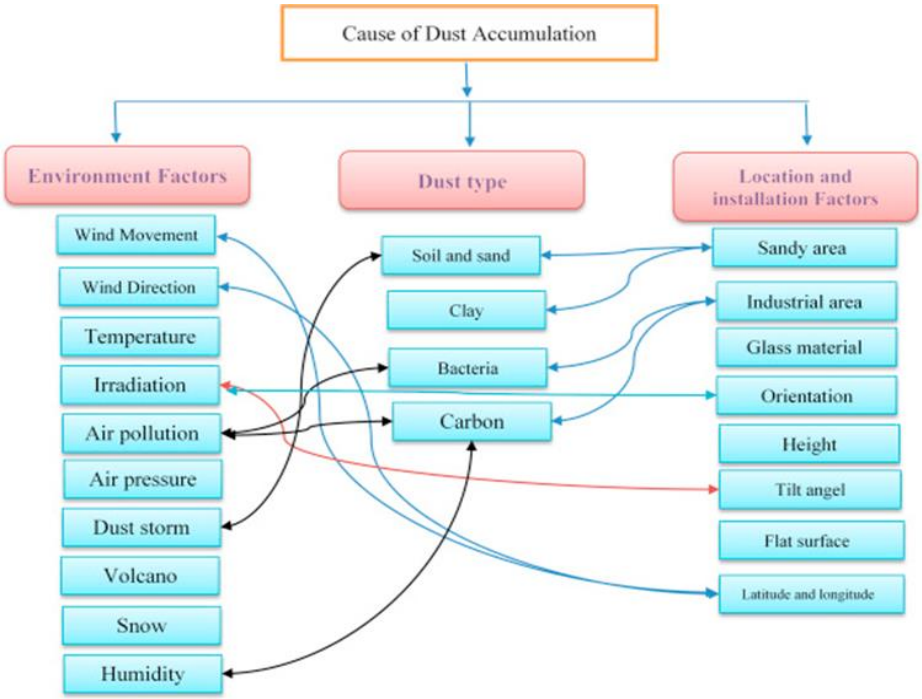

Figure 1. Causes of dust that accumulates on solar panels
Source: Processed Data

The figure above illustrates the factors that affect the buildup of dust on solar panels, which are divided into three main categories: Environmental Factors, Dust Types, and Location and Installation Factors. Environmental factors such as wind movement, temperature, air pollution, and dust storms affect the type of dust that sticks to the solar panels, which ultimately lowers the energy efficiency of the panels. *"Effect of dust accumulation on the performance of photovoltaic panels"*, these factors have a major impact on the performance of photovoltaic panels. In addition, dust types such as soil and sand, clay, and carbon can reduce the efficiency

of the panels, *"The Impact of Dust Deposition on PV Panels' Efficiency and Power Output".* Location and installation factors such as area type and panel orientation also play a role in dust buildup *"Soiling loss in solar systems.*

Inverter Room Temperature Factor

Factors that can affect the decline in inverter performance at PT PIM Pasuruan Solar Power Plant, The temperature of the inverter in the solar PV system is significantly affected by the ambient air temperature. When the room temperature rises, internal components such as semiconductors and capacitors experience increased resistance, which leads to the onset of overheating. This condition can reduce energy conversion efficiency and accelerate damage or decrease the service life of the device."*liberry. How Does Ambient Temperature Impact Inverter Efficiency? April 24, 2025".*Ultimately, if the temperature exceeds the operational safe limit, which is generally in the range of 30–40 °C to a maximum of 45–60 °C, the inverter will automatically reduce the output power (derating) or even stop its operation completely as a protective measure.*"Jouvoli. Derating of Solar Inverters Due to High Operating Temperature. March 3, 2025".*Another important factor is ventilation and airflow. If the room does not have an adequate ventilation system, heat will be trapped and cause internal coolers such as heatsinks or fans to not function optimally. So that good ventilation design can help improve the efficiency and reliability of inverter performance.

To overcome the problem of high temperatures in solar inverters, it is necessary to implement proper preventive and handling measures. One of the first steps that can be made is to place the inverter in a cool area, protected from direct sunlight, and have adequate air circulation. Smooth air circulation can be achieved by ensuring ventilation holes for incoming and outgoing airflow, and maintaining sufficient distance around the device to prevent heat from being trapped. In high-temperature environments, the use of additional cooling systems such as automatic fans, exhaust fans, or air conditioners can help keep the inverter's temperature stable.

RESULTS AND DISCUSSION

Results of Soiling Discussion

Table 1. Data Collection Data from Sensors Before the Cleaning Process

Stactical Era	Total String Capacity (KWp)	Global Irradiation (kWh/m²)	Theoretical Yield (kWh)	Inverter Yield (kWh)	Performance Ratio (%)
2024-07-15	415.150	4.857	2,016.322	1,559.860	77.4
2024-07-16	415.150	5.890	2,445.041	1,872.060	76.6
2024-07-17	415.150	5.893	2,446.387	1,867.610	76.3
2024-07-18	415.150	6.145	2,551.135	1,931.677	75.7
2024-07-19	415.150	5.621	2,333.643	1,806.49	77.4

Source: Processed Data

The table above presents the data from the measurement of the photovoltaic (PV) system from the sensor before the cleaning process of the solar panel. The parameters recorded include the total capacity of the PV system (Total String Capacity) of 415,150 kWp, daily

global irradiation (Global Irradiation) in units of kWh/m², theoretical yield, actual yield produced by inverter (Inverter Yield), and system performance ratio (PR). Theoretical Yield represents the maximum potential energy that can be generated based on the irradiation value received, while Inverter Yield reflects the actual energy converted from direct current (DC) to alternating current (AC) by the inverter.

The Performance Ratio (PR) in this table is calculated as a comparison between *Inverter Yield* and *Theoretical Yield*, which describes the operational efficiency of the photovoltaic (PV) system before the cleaning process is carried out. This PR value indicates the extent to which the PV system can convert solar energy into usable electrical energy, taking into account various factors such as temperature, shading, dirt on the panels, and the efficiency of the inverter. Based on data, the PR value for the period from 15 to 19 July 2024 ranged from 75.7% to 77.4%. As of July 15, 2024, PR was recorded at 77.4%, which indicates good operational efficiency despite no cleanup of the panels.

On July 18, 2024, the PR decreased to 75.7%, indicating a decrease in efficiency, likely due to the accumulation of dust or dirt on the solar panels. This can reduce the ability of the panel to absorb solar irradiation to the maximum. However, on July 16 and 17, 2024, PRs were recorded slightly higher, at 76.6% and 76.3%, indicating that although no cleaning has been carried out, the system is still operating with fairly good efficiency. The drop back on July 19 to 77.4% indicates a fluctuation in the operating conditions of the system, which is affected by changes in irradiation or other factors affecting the performance of the photovoltaic panels.

Table 2. Data Collection Data from Sensors After Cleaning Process

Stactical Era	Total String Capacity (KWp)	Global Irradiation Daily (kWh/m²)	Theoretical Yield (kWh)	Inverter Yield (kWh)	Performance Ratio (%)
2024-07-21	**415.150**	**4.906**	**2,036.849**	**1,616.63**	**79.3**
2024-07-22	**415.150**	**5.090**	**2,113.075**	**1,677.42**	**79.4**
2024-07-23	**415.150**	**4.257**	**1,767.347**	**1,393.79**	**78.8**
2024-07-24	**415.150**	**5.688**	**2,361.204**	**1,834.400**	**77.7**
2024-07-25	**415.150**	**5.696**	**2,364.625**	**1,834.460**	**77.6**

Source: Table of data collection results from sensors after the cleaning process

The table above shows the results of measuring the performance of the solar power plant system (PLTS) after the cleaning process of the solar panels. The parameters listed include the total capacity of the system of 415,150 kWp, the value of global irradiation daily (Global Irradiation Daily) in units of kWh/m², the theoretical yield (Theoretical Yield) calculated based on the irradiation value and system capacity, the actual yield of the inverter (Inverter Yield) as the output of the electrical energy produced, and the Performance Ratio (PR) which shows the efficiency of the system.

In the table above, the data shows the Performance Ratio (PR) of the photovoltaic system after panel cleaning. PR is calculated as a comparison between *Inverter Yield* and *Theoretical Yield*, which describes the operational efficiency of a PV system in converting solar energy into usable electrical energy. After the cleaning process, there was a significant increase in the PR value compared to the previous data.

On July 21, 2024, the PR value was recorded at 79.3%, and on July 22, 2024, it increased to 79.4%, indicating higher efficiency after cleaning. This increase is most likely due to a reduction in dust or dirt that decreases the panel's ability to absorb solar irradiation to the fullest before cleaning. Although there was a slight decline on July 23, 2024 with a PR of 78.8%, the PR value remained stable and relatively high during the observation period after the cleanup. On July 24 and 25, 2024, PRs were recorded at 77.7% and 77.6%, respectively, indicating slightly declining efficiency but still in the excellent range. Overall, this data indicates that the cleaning of photovoltaic panels has a significant positive impact on improving the efficiency of PV systems.

Homework scores in the field were carried out for 10 days, namely on July 15-24, 2024. After the cleanup, the PR value showed an improvement compared to the previous condition, with a value range between 76.9% and 79.3%, which indicates that the system is operating close to its optimal performance. PR is calculated by comparing the inverter yield to the theoretical yield, then multiplied by 100%.

The graph above illustrates the comparison between the Performance Ratio (PR) before and after the photovoltaic panel cleaning process on several days of testing. The PR value before cleaning (indicated by the gray bar) shows relatively small fluctuations, ranging from 75.7% to 77.4%, which indicates stable but less than optimal efficiency of the PV system. These fluctuations can be affected by the accumulation of dust and dirt on the solar panel, which naturally reduces the panel's capacity to absorb solar radiation to the maximum.

After the cleaning process, the PR value showed an improvement, with a value range between 77.4% to 79.4%. Although there was a slight decrease on the fifth day of 77.4%, overall these results show that solar panel cleaning contributes to improved energy conversion efficiency. This improvement confirms the importance of regular maintenance of photovoltaic panels, particularly in cleaning up impurities that can inhibit the light absorption process and, consequently, lower the overall efficiency of the PV system.

Results of Inverter Room Temperature Discussion

Table 3. Thermal Extraction Data Prior to Hexos Installation and Reconfiguration

Inverter	Inverter Temperature	Room Ambient Temperature
1	57°C	41°C
2	56°C	41°C
3	58°C	40°C
4	61°C	40°C

Source: Processed Data

Based on the table above, it can be seen that the working temperature of the inverter is in the range of 56°C to 61°C, while the ambient temperature of the room is in the range of 40°C to 41°C. There is a significant temperature difference between the temperature of the inverter and the room temperature, with a difference between 15°C to 21°C. The 4th inverter recorded the highest temperature of 61°C, which indicates quite extreme working conditions and has the potential to accelerate the decline in the service life of inverter components if not handled immediately.

Temperature measurements were carried out using Seaward PV200 tool, which is a multifunctional instrument commonly used in the testing of photovoltaic (PV) systems. In addition to voltage, current, and power measurements, the PV200 is also equipped with an external temperature sensor that allows direct surface temperature measurement of the inverter and the surrounding environment. This tool was chosen for its high level of accuracy and its ability to record real-time temperature data in the field, thus supporting the validity of the measurement results shown in the table.

The temperature data obtained from PV200 is an important basis for the need to install an additional cooling system in the form of Hexos and reconfigure the layout or ventilation system so that the inverter temperature can be lowered close to the ambient temperature of the room. Thus, this effort is expected to be able to maintain the stability of the inverter's working temperature and extend the overall operational life of the equipment.

Table 2. Temperature Retrieval Results After hexos installation and reconfiguration

Inverter	Inverter Temperature	Room Ambient Temperature
1	38°C	28°C
2	40°C	30°C
3	39°C	29°C
4	40°C	30°C

Source: Processed Data

After the installation of an additional cooling system in the form of a Hexos layout system or ventilation, there is a significant decrease in temperature in the inverter. Based on Table 2, the inverter temperature drops to the range of 38°C to 40°C, with the ambient temperature of the room ranging from 28°C to 30°C. When compared to the conditions before the installation of Hexos, the temperature difference between the inverter and the room temperature is now much smaller, at only about 10°C to 12°C. This shows that the additional cooling system functions effectively in lowering the overall working temperature of the inverter.

CONCLUSION

Real-time monitoring of the 415.15 kWp solar power system at PT PIM Pasuruan demonstrates that dust *soiling* and high inverter temperatures are critical factors reducing system efficiency, with performance ratios dropping to 75.7% due to dust accumulation but improving to 79.4% after panel cleaning; similarly, inverter temperatures were effectively lowered from over 60°C to below 40°C through Hexos ventilation, enhancing reliability and energy conversion. To sustain optimal performance, it is recommended that operators implement regular panel cleaning and integrate inverter cooling systems, especially in tropical or dusty environments. For future research, longer-term studies spanning multiple seasons should be conducted to evaluate the cumulative effects of *soiling* and temperature, and the potential of automated cleaning and smart thermal regulation technologies should be explored to offer scalable, cost-effective solutions for large-scale solar PV operations.

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