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Design and Implementation of a Mini Off-Grid PV Solar System for Power Optimization

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ABSTRACT
Energy plays a crucial role in every sector of a nation's economy. Solar energy is a prime example of a clean and abundant resource since it harnesses energy from sunlight and converts it. The maximum utilization optimization of solar energy setup or configuration is a huge challenge, where solar system configuration is significantly affected by various factors including solar mounting angle configuration and solar irradiation. There is a lack of comprehensive understanding of how these factors impact the performance of solar power systems, particularly in off-grid settings. The effectiveness of solar panels is compromised by suboptimal mounting angles, varying solar irradiation levels, and inadequate configuration strategies. The aim is to determine appropriate and effective solar mounting angles and solar irradiation indices for power optimization. The study uses two solar system setups of tilt angles of 45°, 55°, 65°, and 75° and solar irradiation levels under sunny and cloudy weather conditions. The result reveals that 45° angles consistently yield 19.5W on sunny days and 11.6W on cloudy days. Also, the results show that irradiance values at noon ranged from 144 W/m² on sunny days to 100 W/m² on overcast days, demonstrating the panel's responsiveness to changes in sunlight intensity. A comprehensive analysis of voltage, current, and power outputs provided insights into the potential for off-grid solar systems and underscored the viability of off-grid solar systems to meet growing energy needs, particularly in underserved rural and urban areas. This work provided valuable insight and a blueprint for future renewable energy initiatives.

Keywords:
Power optimization,
Mounting angles,
Solar energy,
Solar irradiation,
Off-grid,
Renewable energy.

INTRODUCTION

Energy plays a crucial role in every sector of a nation's economy. A country's standard of living is closely tied to its per capita energy usage. The current global energy crisis can be attributed to two main factors: the rapid growth of the population and the rising standard of living across societies. Per capita energy consumption not only reflects individual income levels but also serves as an indicator of a nation's overall prosperity (Rai, 2004). Reliable, affordable, and environmentally friendly energy is crucial for reducing poverty and fostering human and economic progress. According to the International Energy Agency (IEA), approximately 1.2 billion individuals, or about 16% of the global population, lack access to electricity, the majority found in East Asia and sub-Saharan Africa. More than half of this group resides in sub-Saharan Africa, where only 32% of households are linked to the national power grid. The International Energy Agency (IEA) predicts that the electricity demand in sub-Saharan Africa will grow by an average of 4% annually until 2040 (IEA, 2015). Therefore, there is an urgent need to address this situation to avert prolonged negative consequences on Africa's social and economic development Energy is essential for meeting fundamental needs, including cooking, maintaining comfortable indoor temperatures, providing lighting, operating appliances, accessing piped water and sewage systems, ensuring critical health services (such as refrigerated vaccines, emergency care, and intensive care), supporting education, enabling communication (through radio, television, email, and the internet), and facilitating transportation. Additionally, energy drives productive sectors like agriculture, commerce, manufacturing, industry, and mining. On the other hand, insufficient access to energy can lead to poverty and deprivation, potentially resulting in economic downturns. Energy and poverty reduction are not only closely connected, but also with socioeconomic development, which involves productivity, income growth, education, and health (Nnaji et al., 2010).

Power outages in Nigeria have significant economic impacts, with the Council for Renewable Energy of Nigeria (CREN) reporting an annual loss of 126 billion naira (approximately US$ 984.38 million) due to these disruptions (CREN, 2009). This situation is exacerbated by inadequate infrastructure and a high dependency on electricity for socio-economic activities, which hinders overall development. The Nigerian power system experiences frequent failures and fluctuations in supply. Fluctuations in power supply can damage sensitive equipment, and ongoing power outages can lead to distress among citizens. Renewable energy is a crucial alternative electricity source to mitigate these issues (Obi et al., 2019). With growing concerns over global warming, there has been a surge in international interest in researching and developing sustainable energy systems. The costs associated with various technologies have consistently decreased while their effectiveness has improved. Coupled with rising electricity prices, this has opened up the market for sustainable and efficient energy technologies to a broad audience of homeowners, making it less expensive to disconnect from the main grid (Doe and Smith, 2023).

Solar energy is a prime example of a clean and abundant resource. It harnesses energy from sunlight and converts it into usable power. In developing regions, renewable energy is often more cost-effective than traditional electricity supplied by utility companies. (Adesina et al., 2021). Solar photovoltaic (PV) technology is easily available for development in Nigeria. The average annual solar radiation ranges from about 3.5 kWh/m² per day in coastal regions to approximately 7 kWh/m² per day in the semi-arid north (Sambo, 2009; Sambo and Bala, 2012). Solar radiation in Nigeria is relatively well-distributed, with a minimum average of around 3.55 kWh/m² per day. Solar generation can yield about 3.8×10^{23} kW, equivalent to 1,082 million tonnes of oil (Mtoe) worth of energy daily, roughly 4,000 times more than crude oil production and 13,000 times the daily output as of 2009. Approximately 10,000 TW of solar energy strikes the Earth's surface daily (Bosshard, 2006). In 2015, global energy consumption totaled 17.4 TW (Seger, 2016), and energy consumption has seen a modest annual growth of about 1-1.5%. The total energy consumption worldwide is projected to increase by 56% by 2040 (USEPA, 2021). Considering the current consumption rates, the anticipated growth over the next two decades, and the solar radiation received in just one hour, the potential of solar energy is immense.

The world is facing an unprecedented energy crisis, with increasing demand for electricity and dwindling fossil fuel resources. Solar energy has emerged as a viable alternative, but its efficiency and reliability are crucial for widespread adoption. However, solar panels' performance is significantly affected by various factors, including mounting angle, solar irradiation, and configuration (IRENA, 2020). There is currently a limited understanding of how many factors affect the performance of solar power systems, especially in off-grid environments. The effectiveness of solar panels is compromised by suboptimal mounting angles, varying solar irradiation levels, and inadequate configuration strategies. Moreover, the responsiveness of mono and poly-crystalline panels to solar irradiation and weather conditions is not well understood (Energy Matters, 2023; Green et al., 2013). Furthermore, the choice of configuration (series or parallel) and charge controller (MPPT or PWM) significantly influences the overall efficiency of the solar power system. There is still a lack of extensive research comparing the performance of these configurations and charge controllers, especially in off-grid settings.

Nigeria faces consistent power supply failures and voltage fluctuations that affect sensitive equipment and disrupt daily activities. In response, renewable energy, particularly solar energy, has emerged as a viable alternative to traditional electricity. Solar energy is abundant in Nigeria and holds the promise to alleviate the pressure on the conventional grid (Akinyele and Rayudu, 2016). The design and implementation of an off-grid solar power system address the country's need for more reliable power, reduce dependence on fossil fuels, and minimize environmental impacts such as carbon emissions. By creating an off-grid system, users can generate their electricity, thus achieving energy independence from the unreliable grid. This system can supply a stable, uninterrupted power supply to residential buildings, which is crucial in rural and urban areas with limited or inconsistent electricity access. The system can also offer financial benefits by reducing the cost of energy compared to using generators or the national grid, especially with the rising costs of fossil fuels and increasing demand for electricity (Abubakar et al., 2017). By focusing on power optimization, the project not only demonstrates the viability of solar PV systems for off-grid applications but also explores methods to increase the efficiency of energy generation, storage, and usage. This contributes to reducing energy waste, lowering operational costs, and improving overall system performance, making it a practical and impactful solution for renewable energy deployment.

This research seeks to fill existing knowledge gaps by examining how the mounting angle, solar irradiation, and configuration of solar panels impact the performance of a mini off-grid photovoltaic (PV) solar system. By exploring these factors, this study seeks to optimize power generation and provide a reliable, efficient, and sustainable solution for off-grid energy needs.

MATERIALS AND METHODS

The research adopts an experimental approach, to evaluating the performance of a mini off-grid solar power system. Specifically, it focuses on understanding how mounting/inclination angle and solar irradiation affect the efficiency of the monocrystalline solar panel. Controlled tests will measure how changes in panel orientation and solar irradiation influence power output. Data from these experiments will be useful to real-world conditions in optimizing the solar panel setup for better energy generation.

System Design and Construction

The materials and components used for this work is shown in figure 1 and they include:

i. Solar Panels: The Monocrystalline panel will compare their performance. Each panel will have a rated power of around 50Wp (Watts peak).
ii. Solar Charge Controller and Amp-meter: To measure voltage, current, and resistance in the system: PWM of 30A charge controller will be used to regulate the voltage and prevent overcharging of the battery.
iii. Battery: Lead acid 12V18AH/20HR battery will store the energy produced for later use. The system will utilize a configuration
iv. Mounting Structure: Adjustable mounting frames will allow variation of the solar panel inclination angle.
v. Pyranometer: a phone app (Solar Meter) was used to measure the intensity of solar radiation throughout the day.

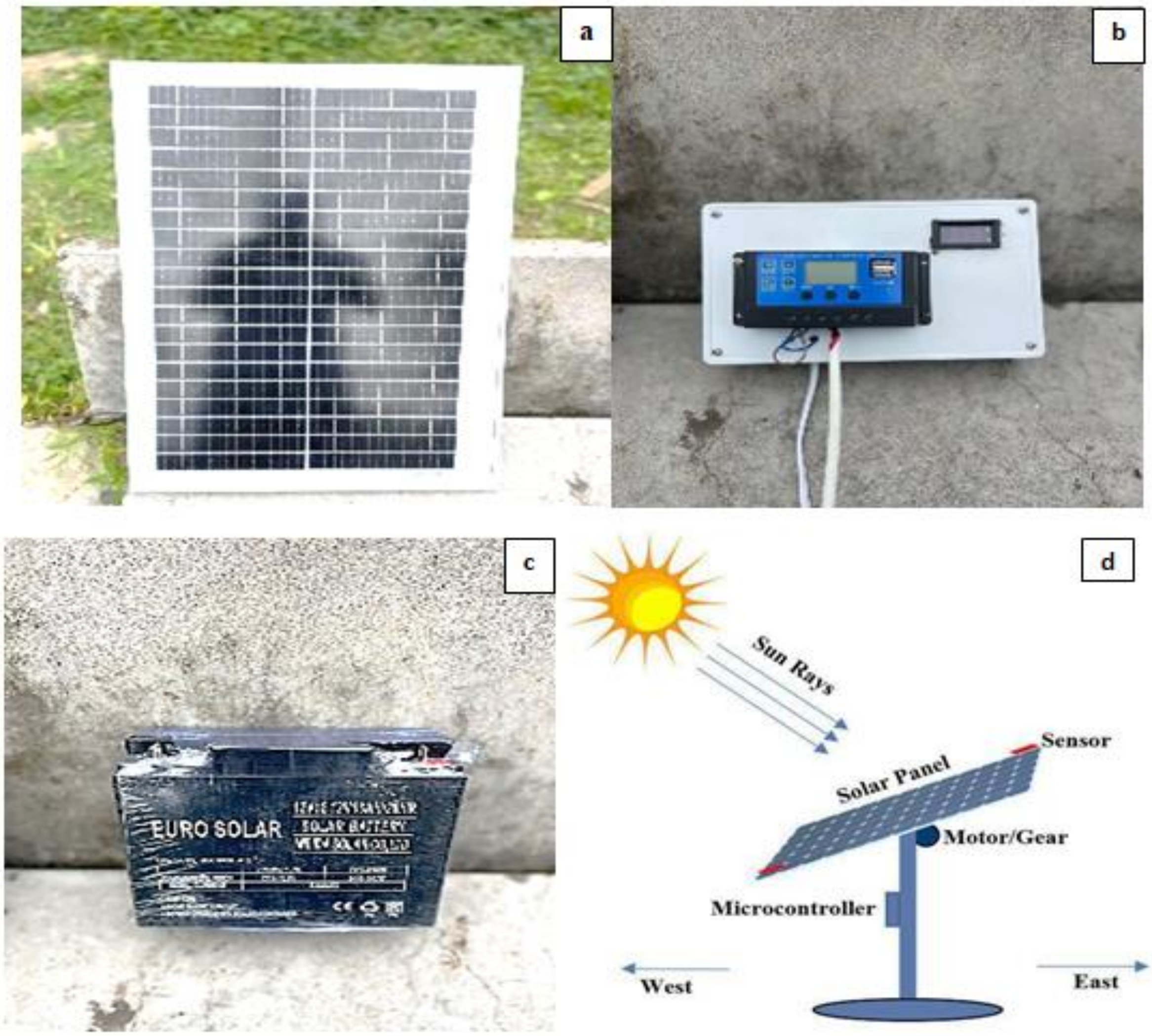

Figure 1: Diagram of Materials and components used for this work

Construction Process

The panels were mounted on adjustable frames to enable changes in tilt angles. These angles will be varied in increments (35°, 45°, 55°, 75°) using a protractor in figure 2 to find the optimal positioning for maximum power output. The solar panels were connected to the charge controller, which is then connected to the battery as shown in the block diagram in figure 3.

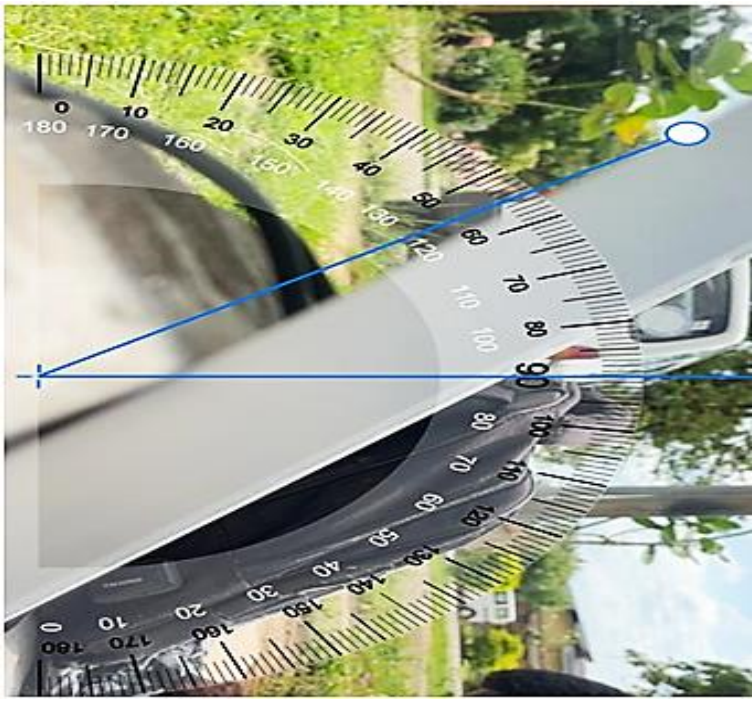

Figure 2: Diagram of protractor for angle measurements

Figure 3: Block Diagram of the Off-Grid System

Data Collection and Analysis

The Data were collected on the system's performance under various conditions which include the Solar Irradiation which is the data from the Pyranometer which tracked the changes in sunlight intensity. Also the Panel Power Output were recorded where voltage and current readings from the panels were recorded to calculate the electrical power output. Similarly, the angles of inclination indicated the performances of the solar panels at different tilt angles and were compared. The comparative analysis involved the power outputs from the monocrystalline panel which were compared under different conditions to evaluate its efficiency. The plots the power output versus time of day, tilt angle, and irradiation were plotted to observe trends. Furthermore, the regression analysis was determined to show the relationship between the solar panel performance and solar irradiation. Likewise, the optimal angles for different weather conditions and times of the year were calculated.

RESULTS AND DISCUSSION

Inclination Angle and Optimal Performance

The experimental results clearly show that the inclination angle is a key factor in getting the best performance from solar panels. The data suggests that the monocrystalline panel performs best at an angle of 45°, which aligns with the latitude of the installation site. This is consistent with findings from previous studies, which indicate that adjusting the panel's inclination to match the latitude improves solar power generation efficiency.

Solar Irradiation and Panel Responsiveness

The results show that monocrystalline panels are more responsive to varying levels of solar radiation intensity, making them more efficient in low-light conditions.

Cloudy weather leads to greater fluctuations in irradiance, which are affected by the density of the clouds. The panel angles continue to affect the 45° angle typically harnessing the highest irradiance values. This confirms that solar irradiation is a critical factor in energy production.

Implications for Off-grid Solar System Design

The findings of this study have practical implications for designing off-grid solar systems to maximize power generation, it is important to optimize the angle of the solar panel and choose the right type of solar panel based on the environmental conditions. Additionally, understanding the variations in power output based on weather conditions is essential for designing battery storage systems that can compensate for periods of low energy production.

Solar Panel Performance at Different Inclination Angles

The results for the solar panel's power output at different inclination angles (45°, 55°, 65°, and 75°) are given in a table 1 and the plots of inclination angles against power output are shown in figures 4 and 5.

Table 1: Data for the Inclination Angle (°) Output

No. Days	Inclination Angle	Voltage (V)	Current (I)	Power output (W)
Day 1	45°	13.0	0.75	9.75
	55°	13.2	0.61	8.12
	65°	13.5	0.35	4.73
	75°	13.0	0.57	7.41
	45	13.3	1.57	20.72
	55	13.5	1.41	18.47
	65	13.3	0.94	12.22
	75	13.4	0.85	11.31
	45	13.2	0.41	5.53
	55	13.1	0.22	2.97
	65	13.0	0.25	3.33
	75	13.3	0.20	2.68
Day 2	45°	13.0	0.55	7.15
	55°	13.0	0.41	5.33
	65°	13.5	0.35	4.73
	75°	13.0	0.47	6.11
	45	13.3	1.37	18.2
	55	13.5	1.11	15.0
	65	13.3	1.24	16.5
	75	13.4	0.95	12.7
	45	13.2	0.75	9.9
	55	13.1	0.62	8.1
	65	13.0	0.65	8.5
	75	13.3	0.70	9.3
Day 3	45°	13.0	0.89	11.6
	55°	13.2	0.71	9.4
	65°	13.5	0.85	11.5
	75°	13.0	0.77	10.0
	45	13.3	1.47	19.5
	55	13.5	1.21	16.3
	65	13.3	1.04	13.8
	75	13.4	1.15	15.4
	45	13.2	0.65	8.6
	55	13.1	0.52	6.8
	65	13.0	0.45	5.9
	75	13.3	0.50	6.7

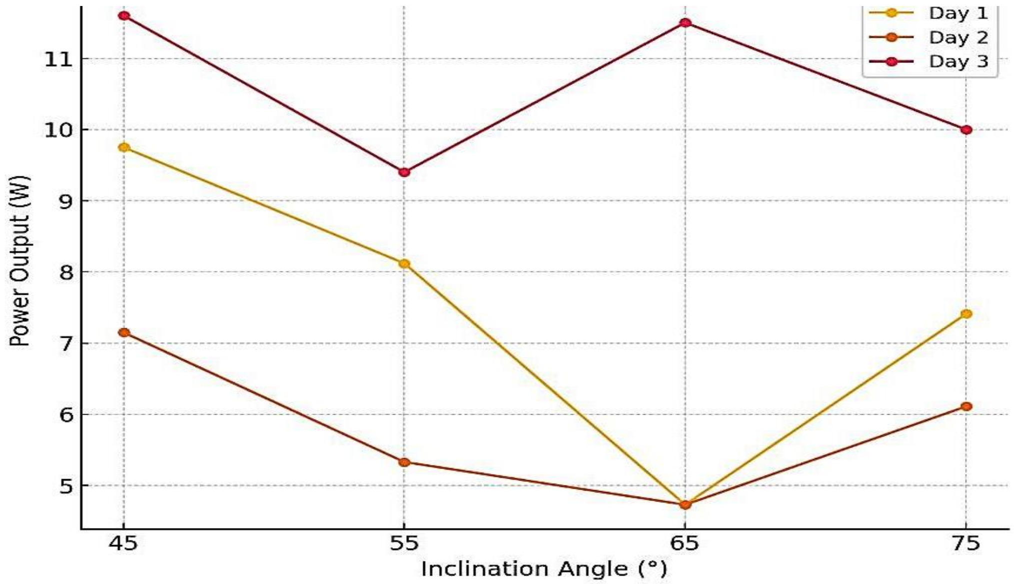

Figure 4: Plot of Inclination Angles against Power Output

Figure 4 shows how the power output varies with different panel tilt angles (45°, 55°, 65°, and 75°) across the days, giving insight into the optimal angle for maximum energy generation. The plot shows that the inclination angle of **45°** consistently produces the highest power output across all three days, making it the optimal angle for maximum energy generation in this setup.

Effect of Solar Irradiation on Panel Performance

The table 2 shows the data collected on sunny weather. It indicted how the varying levels of solar irradiance (sunlight intensity) affected the performance of the mono-crystalline panel.

Table 2: Data acquisition for the Sunny Weather

No. Days	Time of the day	45° (W/m^2)	55° (W/m^2)	65° (W/m^2)	75° (W/m^2)
Day 1	09:00 am	135.00	110.00	114.00	104.00
	12:00 pm	144.00	120.00	110.00	100.00
	03:00 pm	115.00	105.00	115.00	104.00
Day 2	09:00 am	144.00	100.00	144.00	104.00
	12:00 pm	144.00	113.00	110.00	110.00
	03:00 pm	110.00	100.00	104.00	104.00
Day 3	09:00 am	114.00	110.00	102.00	101.00
	12:00 pm	144.00	104.00	111.00	112.00
	03:00 pm	134.00	114.00	104.00	110.00

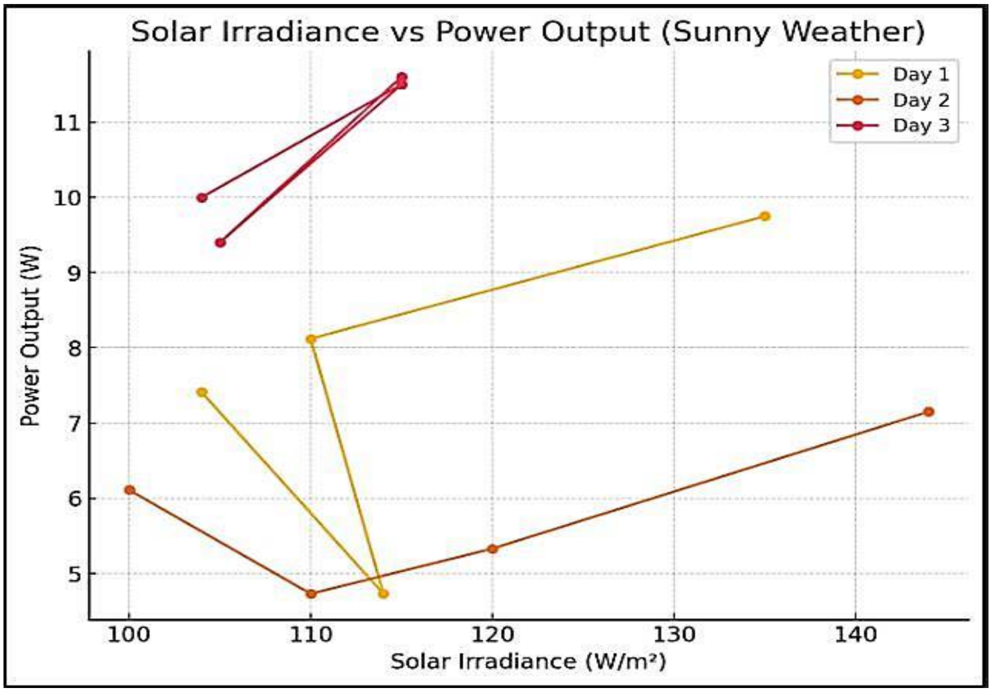

Figure 5: Plot of Power Output against Solar Irradiance (Sunny Weather)

Figure 5 shows the relationship between solar irradiance (W/m²) and power output (W) on sunny days. From the data, the 45° angle consistently delivers the highest power output across all levels of irradiance, reaffirming it as the best angle for optimal performance. The table 3 shows the data collected on cloudy weather. It indicted how the varying levels of solar irradiance (sunlight intensity) affected the performance of the monocrystalline panel. The figure 6 shows the plot for cloudy weather which illustrated the connection between solar irradiance (W/m²) and power output (W) during overcast days. Despite the cloudy conditions, the 45° angle consistently delivers the highest power output compared to other angles, confirming it as the optimal tilt for both sunny and cloudy weather**.**

Table 3: Data acquisition for Cloudy Weather

No. Days	Time of the day	45° (W/m^2)	55° (W/m^2)	65° (W/m^2)	75° (W/m^2)
Day 1	09:00 am	95.00	95.00	95.00	95.00
	12:00 pm	100.00	10.00	100.00	100.00
	03:00 pm	98.00	70.00	85.00	95.00
Day 2	09:00 am	95.00	95.00	95.00	95.00
	12:00 pm	100.00	100.00	100.00	100.00
	03:00 pm	100.00	100.00	98.00	100.00
Day 3	09:00 am	95.00	85.00	75.00	68.00
	12:00 pm	95.00	85.00	88.00	90.00
	03:00 pm	89.00	75.00	95.00	95.00

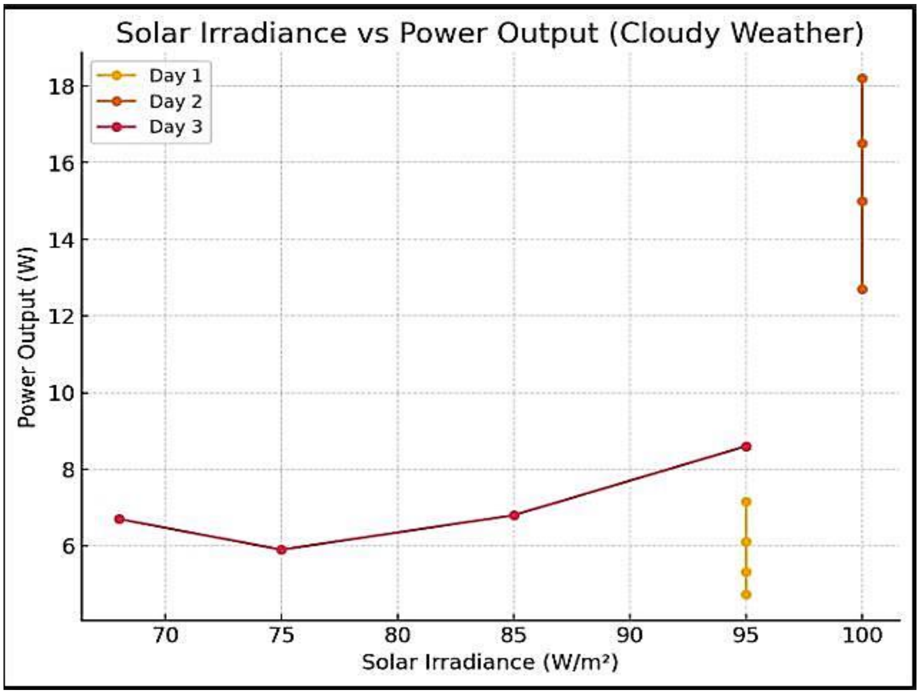

Figure 6: Relationship between solar irradiation and power output for cloudy weather

CONCLUSION

Based on the findings of this study, the following conclusions can be drawn. For the optimal inclination angle, the ideal inclination angle for solar panels is crucial for maximizing power generation. For the geographical location of this study, the most efficient angle was found to be 45°, improving overall system efficiency. Considering the panel type performance, the mono-crystalline panels proved to be more versatile and responsive under varying weather conditions, especially in low-light environments. Furthermore, the weather and time influence in view of environmental factors such as cloud cover and temperature had a notable impact on the performance of the solar panels. Mono-crystalline panels demonstrated greater adaptability to changes in weather and irradiance, making them suitable for regions with inconsistent weather patterns. These conclusions reinforced the importance of optimizing the design of solar systems for specific environmental conditions and highlight the significance of inclination angle in off-grid solar system performance.

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