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Effect of Solar Irradiance and Tilt Angle on the Performance of a 12 Volt Off Grid Solar Power System with 400 Wp Panel Capacity

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ABSTRACT

This study aims to analyze the effect of varying solar irradiance and panel tilt angles on the efficiency of a 12-Volt off-grid Solar Power Generation System (PLTS) with a panel capacity of 400 Wp. The system used in this study consists of a monocrystalline solar panel, an MPPT-type solar charge controller, a 12-Volt VRLA battery, and a pure sine wave inverter. The tests were conducted with solar irradiance levels ranging from 865.5 W/m² to 1242 W/m² and panel tilt angles of 0°, 10°, and 20°. The results show that the efficiency of the PLTS system is significantly influenced by both variables. The highest efficiency was achieved with a combination of solar irradiance between 1179 W/m² and 1242 W/m² and tilt angles between 0° and 10°, where the inverter efficiency reached 89.06%. This combination also provided optimal battery charging performance. A tilt angle between 0° and 10° is recommended as the optimal configuration for solar panel installations on residential buildings in tropical regions, as it yields high efficiency. The combination of high solar irradiance and optimal tilt angle also contributes to efficient battery charging and ensures continuous power supply in an off-grid PLTS system

Keywords: *Off-Grid PV System, Solar Irradiance, Tilt Angle, Inverter Efficiency, Renewable Energy.*

1. INTRODUCTION

The need for electrical energy in many parts of human existence is growing in tandem with the rate of technological advancement. The transformation of fuels like coal, natural gas, and petroleum into electrical energy is a common process. Renewable energy and non-renewable energy are the two main categories of energy. Natural resources used to generate renewable energy are plentiful and will remain so indefinitely despite heavy consumption. On the other hand, fossil fuels, which have been around for millions of years and cannot be renewed, are the source of non-renewable energy. [1].

In Indonesia, the use of electrical energy is still largely dominated by fossil fuel sources, which are limited in quantity. According to data from the Ministry of Energy and Mineral Resources 2025, the total installed capacity for power plants in Indonesia reached 101 GW in 2024. The main energy structure within Indonesia's electricity grid still relies heavily on fossil fuels, which account for approximately 85% or 86 gigawatts (GW). Reports indicate that only 15.1% or 15 GW comes from renewable energy sources, contributing to the current installed power generation capacity in the country. This condition remains far from the government's target of increasing the share of renewable energy to 23% of the national primary energy mix by 2025.

The use of fossil fuels such as coal, petroleum, and other types of fuel has several negative impacts, including environmental pollution caused by the greenhouse effect, which leads to rising temperatures, acid rain, ozone layer depletion, and the destruction of tropical forests [2]. Prolonged dependence on fossil energy poses significant risks to the stability of the national energy supply in the future, especially as reserves begin to decline. Therefore, concrete steps are needed to develop and utilize alternative energy sources that are more sustainable and environmentally friendly as a long-term solution [3]. Indonesia is one of the countries with tremendous solar energy potential, receiving an average of 4.5 to 4.8 kWh/m² of sunlight per day. Therefore, solar energy is one of the most promising renewable alternative energy sources to be developed in the country [4].

Solar energy is one of the alternative energy sources that can be utilized for electricity generation by converting sunlight into electrical energy [5]. This conversion process is carried out through a Solar Power Plant (PLTS) system, which

consists of several main components: solar panels, a solar charge controller, an inverter, and batteries as the energy storage medium [6]. Solar Power Plants (PLTS) offer several advantages, including the use of an abundant and free energy source, automatic operation, environmental friendliness due to zero emissions, and a modular nature that makes them easy to install and scale according to needs.

Currently, the use of solar power plants is steadily increasing, as seen in applications such as street lighting, railway crossings, and electricity supply for households in areas not yet reached by the power grid. The system used in these solar power plants operates based on the principle that the greater the intensity of sunlight received by the solar panels, the better their performance [7]. Another environmental factor that affects the performance of solar cells is the tilt angle of the panel. By adjusting the panel's tilt angle and measuring sunSolar Irradiance over a specific period, it is expected that the power output of the panel will increase, thereby improving its efficiency [8].

Based on the explanation above, the scope of this research is intended to further investigate the effects of Solar Irradiance and panel tilt angle on the efficiency of a 12-volt off-grid solar power system.

2. MATERIAL AND METHODS

This research was conducted at the Energy Engineering Laboratory of Sriwijaya State Polytechnic.

2.1 Materials

The research procedure was carried out in several stages as follows: first, preparing the tools and materials to be used, including a 400Wp monocrystalline solar panel, one 12-volt VRLA battery, an MPPT-type Solar Charge Controller, a Pure Sine Wave inverter, measuring instruments such as a lux meter, watt meter, multimeter, clamp meter, and electrical load. After the equipment and materials were properly prepared, the solar power system (PLTS) was started.

2.2 Methods

In this study, several key variables were involved. The controlled variables included a solar panel with a capacity of 400 Wp, a 12-volt VRLA battery, and a 400-watt load. The independent variables were Solar Irradiance measured in lux and the tilt angle of the solar panel at 0°, 10°, 20°, 30°, and 40°. Meanwhile, the dependent variables consisted of voltage (V), electric current (A), and electrical power output measured in watts.

During the running process, the researcher prepared a research matrix based on the variables to be observed: the average Solar Irradiance over five different days, from June 20, 2025, measured every 30 minutes between 11:00 AM and 1:30 PM (WIB) in lux, and the tilt angles of the solar panel (0°, 10°, 20°, 30°, and 40°).

The system was then operated until the battery charging and panel output reached a steady state. Once the PLTS system reached stable operating conditions, data collection was performed. The data collected included panel input, panel output, Solar Charge Controller (SCC) output, battery capacity percentage, inverter input, and inverter output. After all data were obtained from the experiment, analysis and calculations were carried out to evaluate the performance of the PLTS system. Finally, conclusions were drawn based on the results of the study.

These test uses the following components:

A. Solar Panel

A solar panel is an electronic component designed to capture and convert sunlight into electricity using the principle known as the photovoltaic effect, which occurs when certain semiconductor materials generate electric current upon exposure to sunlight. The electricity produced can then be used directly to meet everyday electrical needs. To determine the efficiency produced by the solar panel, the following formula can be used:

$$Pin = It\ x\ Ap \quad \ldots (1)$$

Where:
P_{in} : Solar Panel Input Power (W)
I_t : Solar Irradiance (W/m²)
A_p : Solar Panel Surface Area (m²)

Next, calculate the output power from the solar panel using the formula:

$$Pout = Vout\ x\ Iout \quad \ldots (2)$$

Where:
P_{out} : Solar Panel Output Power (W)
V_{out} : Solar Panel Output Voltage (V)
I_{out} : Solar Panel Output Current (A)

Then, the efficiency (η) of a solar panel module can be calculated using the formula:

$$\eta = \frac{Pout}{Pin} x\ 100\% \quad \ldots (3)$$

Where:
P_{in} : Solar Panel Input Power (W)
P_{out} : Solar Panel Output Power (W)

B. Solar Charge Controller (SCC)

The Solar Charge Controller (SCC), also known as a battery charge controller, functions to regulate the current flowing into the battery from the solar panel to ensure optimal charging. This means preventing both undercharging and overcharging of the battery. To determine the efficiency of the Solar Charge Controller (SCC), the following formula can be used:

$$Pin = Vin\ x\ Iin \quad \ldots (4)$$

Where:
Pin : SCC Input Power (W)
Vin : Input Voltage (V)
Iin : Input Current (A)

Next, calculate the output power of the SCC.

$$Pout = Vout\ x\ Iout \quad \ldots(5)$$

Where:
Pout : SCC Output Power (W)
Vout : Output Voltage (V)
Iout : Output Current (A)

Then, the efficiency (η) of the SCC can be calculated using the formula:

$$\eta = \frac{Pout}{Pin} x\ 100\% \quad \ldots (6)$$

Where:
Pin : SCC Input Power (W)
Pout : SCC Output Power (W)

C. Battery

A battery serves as an energy storage device for various purposes, especially in the field of electricity. It functions as a power supplier for the load when the solar panel's power supply is interrupted, and also provides backup power during cloudy, overcast, rainy weather, or other emergency conditions. In general, the battery capacity can be expressed by the following equation:

$$Ah = \frac{Battery\ Capacity\ (\%) x\ Battery\ Capacity\ (A)}{100} \ldots (7)$$

Where:
Ah : Available Battery Capacity
Battery Capacity (%) : Percentage (%)
Battery Ampere CapacityCurrent Strength (A)

Next, to calculate the battery operating time, the following formula is used:

$$Operating\ Time\ (h) = \frac{Ah\ x\ V\ x\ Battery\ Efficiency}{PLoad} \ldots (8)$$

Where:
Ah : Battery Capacity Used (Ah)
V : Battery Voltage (V)
Battery Efficiency : Battery Efficiency,typically 90%
Pload : Load Power (Watts)

D. Inverter

An inverter, also known as a power inverter, is a power electronic device that functions to convert direct current (DC) voltage into alternating current (AC) voltage. To determine the efficiency of the inverter, the following formula can be used:

$$Pin = Vin\ x\ Iin \quad \ldots (9)$$

Where:
Pin : Inverter Input Power (W)
Vin : Input Voltage (V)
Iin : Input Current (A)

Next, calculate the output power of the inverter.

$$Pout = Vout\ x\ Iout \quad \ldots (10)$$

Where:
Pout : Inverter Output Power (W)
Vout : Output Voltage (V)
Iout : Output Current (A)

Then, the efficiency (η) of the Inverter can be calculated using the formula:

$$\eta = \frac{Pout}{Pin} x\ 100\% \quad \ldots (11)$$

Where:
Pin : Inverter Input Power (W)
Pout : Inverter Output Power (W)

E. Solar Power System Efficiency

The efficiency of a Solar Power System (Photovoltaic System) is a measure of how much solar energy is successfully converted into usable electrical energy for loads (such as lights, pumps, electronic devices, etc.). The efficiency of the solar power system is calculated using the following formula:

$$\eta = \eta Panel\ x\ \eta MPPT\ x\ \eta Inverter\ x\ 100\% \quad \ldots (12)$$

Where:
ηPanel : Panel Efficiency (%)

ηMPPT : MPPT Efficiency (%)
ηInverter : Inverter Efficiency (%)

3. RESULT AND DISCUSSIONS

The research was conducted with variations in intensity, averaging (109,570 lux; 123,042 lux; 134,531 lux; 149,246 lux; and 157,311 lux), and panel tilt angles (0°, 10°, 20°, 30°, and 40°). Data collection was carried out over five different days, from June 16 to June 20, 2025. Observations were conducted from 11:00 AM to 1:30 PM (WIB) with a capacity of 400WP and a constant load of 400 Watts.

The MPPT solar charge controller (SCC) efficiency ranges from 96% to 97%, the inverter shows the best efficiency between 87% and 89%, Overall, the PV system efficiency reaches 13% to 13.5%, which is the accumulated result of the panel, SCC, and inverter performance under these optimal conditions,

3.1 Effect of Solar Irradiance and Tilt Angle on Panel Efficiency (%)

The graph illustrated the effect of Solar Irradiance and tilt angle on panel efficiency that can be seen in Figure 1.

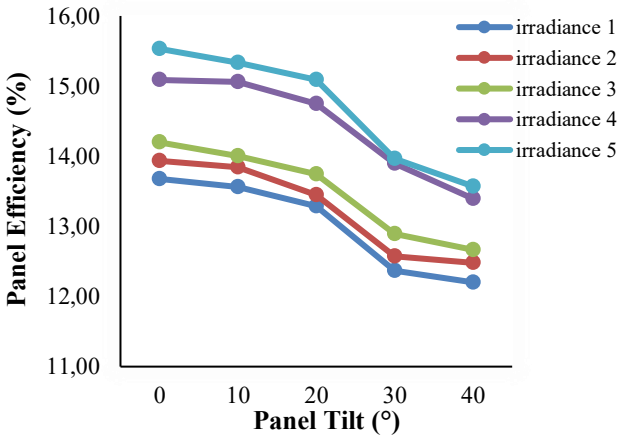


Figure 1. Effect of Solar Irradiance and Tilt Angle on Panel Efficiency (%)

Based on Figure 1, there is a clear direct relationship between solar irradiance, the tilt angle of the solar panel, and the output efficiency of the photovoltaic system. System efficiency increases as solar irradiance rises, reaching its maximum range between 14% and 15% at the highest recorded irradiance of 1242 W/m². In semiconductor-based solar panels such as monocrystalline silicon, this efficiency heavily depends on the excitation process of electron-hole pairs, which occurs when photons from sunlight carry sufficient energy. Adequate photon energy enables electrons to transition from the valence band to the conduction band, forming electron-hole pairs that are then separated by the internal electric field in the p–n junction region, producing an electric current. The higher the solar irradiance, the greater the number of photons striking the panel surface per unit time and area, ultimately increasing the photocurrent and overall power output.

However, the system does not reach optimal efficiency at the first three irradiance levels (865.5 W/m², 972.029 W/m², and 1063 W/m²). These intensity levels do not provide enough photon energy to fully optimize electron-hole excitation, resulting in moderate current and voltage outputs, and conversion efficiencies only ranging from 12% to 14%, even when the panel is positioned at an ideal tilt angle. In contrast, at the fourth (1179.04 W/m²) and fifth (1242 W/m²) irradiance levels, panel efficiency increases significantly and demonstrates stable performance. These two intensity levels supply sufficient photon energy to fully support the excitation process. Therefore, although the fifth intensity level is the highest, the fourth is already considered optimal, as it consistently achieves nearly 15% efficiency while maintaining the panel temperature within safe limits. This intensity level is recommended as a reference for further research, as it provides technically and practically optimal results without significant thermal degradation risks and reflects real-world solar exposure conditions in tropical regions.

In addition, the tilt angle of the panel has a significant effect on power conversion efficiency. When the panel is set at a low tilt angle between 0° and 20°, sunlight strikes the panel surface almost perpendicularly, allowing a greater number of photons to be absorbed by the semiconductor layer and thus increasing the conversion efficiency. A tilt angle of 0° yields the highest efficiency because photon absorption remains at its maximum throughout the day. However, in real-world applications especially for residential buildings that typically have sloped roofs panels cannot always be installed flat. Therefore, a tilt angle of 20° is considered optimal, as it still provides high efficiency while being structurally realistic for residential installations. On the other hand, tilt angles above 30° to 40° cause sunlight to strike the panel at a steeper angle, increasing light reflection and reducing the number of photons absorbed by the semiconductor material, thus lowering system efficiency.

The study conducted also reinforces these findings, stating that solar solar irradiance is influenced by the tilt angle of the solar panel. The highest solar irradiance was recorded at a 20° tilt,

reaching 1147 W/m² with a voltage output of 20.7 volts, while tilt angles of 30° and 40° yielded lower values compared to 20° [9]. Other studies also support this, indicating that an optimal tilt angle produces higher panel output power, with maximum voltage and current, thereby improving the overall efficiency of the solar panel [10]. Monocrystalline-type panels are known for their good efficiency, typically ranging from 12% to 18% [11]. This range is highly consistent with the results shown in the graph, where solar irradiances between 1179 W/m² and 1242 W/m² (irradiances 4 and 5) combined with tilt angles between 0° and 20° yield the highest efficiency, approximately 15%.

The relationship between solar irradiance and tilt angle greatly influences battery charging performance and the overall efficiency of an off-grid photovoltaic system (PLTS). Low conversion efficiency leads to reduced power output, which can result in suboptimal battery charging (undercharging), accelerating battery cell degradation, and even causing power supply failures during peak loads. Conversely, when panels operate under optimal solar irradiance and tilt angle conditions, the charging current becomes more stable and efficient, ensuring continuous power supply even without a connection to the main grid.

Therefore, selecting the appropriate tilt angle and maximizing the use of available solar solar irradiance are crucial for designing efficient and durable off-grid photovoltaic systems, especially in tropical regions like Indonesia.

3.2 Effect Between Solar Irradiance and Tilt Angle on SCC Efficiency (%)

The graph showing the Effect between solar irradiance and tilt angle on SCC efficiency can be seen in Figure 2.

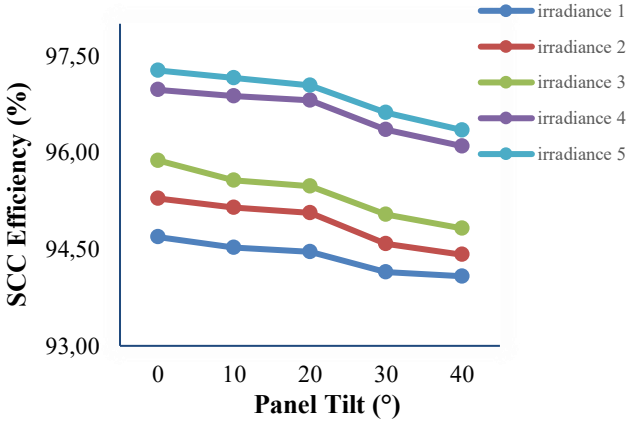


Figure 2. Effect of Solar Irradiance and Tilt Angle on SCC Efficiency (%)

Figure 2 illustrates the effect between Solar Irradiance and tilt angle on the efficiency of the Solar Charge Controller (SCC) using the Maximum Power Point Tracking (MPPT) method in an off-grid photovoltaic (PV) system. It can be seen that increasing solar irradiance tends to improve SCC efficiency, while increasing the tilt angle generally decreases it although the magnitude of change varies across different intensity levels.

At lower irradiances specifically irradiance 1 (865.5 W/m²), irradiance 2 (972.03 W/m²), and irradiance 3 (1063 W/m²) SCC efficiency ranges from approximately 94% to 95%, with a steeper decline observed as the tilt angle increases. This suggests that the available photon energy at low intensity is insufficient to fully excite electron-hole pairs in the monocrystalline silicon semiconductor layer, limiting panel output current and making it difficult for the SCC to reach an optimal maximum power point. The wide gap between trend lines at these intensity levels also indicates SCC performance instability caused by the combination of low irradiance and suboptimal panel orientation.

In contrast, at irradiance 4 (1179.04 W/m²) and irradiance 5 (1242 W/m²), the SCC demonstrates its best performance, with efficiency values closely grouped between 96.5% and 97%. This indicates that these intensities supply sufficient photon energy to drive maximum electron excitation from the valence band to the conduction band. The resulting output current and voltage become more stable, enabling the SCC to operate more efficiently. Since the efficiency at intensity 5 does not show a significant increase over that of intensity 4, intensity 4 is considered the optimal point it already delivers high efficiency without the additional risks of increased temperature or thermal stress. While efficiency still decreases at higher tilt angles, the decline is more gradual compared to that seen under lower intensities.

In terms of tilt angle, the best results are achieved at 0°, 10°, and 20°, where sunlight strikes the panel surface more directly, maximizing photon absorption and minimizing reflection. At these angles, SCC efficiency remains relatively high and stable. However, in practical off-grid PV system applications, a 20° tilt is considered the most optimal configuration, as it closely aligns with ideal orientation while being realistic for installation on sloped residential rooftops. SCC efficiency starts to decline sharply at angles of 30° to 40°, particularly under low light conditions, as sunlight hits the panel at steeper, less efficient angles—causing a portion of the photon energy to be reflected rather than absorbed by the semiconductor cells.

The SCC plays a critical role in ensuring the system's output remains at the maximum power point by continuously monitoring changes in current and voltage from the PV modules due to fluctuations in irradiance and tilt. However, SCC efficiency is not solely determined by the device itself it is also heavily influenced by the physical conditions of the system. Based on specifications, the PowerMR 30A MPPT SCC used in this study is designed to maximize current and voltage from the solar panels and deliver it to the battery with a theoretical efficiency of up to 98%. However, observations show actual efficiency ranging between 93% and 97%, depending on Solar Irradiance and tilt. These values are consistent with studies showing that MPPT system efficiency in solar power generation generally falls within the 90–95% range, depending on the algorithm used [12]. Moreover, other research also shows that increasing the panel tilt angle up to 40° can reduce photovoltaic system efficiency by as much as 6% at 750 W/m², which prevents the SCC from operating optimally and reduces its efficiency [13]. This finding is in line with the downward trend in efficiency shown in Figure 4.2.

In off-grid PV systems, the success of battery charging is highly dependent on SCC efficiency. The optimal power generated by the panels must be transferred efficiently to the energy storage system. If Solar Irradiance is low or panel tilt is incorrect, power output will decrease, preventing the SCC from reaching the maximum power point and lowering its efficiency resulting in suboptimal battery charging. Repeated undercharging can accelerate battery degradation, reduce lifespan, and cause power supply instability during peak load periods. Therefore, the optimal system configuration irradiance 4 (1179.04 W/m²) and a 20° tilt is the most effective combination to maintain high SCC efficiency, support stable battery charging, and ensure long-term reliability of the off-grid PV system, particularly in tropical regions with high and fluctuating solar radiation.

The consistent decrease in SCC efficiency under low intensity and increased tilt angle, as shown in the graph, indicates that the physical configuration of the solar panel must account for optimal irradiance and tilt to allow the SCC to operate at its maximum power point more stably. Therefore, for efficient off-grid PV system implementation, it is not enough to rely solely on advanced SCC algorithms optimal panel placement aligned with the sun's path and installation site conditions is equally essential.

3.3 Effect of Solar Irradiance and Tilt Angle on Battery Capacity Percentage (%)

The graph illustrated the effect between solar irradiance and panel tilt angle on battery capacity percentage can be seen in Figure 3.

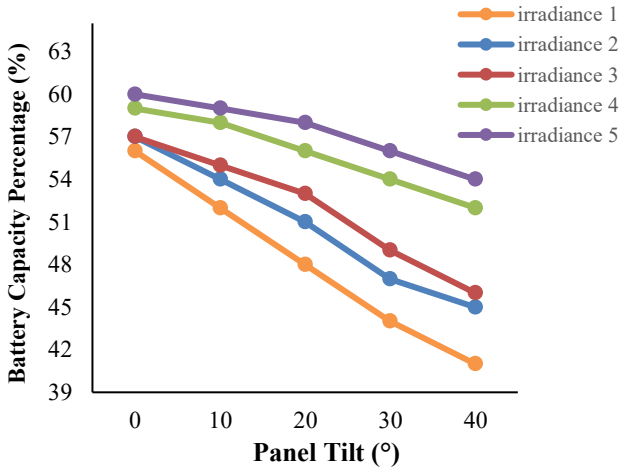


Figure 3. Effect of Solar Irradiance and Panel Tilt Angle on Battery Capacity Percentage (%)

Figure 3 illustrates the influence of solar irradiance and panel tilt angle on the percentage of battery capacity charged in an off-grid solar photovoltaic (PV) system. According to the graph, the battery charging capacity increases along with the rise in solar irradiance, where irradiance 4 (1179 W/m²) and irradiance 5 (1242 W/m²) demonstrate higher charging performance compared to irradiances 1–3. At irradiance 1 (865.5 W/m²), irradiance 2 (972.03 W/m²), and irradiance 3 (1063 W/m²), the amount of photon energy received by the semiconductor surface is relatively low, thus generating only a limited electric current. As a result, the electrical power delivered to the battery is insufficient to optimally charge the storage capacity. Low solar irradiance also causes the Solar Charge Controller (SCC) to operate in a mid-power zone, leading to suboptimal energy conversion efficiency from the panel to the battery.

Conversely, under irradiance 4 and irradiance 5, the increased photon energy absorbed by semiconductor materials such as monocrystalline silicon results in the generation of more electron-hole pairs. This excitation process boosts both current and voltage output, and shifts the Maximum Power Point (MPP) to a higher level. As a consequence, the SCC is able to regulate power delivery to the energy storage system more efficiently. This is supported by studies indicating that fluctuations in solar irradiance directly affect the performance of the SCC and the amount of energy transferred to the battery [12]. Based on the trend in the graph, Intensities 4 and 5 both result in

the highest battery capacities, ranging from 58% to 60% at lower tilt angles, suggesting that Intensity 4 is already sufficiently optimal. It delivers near-maximum performance, remains within safe thermal limits, and is representative of tropical solar radiation.

In addition to solar irradiance, the tilt angle of the solar panel also plays an important role in determining the amount of energy absorbed. The graph indicates that tilt angles of 0°, 10°, and 20° result in higher battery charging compared to 30° and 40°. This is due to the angle of solar incidence at lower tilt angles, sunlight strikes the panel surface almost perpendicularly, increasing the number of absorbed photons and minimizing reflection. This correlates closely with studies which state that a tilt of up to 40° may reduce panel efficiency by as much as 6%, causing the SCC to operate inefficiently and thus slow down battery charging [13]. In this case, a 20° tilt angle is considered both optimal and practical, as it maintains high power output while also allowing installation compatible with typical residential roof slopes. Meanwhile, tilt angles of 30° and 40° result in a significant decrease in battery capacity due to sunlight striking the panel at a more oblique angle, increasing reflection and reducing energy absorption.

The relationship between solar irradiance and tilt angle has a direct impact on the efficiency of the SCC, which regulates battery charging. High SCC efficiency ensures that power obtained from the panel is effectively delivered to the battery. The data show that the highest battery charging capacity occurs with the combination of irradiance 5 (1242 W/m²) and a 0° tilt angle (approximately 60%), while the lowest value is observed at irradiance 1 (865.5 W/m²) and a 40° tilt angle (around 40%). This difference reflects that the higher the Solar Irradiance and the closer the panel's tilt is to a perpendicular angle with the sun, the more photon energy can be absorbed by the surface of the solar cells. Consequently, the energy generated increases, allowing for more efficient battery charging. This energy is not only used to recharge the battery but is also directly supplied to the load. On the other hand, under low solar irradiance and non-optimal tilt conditions, the power generated by the panel is insufficient to serve the load. As a result, the system automatically draws energy from the battery. When this happens continuously, especially under high load conditions, the battery capacity will quickly decrease due to insufficient power input for recharging.

Although the battery capacity percentage remains within safe limits, it is important to note that VRLA (Valve Regulated Lead-Acid) batteries ideally operate within a 25% to 80% State of Charge (SoC) to avoid overcharging and undercharging, both of which can accelerate capacity degradation and shorten the battery's lifespan. This aligns with studies indicating that charging below 40% can cause sulfation (crystal buildup on the battery plates), while charging above 80% increases the risk of overcharging and corrosion [14]. This shows that operation within the mid-range SoC can slow down capacity degradation and extend the battery's cycle life. Therefore, the configuration of irradiance 4 (1179 W/m²) and 20° tilt angle is not only energy-efficient but also safe for the battery's long-term lifespan.

In conclusion, to ensure optimal performance of an off-grid PV system, it is essential to operate the solar panels under high solar irradiance and an appropriate tilt angle. The combination of irradiance 4 and a 20° tilt has been proven to deliver near-maximum battery charging performance, remain within high SCC efficiency levels, and avoid premature degradation of the energy storage system.

3.4 Effect of Solar Irradiance and Tilt Angle on Inverter Efficiency (%)

The graph illustrated the effect of solar irradiance and panel tilt angle on inverter efficiency that can be seen in Figure 4.

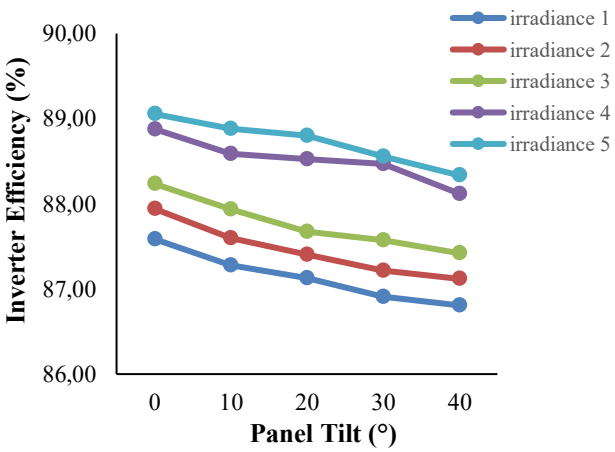


Figure 4. Effect of Solar Irradiance and Panel Tilt Angle on Inverter Efficiency (%)

Based on the test results shown in Figure 4, the Effect between solar irradiance and panel tilt angle can be systematically explained as follows. Regarding solar irradiance, it is known that irradiances 1 (865.5 W/m²), 2 (972.03 W/m²), and 3 (1063 W/m²) produce the lowest inverter efficiency, ranging from 86% to 87%. This occurs because the solar panel output power at these three intensity levels is insufficient to optimally supply energy to

the battery, causing the battery's available energy to deplete faster and reducing the voltage supplied to the inverter. The inverter input voltage was recorded between 12.00 and 12.10 volts, which is near the lower limit of 12 volts. According to research, when the resting voltage drops below 12.1 V, the battery enters an undercharge zone [15]. A battery voltage of 12.1 V represents a State of Charge (SoC) of about 50%, while voltages above 12.2 V indicate the battery is at an SoC of 55–60% or higher, meaning the battery's energy capacity is still relatively stable. Voltages below 12.1 V indicate weakened battery capacity due to insufficient power supply from the panel, forcing the inverter to operate under heavy load conditions. Under these conditions, the inverter must maintain a 220 Volt AC output to a fixed 400-watt load despite minimal input power, causing the inverter to operate inefficiently. Additionally, unstable inverter input current at low light intensities also causes inverter performance disturbances.

Conversely, at irradiance 4 (1179 W/m²) and irradiance 5 (1242 W/m²), inverter efficiency improves significantly. The inverter input voltage was stable between 12.20 and 12.40 volts, while the input current reached 38.5 to 39 amperes, indicating that the battery received an optimal power supply from the solar panel. This stable input power allows the inverter to consistently produce an AC output voltage of 220–221 volts and an output current of 1.83 to 1.89 amperes, sufficient to meet the fixed load demand. Between intensity 4 and intensity 5, both show nearly equal inverter efficiency values. Therefore, it can be concluded that intensity 4 (1179 W/m²) is the optimal condition because the efficiency increase at intensity 5 is insignificant, though technically still acceptable.

optimal condition because the efficiency increase at intensity 5 is insignificant, though technically still acceptable.

Regarding panel tilt angle, it was found that tilt angles of 0°, 10°, and 20° provide the best inverter efficiency results. At these angles, the solar panels receive sunlight more optimally due to a more perpendicular incidence angle, resulting in stable panel output power and inverter input voltage within the optimal range. Conversely, at tilt angles of 30° and 40°, inverter efficiency decreases significantly. This is because the panels are too tilted, reducing light reception, decreasing panel output, causing inverter input voltage to approach 12 volts again, and forcing the inverter to work harder to maintain its energy output.

Under such heavy inverter load conditions, the internal temperature of the inverter rises. Electrical energy that is not fully converted into AC output turns into heat within the inverter circuit. As explained in a study, when the DC input voltage from the PV is low due to solar irradiance and tilt the inverter not only reduces efficiency but also generates more heat due to switching and internal resistance [16]. Inverters operating outside their optimal point tend to produce power losses in the form of excess heat, which, if not managed with a good cooling system, can cause overheating, reduced thermal efficiency, and even damage to electronic components.

This is also influenced by the inverter specifications, which in this case have a capacity of 5500 W while the load used is 400 W. According to another study, if the load does not match the capacity, most energy is consumed only for the inverter's operational needs, causing the AC output power ratio to be smaller than the input power and leading to decreased efficiency [17]. Pure sine wave inverters typically have efficiencies of 85–95%. The test results in this study show inverter efficiencies ranging from 87% to 89%, indicating fairly good performance within specifications, although not reaching 90%, due to unstable input power supply—especially at low intensities, large tilt angles, and mismatched inverter capacity. Therefore, in an off-grid solar system with a fixed load, it is crucial to keep the panels operating at high solar irradiance, low tilt angle, and with appropriate capacity to maintain inverter efficiency and avoid unnecessary power losses.

In conclusion, the configuration of irradiance 4 combined with tilt angles of 0°, 10°, or 20° is the most optimal combination to maintain stable inverter input power, sustain energy conversion efficiency, and avoid excessive heavy load conditions that cause inverter overheating and efficiency reduction. Conversely, low intensities (irradiance 1 at 865.5 W/m², irradiance 2 at 972.03 W/m², irradiance 3 at 1063 W/m²) and panel tilts of 30° and 40° should be avoided in a 400-watt fixed load off-grid solar system as they result in suboptimal efficiency, increased risk of inverter overheating, and poor energy conversion.

3.5 Effect of Solar Irradiance and Tilt Angle on PV System Efficiency (%)

Figure 5 demonstrates the combined impact of solar irradiance and panel tilt angle on the operational efficiency of the photovoltaic (PV) system, highlighting the sensitivity of system performance to changes in these parameters

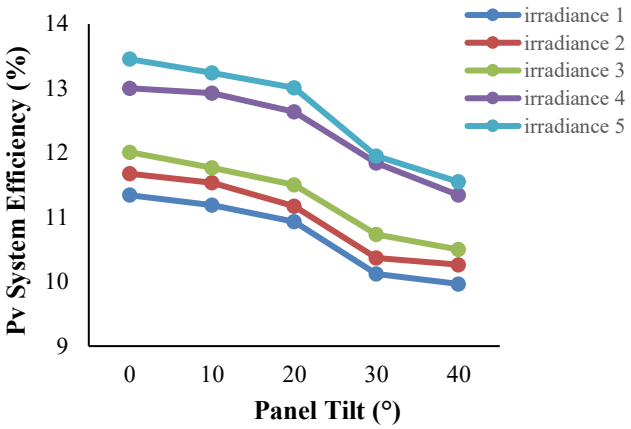


Figure 5. Effect of Solar Irradiance and Panel Tilt Angle on PV System Efficiency (%)

Figure 5 shows the Effect between solar irradiance and panel tilt angle on the efficiency of the PV system (%) using monocrystalline solar modules. In general, the graph illustrates that PV system efficiency increases with rising Solar Irradiance. irradiance 4 (1179 W/m²) and irradiance 5 (1242 W/m²) demonstrate the most optimal performance, with efficiencies reaching 13–13.5% at low tilt angles. Meanwhile, low irradiances such as irradiance 1 (865.5 W/m²), irradiance 2 (972.03 W/m²), and irradiance 3 (1063 W/m²) produce efficiencies only within the 9–12% range, even at the same tilt angles. This indicates that the number of photons received by the solar module largely determines the amount of electrical energy generated, especially since monocrystalline material is highly responsive to high Solar Irradiance due to its higher conversion efficiency compared to other types such as polycrystalline.

The panel tilt angle also plays a significant role. The graph shows that tilt angles of 0°, 10°, and 20° yield much higher system efficiencies compared to 30° and 40°. This is because at low tilt angles, sunlight strikes the panel surface almost perpendicularly, maximizing absorbed energy. Conversely, at higher tilt angles, light arrives at an oblique angle, increasing reflected energy and reducing absorption efficiency, resulting in lower power output. The combination of low intensity and high tilt is the least optimal condition, producing efficiencies below 11%.

The optimal operating point for this PV system is observed at irradiance 4 (1179 W/m²) and irradiance 5 (1242 W/m²) with tilt angles of 0°, 10°, and 20°, where the system efficiency reaches its maximum. This indicates that high intensity and a flat or slightly tilted panel position better capture photons directly at the study location. With this combination, sunlight hits the panel surface more perpendicularly, generating greater DC power to be converted to AC power by the inverter.

The relatively low system efficiency values, ranging from 9–13.5%, can be explained by the components contributing to total efficiency. Studies indicate that overall PV system efficiency results from the cumulative performance of main components, namely the solar panel, SCC (Solar Charge Controller), and inverter [18]. The monocrystalline solar panel efficiency used to produce DC current and voltage from light energy reaches a best efficiency of 15.53%, the SCC with MPPT type optimizes operation to stay at maximum power point with best efficiency at 97.27%, and the inverter converts DC to AC power with best efficiency of 89.06%. Losses at each energy conversion stage accumulate, making the overall system efficiency lower than that of each component individually. This aligns with research showing a PV system efficiency of 9.06% [18].

Therefore, the PV system efficiency shown in this graph represents the real synergy between system components under varying environmental conditions. The combination of irradiance 4 (1179 W/m²) and irradiance 5 (1242 W/m²) with panel tilt angles of 0°, 10°, and 20° produces the highest PV efficiency, falling within the ideal range for household systems in tropical regions. The recommended optimal condition is at irradiance 4 (1179 W/m²), where the energy conversion efficiency approaches the system maximum at irradiance 5 (1242 W/m²), with stable power output and panel temperature remaining within safe limits. Meanwhile, the 20° tilt angle proves to be the most practical optimal configuration for PV system implementation, as its efficiency closely matches that at 0° and 10°, as shown in the graph. This indicates that a 20° tilt provides energy conversion performance nearly equivalent to a flat panel but is structurally more realistic for residential buildings, which typically have sloped roofs. Thus, a 20° tilt angle is recommended as the optimal angle in designing PV systems to achieve the best energy conversion efficiency while maintaining structural compatibility with tropical building characteristics.

Considering these factors, it can be concluded that PV system efficiency is highly determined by panel design and its ability to optimally adjust to conditions of Solar Irradiance and panel tilt angle.

4. CONCLUSIONS

Based on the research on The Effect of solar irradiance and Tilt Angle on the Performance of a 12-Volt Off-Grid PV System with a 400WP Panel Capacity, the following conclusions can be drawn:

1. At the configuration of solar irradiance 1179 W/m² and panel tilt angle of 20°, the PV system demonstrates the most optimal performance across all its main components. The solar panel efficiency is recorded to reach 14% to 15%, indicating maximal absorption of solar energy. The MPPT solar charge controller (SCC) efficiency ranges from 96% to 97%, indicating very efficient power regulation and transfer from the panel to the battery. Meanwhile, the inverter shows the best efficiency between 87% and 89%, ensuring stable and effective DC to AC power conversion to meet the system load. Overall, the PV system efficiency reaches 13% to 13.5%, which is the accumulated result of the panel, SCC, and inverter performance under these optimal conditions, making the system capable of efficiently generating electrical power for off-grid applications in tropical areas.
2. Variations in Solar Irradiance and the tilt angle of the solar panel directly affect the battery's State of Charge (%SoC) in the 12-volt off-grid PV system. The combination of Solar Irradiance at 1179 W/m² and a panel tilt of 20° yields the highest %SoC, approximately 58–60%, indicating optimal and efficient battery charging. Conversely, at low irradiance (865.5 W/m²) and high tilt angles (30°–40°), the %SoC drops to 40–45% due to limited panel power output. Higher Solar Irradiance allows for greater photon energy absorption, while the optimal tilt angle ensures maximum incident sunlight, making the battery charging process more effective. Operating at this optimal combination also keeps the battery within a safe charging zone (around 50–60%), which is important to prevent premature damage from undercharge or overcharge and to extend the battery's service life in the long term.

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