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Effect of Panel Tilt Angle and Electrical Load on Inverter Efficiency in a 24V Off-Grid 200 WP Photovoltaic System

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ABSTRACT

Solar Power Plants (PLTS) are systems that convert solar energy into electrical energy through the principle of the photovoltaic effect. The efficiency of the Solar Power Plant (PLTS) in generating electricity is influenced by several factors, including the angle of the panel and load variations. This study aims to analyze the effect of panel tilt angles (0°, 10°, 20°, 30°, and 40°) and load variations (100, 200, 300, 400, 500 Watts) on the power conversion efficiency of a 200 WP capacity 24V Off-grid PV system inverter. The method used is pure experimentation with stages of preparation, testing, and data analysis. The research results show that a tilt angle of 0°–20° with a load of 500 Watts is the most optimal configuration, producing an input power of around 283–284 Watts and an inverter efficiency of up to 91%. The overall efficiency of the PV system reaches 12.7%. It is recommended that the panel angle be adjusted to the direction of incoming sunlight, and that the load selection and inverter capacity be aligned to improve the overall system efficiency.

Keywords: *Solar Power Plant, Tilt Angle, Electrical Load, Inverter Efficiency, Off-Grid PV.*

1. INTRODUCTION

Electricity consumption in Indonesia reached 1,370,997.44 GWh in 2023, in line with population growth and technological developments [1]. This situation calls for the use of renewable energy sources to reduce dependence on fossil fuels and reduce carbon emissions. Solar energy is a promising alternative, particularly in regions like South Sumatra, which has a potential capacity of 17,233 MW, although its utilization remains low [1]. However, the implementation of Solar Power Plants (SPPs) still faces technical challenges, one of which is optimizing the tilt angle of solar panels, which affects solar radiation absorption and conversion efficiency.

The efficiency of a PLTS system is influenced by various factors such as the quality of photovoltaic modules, solar radiation intensity, ambient temperature, panel cleanliness, and inverter performance [2]. Among these factors, the tilt angle of the solar panel plays an important role in ensuring that sunlight falls with an incident angle close to perpendicular to the panel surface. An inappropriate tilt angle causes most of the solar radiation to be reflected and reduces the electrical power generated.

Previous research has shown that the tilt angle of solar panels significantly affects the output power. Studies using Helioscope simulation found an optimal angle of 10° for rooftop solar panels at Politeknik Negeri Semarang, producing up to 13,577.8 kWh of energy [3].

Another study under sunny weather conditions also identified 10° as the most effective angle, with a maximum power of 50.81 W [2]. Similar results were obtained on 50 Wp monocrystalline panels at the University of Bangka Belitung, where a 10° angle provided the highest efficiency of 15.47% [4]. Inappropriate angle variations were found to significantly reduce irradiation and power output.

In addition to the tilt angle, variations in electrical load also affect the efficiency of the system. A load that is too small makes the inverter work in partial conditions so that part of the power is used only for operational needs, while loads close to the nominal capacity of the inverter tend to produce higher conversion efficiency [5]. Therefore, a combination of panel tilt angle and proper electrical load setting is required to maximize the performance of the solar power system. This research specifically aims to analyze the effect of panel tilt angles (0°, 10°, 20°, 30°, 40°) and variations in electrical load (100-500 W) on the efficiency of electrical power in 24V off-grid PLTS systems with a capacity of 200 Wp. The analysis is carried out to obtain the optimal configuration that is able to maximize the

performance of the inverter and solar panels, so that power production can be more efficient. By testing these parameters, it is expected to identify the best working point that provides a balance between power production and energy consumption

The results of this research are expected to contribute to the development of more efficient solar power plant designs, both for household scale and applications in remote areas that rely on off-grid systems. In addition, these findings can serve as a technical reference in determining solar panel installation angles that are suitable for geographical conditions and load characteristics, thereby supporting efforts to transition to clean energy in Indonesia.

2. MATERIAL AND METHODS

This study was conducted at the Energy Engineering Laboratory, Department of Chemical Engineering, Sriwijaya State Polytechnic, Palembang, from February to June 2025. The experiment was conducted on a 200 Wp off-grid solar power plant (SPP) unit, using a pure experimental method to observe the effect of panel tilt variations (0°, 10°, 20°, 30°, and 40°) and electrical load (100–500 W) on the system.

2.1 Materials

The main equipment included two 100 Wp monocrystalline solar panels (Vmp 18.2 V, Imp 5.49 A), a 12 V 200 Ah VRLA battery of the EATON type, an MPPT solar charge controller (input capacity 24 V to 1040 W), a 5500 W pure sine wave inverter, a DC wattmeter (0–60 V, 0–150 A), a 32 A miniature circuit breaker, and a 100 W LED spotlight as a load. The measuring equipment consists of an XL830L digital multimeter, an AS803 luxmeter, and an MT87 digital clampmeter.

2.2 Methods

The equipment was assembled according to the PLTS system diagram, with solar panels installed in parallel and equipped with MCBs for protection. The energy generated was measured before entering the SCC, then stored in batteries, and converted into AC electricity by an inverter to operate the test load. Each combination of panel angle and load is tested using the following steps: measuring sunlight intensity, adjusting the panel tilt angle, operating the PLTS system, connecting the load, and recording the voltage, current, and power every 30 minutes using a wattmeter, multimeter, and clamp meter. The PLTS system circuit can be seen in Figure 1.

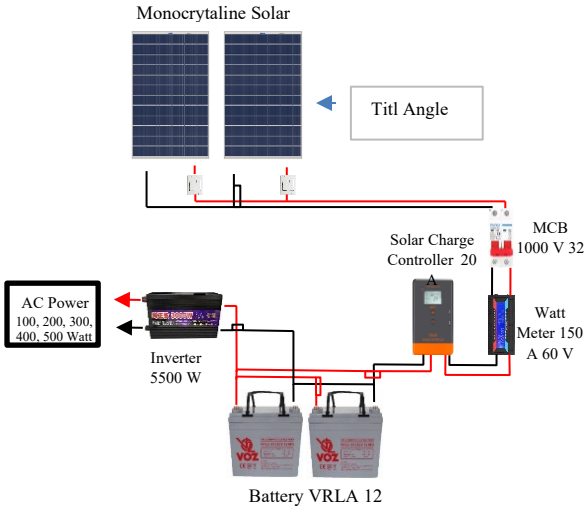


Figure 1 PLTS System Circuit Diagram

The data was analyzed quantitatively by calculating the efficiency of each component using the following equation:

Solar Panel Efficiency Calculation

$$Pin = It \times Ap \quad \text{.... (1)}$$

Where:
Pin = Solar radiation power received (Watts)
It = Sunlight intensity (Watts/m2)
Ap = Panel area (m^2)

$$Pout = V \times I \quad \text{.... (2)}$$

Where:
Pout = Solar panel output power (Watts)
V = Voltage (Volts)
I = Current (Amperes)

$$ŋpanel = \frac{P\ Out}{P\ in} \times 100\ \% \quad \text{.... (3)}$$

Where:
Ɒpanel= Panel Efficiency (%)
Pin = Solar radiation power (Watts)
Pout = Solar panel output power (Watts)

ŋSCC Efficiency Calculation

$$ŋSCC = \frac{P\ Out}{P\ in} \times 100\% \quad \text{.... (4)}$$

Where:
ŋSCC = SCC efficiency (%)
Pin = Solar panel output power (Watts)
Pout = SCC output power (Watts)

Inverter Efficiency Calculation

$$ŋinv = \frac{P\ AC}{P\ DC} \text{ x } 100\ \% \quad \text{.... (5)}$$

Where:
Ɒinv= Inverter efficiency (%)
PAC= Inverter output power (AC Watts)
PDC= Power input to the inverter (DC Watts)

3. RESULTS AND DISCUSSIONS

This experimental study was conducted by changing the tilt angle of the solar panel (0°, 10°, 20°, 30°, 40°) and electrical load (100–500 W) to determine their effect on the efficiency of the inverter in a 24V off-grid PV system with a capacity of 200 Wp. The system was evaluated based on the input power from the panels, the output power after the inverter, and the resulting efficiency.

The highest inverter efficiency was found at an inclination angle of 0° with 91.85%, followed by 10° (91.49%) and 20° (91.26%). Efficiency values began to decrease at steeper tilt angles, with 90.20% at 30° and 90.12% at 40°. These results indicate that panel placement plays a crucial role in maximizing energy transfer within the system.

3.1 The Effect of Panel Tilt Angle on Inverter Input Power

The tilt angle of solar panels is an important factor in determining how much sunlight can be absorbed by the panel surface and converted into electrical energy. Solar panels work based on the principle of converting light energy into electrical energy through the excitation of electrons by photons in semiconductor materials.

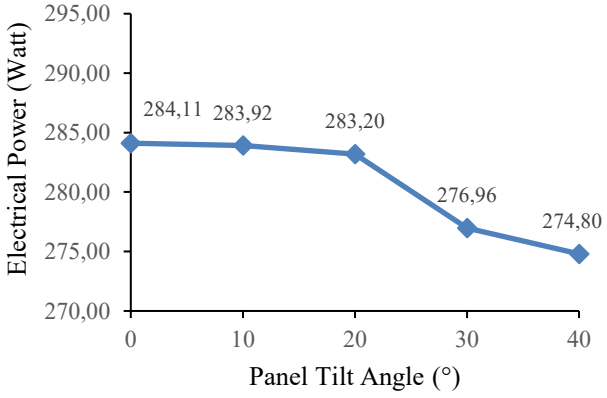


Figure 2. Effect of Panel Tilt angle on Inverter Input Power

As shown in Figure 2, in an off-grid solar power system, the highest electrical power is achieved at an angle of inclination between 0° and 20°, with inverter input power ranging from 284 to 283 Watts. However, there is a significant decrease in power when the angle of inclination increases to 30° and 40°, where power drops to approximately 275 Watts. This decrease is caused by the reduced intensity of light falling perpendicular to the panel, as well as the reflection effect of light due to the large angle of incidence. When the tilt angle of the panel aligns with the direction of sunlight, especially in the range of 0° to 20°, the amount of solar energy absorbed is optimal. This causes an increase in the number of excited electrons, thereby increasing the electrical current generated.

Conversely, an improper tilt angle causes a decrease in the number of photons absorbed, as most of the sunlight is reflected or scattered, resulting in a decrease in the electrical power output of the solar panel.

3.2The Effect of Electrical Load on Inverter Output Power

The use of electrical loads has a direct effect on the output power generated by the inverter. In principle, an inverter functions to convert direct current (DC) into alternating current (AC) with output power adjusted to the load requirements.

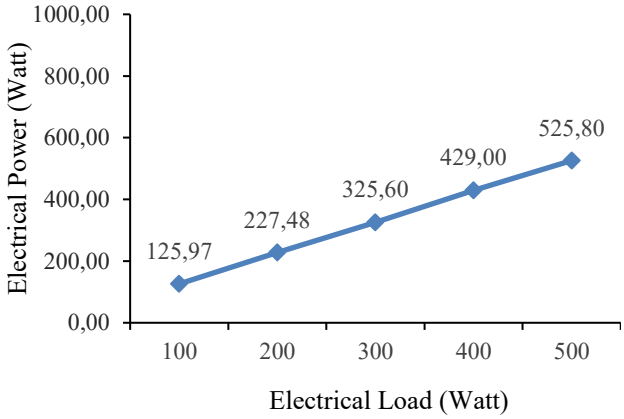


Figure 3 Effect of Electrical Load on Inverter Output Power

Figure 3 shows that as the load increases from 100 Watts to 500 Watts, the inverter's output power also increases linearly. This indicates that the inverter is capable of responding to load changes by proportionally increasing its output.

In this study, the inverter with a peak capacity of 5500 Watts was only used to serve loads ranging from 100 to 500 Watts, which are classified as light loads. As a result, the inverter operates under partial load conditions, meaning that part of the converted energy is used for internal consumption, such as the cooling system and control circuits. Based on the measurement data, there is a linear relationship between the

increase in load and the inverter's output power, indicating the inverter's ability to respond to load requirements. However, since the load power is still far below the inverter's capacity, power conversion efficiency is not yet optimal [6]. This condition causes a difference between the input power from the solar panels and the output power utilized by the load. Additionally, selecting an inverter capacity that is too large for a small-scale system like this not only results in energy waste but is also economically inefficient.

3.3 The Effect of Panel Tilt Angle and Electrical Load on Inverter Efficiency

Inverter efficiency in a solar power system is optimal when solar panels are installed at the correct tilt angle to receive maximum solar radiation and produce stable DC power. This stability supports MPPT performance in converting DC power to AC power with minimal loss. Additionally, the highest efficiency is achieved when the load is close to the inverter's nominal capacity, avoiding overloading or underloading conditions that can reduce power conversion performance.

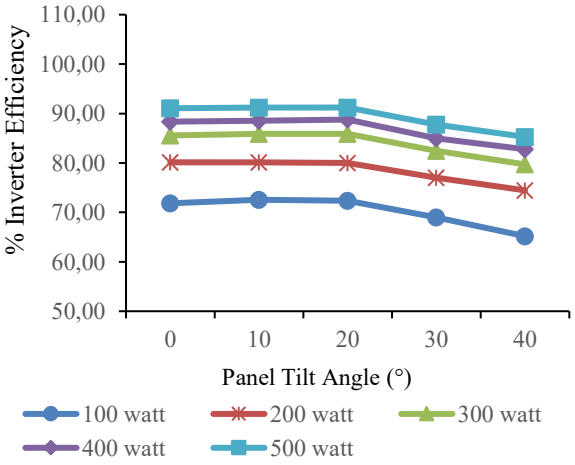


Figure 4 Effect of Tilt Angle and Electrical Load on Inverter Efficiency

Figure 4 shows that inverter efficiency in a solar power system increases with the optimal tilt angle of the panels (10°–20°) and as the load approaches the inverter's operating capacity. The highest efficiency, around 91%, is achieved at a load of 500 W with an angle of 10°–20°, while the lowest efficiency (65%) occurs at a load of 100 W with an angle of 40°. The optimal angle allows sunlight to fall perpendicular to the panel, producing stable DC power to support inverter performance, while a larger angle reduces the intensity absorbed due to increased reflection [7]. Large loads such as 400–500 W can maintain efficiency above 82% even if the angle is less than ideal, while small loads reduce efficiency because the inverter still requires minimum power for operation [8]. The combination of optimal tilt angle and load close to nominal capacity has been proven to maximize solar energy absorption and power conversion efficiency.

3.4 The Effect of Panel Tilt Angle and Electrical Load on The Efficiency of Solar Power Systems

The efficiency of solar power systems indicates their ability to convert the solar radiation received by the panels into electrical energy for the load. This value is mainly influenced by the panel tilt angle and electrical load, with optimal performance achieved when the load is close to the nominal capacity of the inverter. Other factors such as module quality, MPPT performance, inverter efficiency, temperature, panel cleanliness, and battery condition also play a significant role [9].

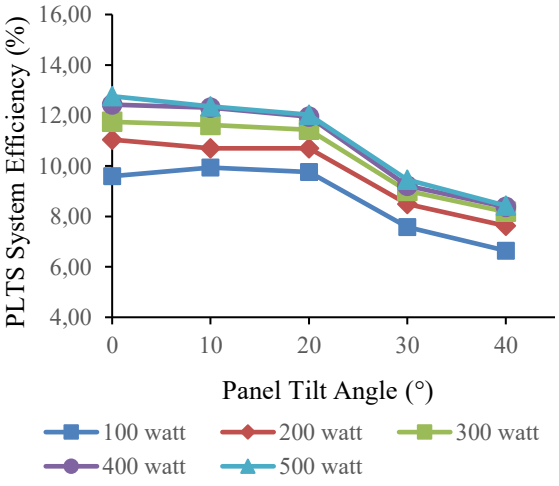


Figure 5 Effect of Panel Tilt Angle and Electrical Load on PLTS System Efficiency (%)

In Figure 5, based on efficiency analysis, the PLTS system tends to decrease as the panel tilt angle increases, with the highest value around 12.7% at an angle of 0°–20° and a load of 500 W, and the lowest at 9.5% at a load of 100 W at the same angle. The optimal angle allows sunlight to fall perpendicular, generating greater DC power for inverter conversion, while a high load (400–500 W) maintains higher efficiency compared to a low load by reducing losses under partial load conditions. The low total efficiency (6%–12.7%) causes accumulated losses at the solar panel,

MPPT, and inverter stages, necessitating angle optimization based on location, load adjustment close to inverter capacity, and proper power management to maximize off-grid system performance [10].

4. CONCLUSIONS

The results of the study indicate that the tilt angle of the panels and variations in electrical load significantly affect the power conversion performance of a 200 WP off-grid solar power system. An optimal tilt angle of 10°–20° allows for maximum absorption of solar radiation, resulting in the highest inverter input power, and at a load of 500 W, it achieves an inverter efficiency of 91% and a system efficiency of 12.7%. Conversely, tilt angles ≥30° and small loads ≤200 W reduce efficiency due to decreased radiation intensity and increase inverter operational power losses.

The best system configuration is achieved at an inclination angle of 10°–20° with a load close to the inverter's nominal capacity, which minimizes energy losses and maximizes conversion performance. These findings confirm that optimizing panel angle and load settings are key factors in improving the efficiency of off-grid solar power systems, and are relevant for the development of small-scale systems in households or remote areas.

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