How Light Incident Angle Impacts Power Output of Consumer Grade Solar Panels

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Abstract

Rising global energy demand, driven in part by the growth of AI, has heightened the need for efficient and accessible renewable energy solutions. Although solar power adoption has grown substantially, the performance of low-cost, consumer-grade photovoltaic panels under varying light incidence angles remains unproven. This study investigates how the angle of incoming light affects the power output of inexpensive off-the-shelf solar panels. A controlled test fixture was developed to measure real-time power as the panel was swept through a 180° rotation under a fixed LED light source. Measured power output was compared to theoretical predictions based on the projected area of the light. Results show that the panel's power output generally follows a sinusoidal dependence expected for ideal photovoltaic cells, with deviations likely due to reflection, scattering, and other losses inherent in inexpensive materials and the mounting configuration. Analysis further indicates that simple sun-tracking could provide up to 97% more total power than fixed-angle mounting, highlighting the strong geometric dependence of consumer-grade photovoltaic performance and the sizable gains possible through low-cost tracking systems.

Introduction

Energy demand has increased substantially over time and will continue to grow as AI data centers require more energy [1]. This increase in energy demand highlights the growing need to diversify energy sources [2]. As global climate change and rising oil prices increase costs, the world is becoming more reliant on renewable forms of energy [3]. Solar energy usage has risen eightfold in the last decade and is therefore set to become the largest renewable energy source by 2029 [4]. When used in a consumer context, such as charging phones or powering a house, solar panels use a technology called a photovoltaic cell. Because the output of photovoltaic cells depends on how much light effectively reaches the cell, the angle at which light hits the panel strongly influences its power production. Light striking the cells causes electrons to shift, which in turn creates the current that is used to power devices. As technology has developed, solar cells have become easier to mass-produce, resulting in lower costs and making solar panels readily available for the average consumer.

The angle of light incidence on solar panels has been well studied on expensive solar panels often used in power stations. The effect of light incidence on smaller consumer-grade solar cells, however, remains understudied [5]. This lack of research and the common practice of fixing solar panels likely mean that consumers are not using their solar panels efficiently, resulting in lost power.

The objective of this study is to quantify how the light incidence angle affects the power output of a low-cost consumer solar panel and to estimate the potential energy gains from sun-tracking. The power output is expected to follow a sinusoidal dependence, with deviations arising from reflection, scattering losses, and inefficient consumer-grade components.

Methods

The panel tested was the FellDen Micro Solar Panel, which produces a maximum of 5V at 200mA of current. Standard DAQs are unable to record power, which is required for this experiment, so an INA228, which is designed to measure power by measuring voltage and current simultaneously, was used. An ESP32 microcontroller was used to read the measurements taken on the INA228 and to store the recorded data. This setup had a response time of less than 1 ms, which is sufficient for the 3-minute test time. Although the INA228 is factory calibrated, its accuracy was verified against a known voltage and current.

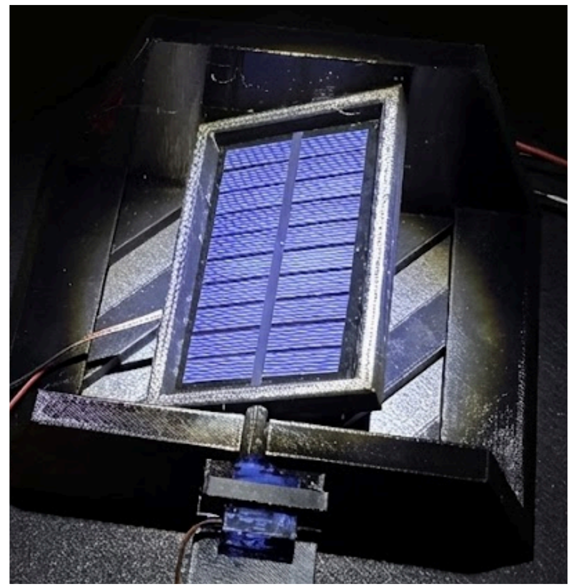

Figure 1: Solar Panel Mounted to Stand

To measure the power output of the solar panel, a 3D printed fixture was created, as shown in Figure 1. The solar panel was mounted on a tray supported by a stand that allowed the tray and solar panel to rotate freely. The tray arm was then connected to a servo, which was connected to the ESP32. An XML-T6 LED flashlight with a 300 Lumen output was mounted one meter above the fixture, ensuring the light covered the entire area of the solar panel.

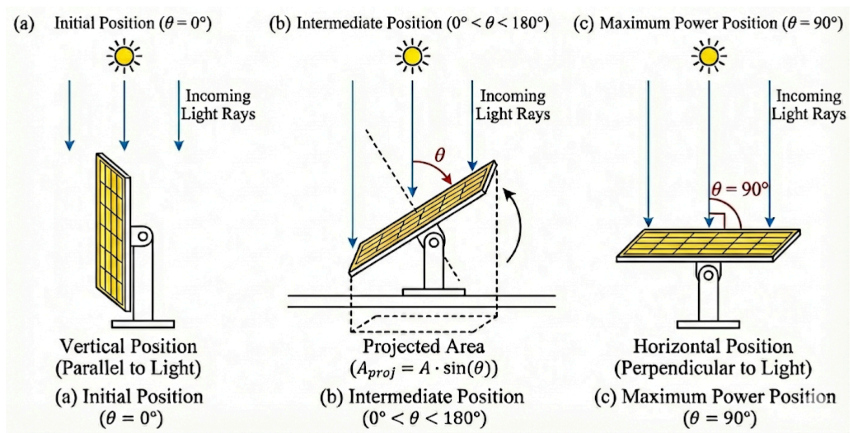

Figure 2: Schematic to define the angle of the solar panel relative to incoming light rays. The projected area is also shown pictorially. Schematic created with the help of Google's Gemini

Each test run was performed using the following steps. A script on the ESP32 was started that began recording power measurements from the INA228 while simultaneously rotating the solar panel using the servo. The servo started at what we defined as 0 degrees, where the solar panel was vertical and pointing toward the left, as shown in Figure 2a. The solar panel was rotated at a rate of 2 degrees per second until it arrived at 180 degrees, where the solar panel was again vertical, but facing the opposite direction. This method was performed 5 times to record a total of 49,782 datapoints.

The INA228 measured power at a high rate compared to the test time, resulting in high-frequency noise in the data collected. To analyse this data, the measurements were grouped into 5-degree bins. The servo used had a reported uncertainty of 3 degrees, so any bin size smaller than 5 degrees would imply a precision not supported by the hardware. Larger bin sizes could smooth out real angular dependence. For each of the bins, the mean and standard deviation were calculated. These values were then normalized by dividing each one by the maximum mean power and multiplying by 100 to get a percentage of maximum power output.

Using this data, the increase in power output while using a tracking system versus a fixed system was calculated. To estimate the total energy for a tracking system, the panel was assumed to operate at its maximum measured power at all angles, so the tracked energy was computed as this maximum value multiplied by the angular range and the angular rate. For a fixed panel, the normalized power values were integrated using the trapezoidal rule, which was then multiplied by the angular rate, representing a panel that remains at one orientation while the light source moves. These two outputs were then compared to quantify the potential gain from a tracking panel relative to a fixed one. The corresponding expressions are

$$P_{tot,fixed} = r\sum_{i=0}^{n-1} \frac{x_{i+1}-x_i}{2}(y_i + y_{i+1}) \quad \text{and} \quad P_{tot,track} = r\sum_{i=0}^{n} y_{max}$$

Where x_i is the angle at bin i, y_i is the normalized power at that angle, y_{max} is the maximum normalized power measured, and r is the angular rate, which was 2 degrees per second.

The measured data were then compared to our predicted power output based on the projected area of light. The projected area model was calculated as

$$P_{proj} = A\sin(\theta)$$

Where θ is the incidence angle of the light in relation to the solar panel as described above.

The uncertainty for each normalized power value was estimated by combining three contributions in quadrature.

$$u = \sqrt{u_0^2 + u_I^2 + u_{SEM}^2}$$

Where u_0 is the zeroth uncertainty that comes from using a 20-bit analog-to-digital converter in the INA228, u_I is the instrument uncertainty, which is reported on the INA228 as 0.05% of the measurement, and u_{SEM} is the uncertainty that comes from the noise in the data, which was calculated as 1.96 times the standard error of the means which implies a 95% confidence. The uncertainty for each data point can be seen in Figure 3 as the vertical error bars. The uncertainty changes depending on the measurement, so at small angles the vertical error bars are smaller than the data marker, but at intermediate angles the vertical error bars are slightly larger. The uncertainty model does not include lighting non-uniformity or LED output fluctuations; these were assumed small relative to sensor uncertainty but may introduce additional deviation.

In addition to the uncertainty of the measured variable, there is also uncertainty in the angle due to the servo. This uncertainty is reported for servos from the factory as being 3° and is shown in Figure 3 as horizontal error bars. The primary contributor to angular uncertainty was the servo motor itself, since it was the sole mechanism determining the orientation of the solar panel. The dominant source of uncertainty for the power, however, arose from the instrument uncertainty associated with the INA228. Because this instrument uncertainty scales with the magnitude of the measurement, Figure 3 shows that it becomes increasingly significant at higher power levels, where it overtakes all other sources of error.

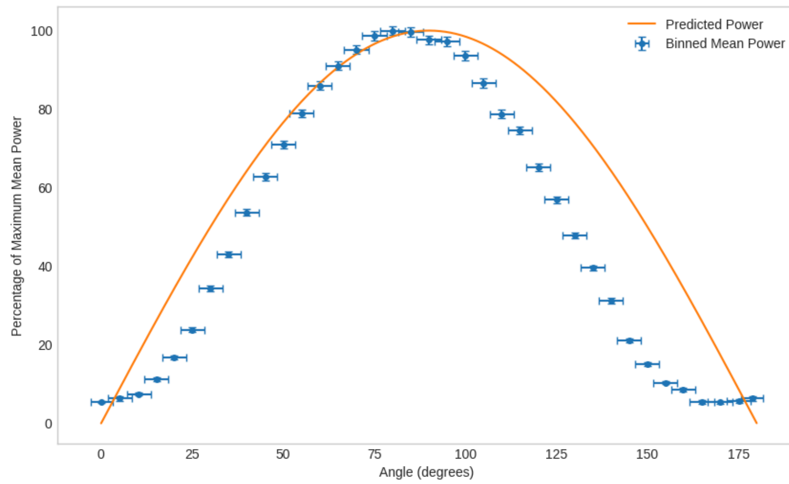

Figure 3: Percentage of maximum power output vs angle. Measured and predicted (projected area). Error bars represent calculated uncertainty

Results and Discussions

The percentage of the maximum power output of the solar panel at different angles is shown in Figure 3, along with the corresponding percentage based on the projected area of light on the panel. The trend of power closely matches the predicted power output based on the projected area of light, but deviates more strongly at extreme angles, where the data fall noticeably below the ideal curve. At these angles, the measured power output drops to roughly half of the ideal projected-area prediction, although the overall sine-like trend still indicates that projected area is the primary factor influencing the power output of consumer-grade solar panels. These deviations at extreme angles can be attributed in part to reflection, and to partial shading from the tray overhang visible in Figure 1, both of which reduce the effective light reaching the cells.

The measured power output seems to be slightly shifted to the left. This shift likely corresponds to some inconsistencies in the setup of the testing fixture. For example, the solar panel could be shifted one way or the other, which could cause a shift in the resulting measurement data. Likewise, it is possible that the light was not perfectly aligned with the panel, which could also account for this shift.

Using the formula presented in the methods section, the total energy output from a tracking panel was found to be 97% higher than that of a fixed panel over the same angular range, as can be seen in Table 1. This highlights the importance of tracking the sun and underscores a gap in current technological offerings. This estimate is likely quite generous, however, because in real outdoor conditions, surrounding surfaces reflect additional light onto the solar panel. This likely reduces the gap between fixed and tracking configurations. As a result, the actual power-production advantage of tracking would likely be smaller than the value calculated in this controlled setup. Future work could include deploying sun-tracking versus fixed solar panels in real-world environments to understand the true difference in power production.

Table 1: Total Power Output of a Fixed Solar Panel and a Sun-Tracking Solar Panel

Value	Fixed Solar Panel	Sun-Tracking Solar Panel
Total Power Output (Energy) (mJ)	0.129	0.2544

Summary and Conclusion

The collected data show that a solar panel's power output depends on the angle of incoming light, as expected. The measured trend generally follows the sinusoidal projection model, with deviation consistent with reflection losses and shadows caused by the fixture's overhang. Using this data, it was estimated that active sun-tracking could yield up to 97% more total power output than a fixed panel. This estimate is admittedly likely higher than it would be in real life due to the reflection of sunlight on the panel's surrounding surfaces. However, this calculation highlights how critical sun-tracking is for improving the efficiency and overall performance of consumer-grade solar panels.

Sources:

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