Analysis of the Effects of Hard Shading Pattern on I–V Performance Curve

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Abstract

Complex shading on a photovoltaic (PV) module has a disproportionate impact on its power production. Minimizing power losses is critical in the installation of the PV module since it can greatly diminish the module's performance and capacity to generate electricity. Thorough examination of the consequences of hard shading on the PV modules is necessary to lower power losses and maximize the module's efficacy. This paper presents the background and findings from three different types of PV module (Full Cell, Half-Cut and Shingle PV module) operated under a variety of shading pattern (horizontal, vertical, and diagonal), and obscuring percentage (25, 50, and 75%). Experiments are conducted in

Analysis on the Effects of Hard Shading Pattern to I-V Performance Curve

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Abstract— Hard shading on a photovoltaic (PV) module has a disproportionate impact on its power production. Minimizing power losses is critical in the installation of the PV module since it can greatly diminish the module's performance and capacity to generate electricity. Thorough examination of the consequences of hard shading on the PV modules is necessary to lower power losses and maximize the module's efficacy. This paper presents the background and findings from three different types of PV module (Full Cell, Half-Cut and Shingle PV module) operated under a variety of shading pattern (horizontal, vertical, and diagonal), and percentage (25%, 50%, and 75%). Experiments are conducted in a location at Sabah, a state located within Malaysia. Sabah which has a tropical climate with high temperatures and humidity, along with consistent level of solar radiation throughout the year making it well-suited for solar energy production. The experimental technique, which involved testing PV modules under various shading patterns and percentages, was found to be highly accurate in determining the amount of shading loss, particularly in instances of hard shading. The findings are presented by I-V and P-V curve that was traced by using a portable PV power meter (SEAWARD PV200) relating the pattern and percentage of shading to maximum power point (MPP) and power losses of the PV modules.

Keywords: photovoltaic, module, shading, full cell, half-cut, shingle

1. INTRODUCTION

Renewable energy is an energy that comes from natural and replenishable sources such as sunlight, wind, along with water. According to estimations, renewable energy account for more than 50% of all energy consumed worldwide by 2040 [1]. These energy sources are attractive because it is less expensive, and have a smaller impact on the environment. Furthermore, renewable energy sources are more secure than fossil fuel sources for instance coal, oil, and natural gas which are finite and contribute to climate change when burned [2,3].

Solar energy is a clean and renewable energy source that does not produce greenhouse gas emissions or contribute to air pollution when generating electricity [4]. It is also a relatively reliable source of energy, as the sun is available almost everywhere on Earth. Generation of electricity from solar energy is attainable using a photovoltaic (PV) module. The PV module capture the energy from sunlight and convert it into electricity or heat. PV module has become increasingly popular in recent years due to its numerous benefits, including low cost together with the feasibility on the installation and maintenance [5,6]. It is also a good choice for use in remote areas where other sources of energy are not easily accessible.

Power losses are an important factor to consider when installing a PV module. Power losses refer to the reduction in electricity generation that occurs as a result of various factors. Power losses can significantly reduce the overall performance of a PV system and impact its ability to generate electricity [7]. The equation below shows the factors which affected the performance and energy production losses of a PV module [8].

$$P_{max} = P_{max\ STC} \times f_{mm} \times f_{age} \times f_{temp} \times f_g \times f_{clean} \times f_{unshade}$$

Where;

P_{max} = Maximum PV module power

$P_{max\ STC}$ = Maximum power of PV module at Standard Test Condition (STC)

f_{mm} = Factor due to mismatch

f_{age} = Factor due to aging

f_{temp} = Factor due to temperature

f_g = Factor due to irradiance

f_{clean} = Factor due to soiling

$f_{unshade}$ = Factor due to shading

Factors due to mismatch (f_{mm}), aging (f_{age}), temperature (f_{temp}), and irradiance (f_g) are related to the internal functioning of the module, while factors due to the soiling (f_{clean}) and shading ($f_{unshade}$) are related to the external environment. Hard shading is a frequent phenomenon that occurs when the PV module's surface is completely blocked from the sunlight [9]. The occurrence happens when a solid object such as bird droppings, moss, or snow partially or fully covers the cells of the module. Hard shading is a significant problem for PV modules since it causes the affected cells to stop generating electricity, leading to a reduction in the overall power output of the module [10]. In some cases, it causes hot spots on the shaded cells which leads to damage and reduced performance over time [11]. By studying the effect of the hard shading, it is possible to understand how this factor affected the power output of the module and identify strategies to mitigate its impact along with maximization on the power output of the module. Therefore, this study focuses on the effect of the hard shading towards the performance of the PV module.

2. LITERATURE REVIEW

2.1. Photovoltaic Module

A photovoltaic (PV) module, also called a solar panel, is a device that converts light energy into electricity through the photovoltaic effect. The photovoltaic effect is the process where light energy is absorbed by a semiconductor material and generates electricity. Some commercially available PV modules include Full Cell, Half-Cut, and Shingle PV Module.

2.2. Full-Cell PV Module

A Full Cell photovoltaic module, is made up of multiple photovoltaic cells which are electrically connected together in series to form a complete unit [12]. The electricity flows from one cell to the next in a continuous loop. Each cell generates a small amount of voltage (0.5 to 0.6 V), and by connecting it in series, the voltages add up to create a higher overall voltage [13]. Photovoltaic cells are constructed of semiconductor materials, such as silicon and it is specially engineered to absorb sunlight and transform it into electricity. Full Cell PV modules are typically made up of 60 or 72 photovoltaic cells arranged in a grid pattern. The cells are encapsulated in a protective casing, such as a glass or plastic cover, to protect it from the elements and ~~to~~ increase its efficiency.

2.3. Half-Cut PV Module

A Half-Cut photovoltaic module is a type of module that has its PV cells cut in half, which increases the module's efficiency [14]. Half-Cut PV module is resistant to the shading effect since it is split into two sections, where the top and bottom sections function as two separate modules and generates energy even when one half of the section is shaded [15]. In a Half-Cut PV module, the PV cells are connected together in a grid pattern, similar to a Full Cell PV module. The cells in each half of the module are connected in series, and the two sections of the module are connected in parallel. The combination of series and parallel connections allows for a balance voltage and current, optimizing the power output of the module [16].

2.4. Shingle PV Module

According to Kunz et al. [17], Shingle PV module is one of the several technologies currently being considered in obtaining a higher PV module efficiencies. This module is made up of small and enclosed PV cells arranged in a shingled pattern. Shingle PV module is a relatively new technology and was introduce to the PV market in recent years. The cells in a Shingle PV module are connected in a series within each shingle, and the shingles are connected in parallel between each row. This configuration enables the cells to collaborate towards generating a higher overall voltage and power output. The parallel connection of the shingles allows for each row of the module to function independently, which can be beneficial in case of damage or malfunction of a single shingle.

2.5. Hard Shading Method

A number of methods was priorly conducted by preceding studies for the determination on the effect of the hard shading towards the performance of the photovoltaic module. Jumaili et al. [18] applied five different shading test configurations, ranging from no shading to full shading (0%, 25%, 50%, 75%, and 100%). A solar module tester (SMT) was used to simulate standard solar irradiance of 1000W/m^2, and the research utilized a Full-Cell 130W PV module for the investigation. The results of the investigation found that hard shading significantly impacts the performance of PV module, as the module performance decreases along with the increase on the level of shading. Ibrahim A [19] analyzed the effect of edge shadowing which may happen on PV module due to dust accumulated on the tilted PV array. The experiment involved covering the edge of the Full-Cell PV module with an opaque film, which resulted in a gradual reduction of power output ranging from 10-20%. To the best of knowledge, the previous investigation was centered on Full-Cell PV modules. Hence, this study focuses on (i) three different types of PV modules; Full Cell, Half-Cut, and Shingle PV module, with a variety of (ii) shading pattern (horizontal, vertical, and diagonal), along with (iii) shading percentage (0%, 25%, 50%, and 75%).

3. RESEARCH METHODOLOGY

Test was carried out using three different types of PV modules, which were Full Cell, Half-Cut, and Shingle. The modules are fixed at 21° of tilt angle and faced towards south direction. The tilt angle was decided on the basis of the highest irradiance measured by the irradiance meter during the time between 11am and 1pm. The specifications of the PV modules are provided in Table 1.

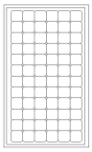
Table 1. Specifications of PV Modules

Specifications	Full-Cell	Half-Cut	Shingle
Brand	SOLAR BLUESUN	Q.ANTUM DUO	SOLAR BLUESUN
Model No.	BSM400M-72/5BB	Q.PEAK DUO-G7 315-330	BSM500PM5-72SB
No of cells	72	120	432
Cell material	Monocrystalline	Monocrystalline	Monocrystalline
V_{oc}	49.55	40.10	46.80
I_{sc}	10.59	10.04	13.40
V_{mp}	40.78	33.47	39.00
I_{mp}	9.82	9.56	12.82
P_{max}	400	320	500

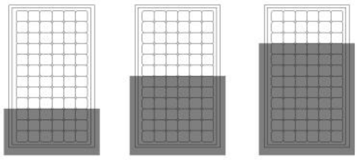
Three patterns of shading experiments, namely, horizontal, vertical, and diagonal, was conducted with shading percentage of 0%, 25%, 50%, and 75% which was presented in Fig. 1. Surface of the PV module was covered with a thick material that completely block the sunlight from reaching the module. I-V and P-V measurement was recorded for each experiment using a portable PV power meter (SEAWARD PV200). The PV200 is a portable and multifunctional PV power meter that can determine various measurements such as maximum power point (P_{max}), maximum power voltage (V_{mp}), maximum power current (I_{mp}), open circuit voltage (V_{oc}), and short circuit current (I_{sc}), as well as plot the I-V and P-V curves of the PV module.

(a) No shading

(b) Horizontal shading pattern

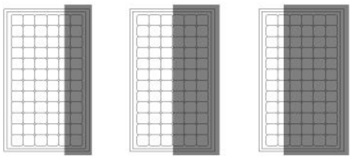


0%



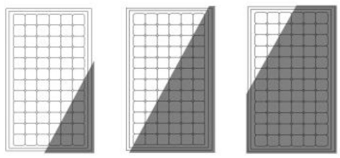
25% 50% 75%

(c) Vertical shading pattern



25% 50% 75%

(d) Diagonal shading pattern



25% 50% 75%

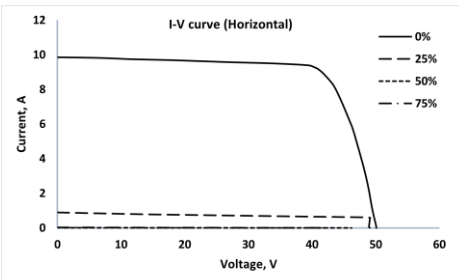
Fig. 1. Three different shading patterns (a) horizontal, (b) vertical, and (c) diagonal, with percentage of shading (i) 25%, (ii) 50%, and (iii) 75%

4. RESULTS AND DISCUSSION

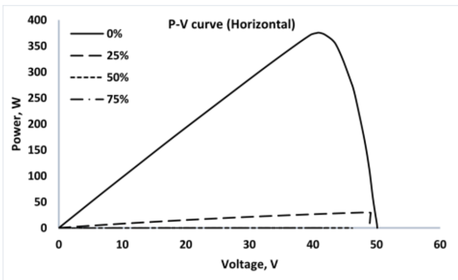
Evaluation on the performance (current, voltage, and maximum power) of the PV modules, together with its electrical characteristics (current-voltage (I-V) and power-voltage (P-V) curves) was successfully conducted under different shading patterns and percentages. Fig. 2 illustrates the I-V and P-V curve of the Full-Cell PV module under horizontal, vertical, and diagonal shading pattern; with no shading (0%), and shading percentage of 25%, 50%, and 75%.

(a) Horizontal shading pattern

(i) I-V curve

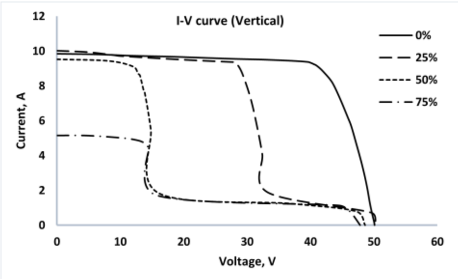


(ii) P-V curve

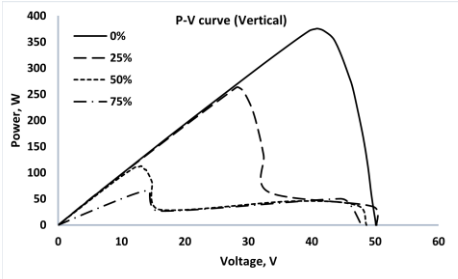


(b) Vertical shading pattern

(i) I-V curve

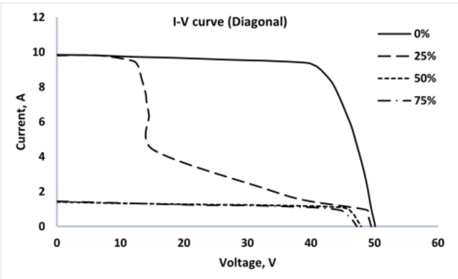


(ii) P-V curve



(c) Diagonal shading pattern

(i) I-V curve



(ii) P-V curve

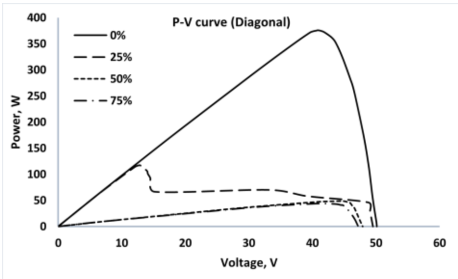


Fig. 2. The (i) I-V and (ii) P-V curve of the Full Cell PV module under (a) horizontal, (b) vertical, and (c) diagonal shading pattern; with no shading (0%), and shading percentage of 25%, 50%, and 75%

A Full Cell PV module consists of cells that are electrically connected in series. Based on Fig. 2, the curves indicate that the Full Cell PV module's performance was exceptionally high when there was no shading on its surface. When the module was not exposed to shading (0% shading), the maximum power (P_{max}) output value measured at 1044 W/m^2 was approximately 376 W. This value was compared to the $P_{max\ STC}$ value provided by the manufacturer under standard test conditions (STC), which was 400 W. Therefore, about 6% of the output difference between the measured P_{max} (376 W) and the STC-provided value (400 W). The power drop of the module could happen due to the internal functioning of the module such as temperature, irradiance, aging, module efficiency or cell defects. The most substantial decrease in performance was observed when the PV module was subjected to a horizontal shading pattern with shading percentage of 25%, 50%, and 75% (Fig. 2a). The shading percentage caused the measured P_{max} value to drop significantly, almost reaching zero (30 - 0 W). According to Fig. 2b, when the PV module was subjected to a vertical shading pattern, it was observed that the measured P_{max} of the module decreased consistently as the shading percentage increased. From Fig. 4c, the diagonal shading pattern shows that the power output of the module reduced to minority of measured values for 50% and 75% shading percentage.

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Commented [KWMJ2R1]: All curves are for Full-Cell PV module? Shading pattern - horizontal, vertical, and diagonal.

Commented [KWMJ3R1]: Some of the lines are not visible, i.e. for horizontal, only 0% and 25% are truly visible, while 50% and 75% are not that visible.
Suggestion - can provide a zoom version either somewhere in the curve/supplementary

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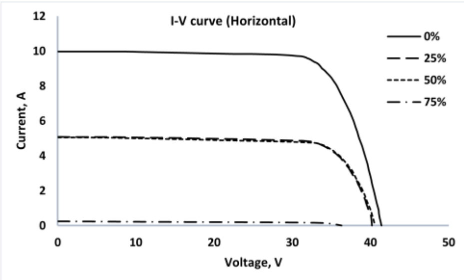
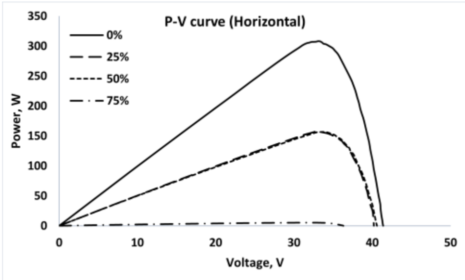
(a) Horizontal shading pattern

(i) I-V curve

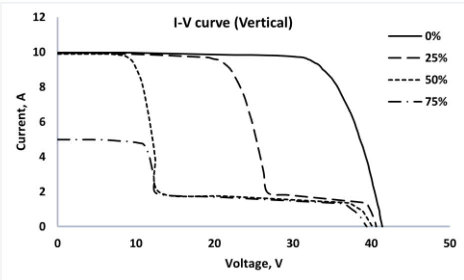


(ii) P-V curve

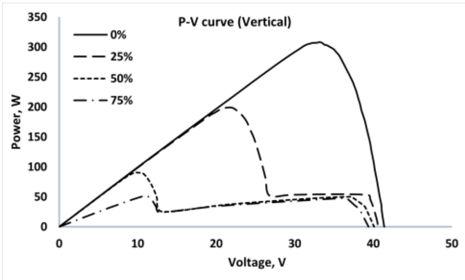


(b) Vertical shading pattern

(j) I-V curve

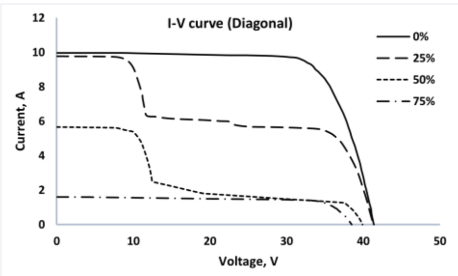


(ii) P-V curve



(c) Diagonal shading pattern

(i) I-V curve



(ii) P-V curve

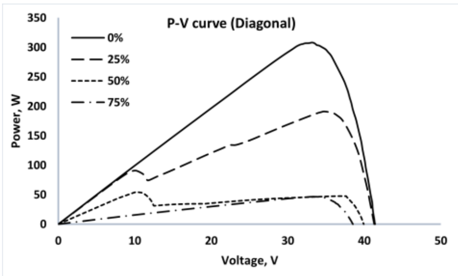
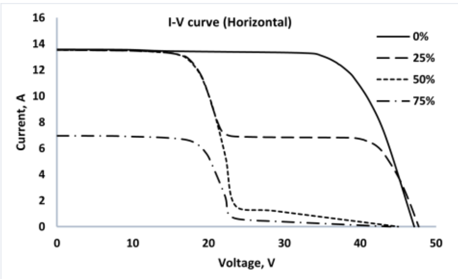


Fig. 3. I-V and P-V characteristics of Half-Cut PV module under horizontal, vertical, and diagonal shading pattern

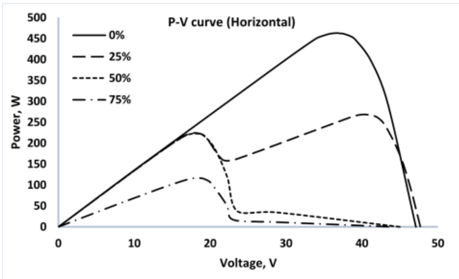
Fig. 3 presents the I-V and P-V curve of the Half-Cut PV module under horizontal, vertical, and diagonal shading pattern; with no shading (0%), and shading percentage of 25%, 50%, and 75%. A Half-Cut PV module is a module that is manufactured by creating two half sections that are electrically connected in parallel and the cells for each section are connected in series. As depicted from the I-V and P-V curves in Fig. 3, reduction of the power output of the module is highly influenced by the shading when both sections of the module were shaded. When there was no shading (0% shading), the Half-Cut PV module produced a P_{max} of about 308 W while being exposed to an irradiance level of 915 W/m^2. The manufacturer's specified $P_{max\ STC}$ value was 320 W, which indicates an output difference of about 4% when compared to the measured value. When the Half-Cut PV module is 75% shaded in horizontal pattern (Fig. 3a), the most significant performance degradation was observed, with a measured P_{max} value at 5 W. Under both vertical (Fig. 3b (ii)) and diagonal (Fig. 3c (ii)) shading patterns, the power output of the Half-Cut PV module decreases significantly as the percentage of shading increases, particularly when both sections of the module were shaded. The power losses increase from 72% to 85% for shading percentages of 50% and 75%.

(a) Horizontal shading pattern

(i) I-V curve

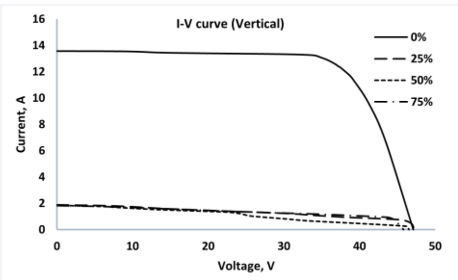


(ii) P-V curve

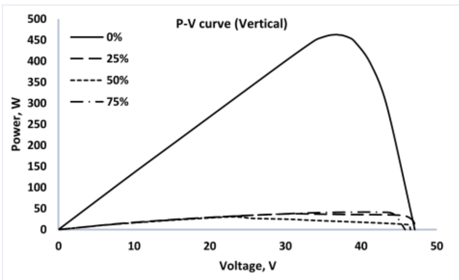


(b) Vertical shading pattern

(k) I-V curve

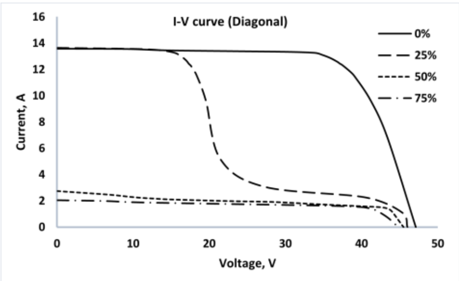


(ii) P-V curve



(c) Diagonal shading pattern

(i) I-V curve



(ii) P-V curve

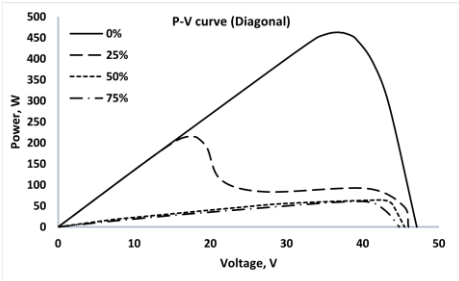


Fig. 4. I-V and P-V characteristics of Shingle PV module under horizontal, vertical, and diagonal shading pattern

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Fig. 4 presents the I-V and P-V curve of the Shingle PV module under horizontal, vertical, and diagonal shading pattern; with no shading (0%), and shading percentage of 25%, 50%, and 75%. In the absence of any shading (0% shading), the measured P_{max} value of the Shingle PV module was found to be 464 W when it was exposed to an irradiance level of 993 W/m2. This value is 7% less than the $P_{max\ STC}$ value of 500 W that was specified by the manufacturer. The highest performance degradation of the Shingle PV module was observed when it was exposed to shading in a vertical pattern (Fig. 4b (ii)), resulting in an output reduction of 92% to 94% compared to when there was no shading. The power output of the module significantly decreases when the shading percentage increases from 50% to 75% as indicated by the P-V curves of horizontal (Fig. 4a (ii)) and diagonal (Fig. 4c (ii)) shaded pattern, with more than 50% reduction in power output.

Another important inference noticed from the I-V and P-V curves between all PV modules, Full-Cell (Fig. 4), Half-Cut (Fig. 5), and Shingle (Fig. 6) are some of the curves have multiple peaks which is known as global and local maximum power point. Global maximum power point (GMPP) refers to the highest point on the curve, which represents the highest power output that the module can produce [20]. On the other hand, the local maximum power point (LMPP) refers to the maximum power output that the module can produce under a specific operating condition, such as temperature and irradiance levels [20].

5. CONCLUSION

Performance of a PV module depends on the specific design and configuration of the module, as well as the conditions under which the module is operated. It is not possible to determine which type of PV module, Full Cell, Half-Cut, or Shingle, is "better" overall, as the performance of each type of module can vary depending on the specific design and configuration. However, one way to maximize the power output of a PV module is to study the shading effects in multiple patterns and determine the best way to install the module to minimize shading. This can involve analyzing the shading patterns at the site where the PV system will be installed, taking into account factors such as the orientation of the module, the position of the sun at different times of the day, and the presence of any objects that may block the sunlight from reaching the module. In the context of Full Cell PV module, the shading pattern and percentage that leads to minimal performance dropped was vertical shading pattern with 25% shading percentage**.** On the other hand, for Half-Cut PV module, both vertical and diagonal shading patterns with 25% shading percentage led to minimal performance drops. As for Shingle PV module, horizontal shading pattern with shading percentage of 25% was found to cause the least performance reduction. These findings highlight the impact of shading on the efficiency of different module types and provide insights for optimizing the power output. Shading effect on a PV module evidently influences the performance of the module. Maximization on the power output of the PV modules can be achieved by determining the best position to install the module with minimal shading.

Commented [KWMJ7]: Conclusion should include what is the findings. With no shading (0%) or minimal shading (25%), the value of Pmax was similar to the Pmax STC. In comparison, with shading (50% and 75%), Pmax significantly decreases. Hence, the shading effect on the PV module affected the overall performance of the module.

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Commented [KWMJ9R7]: Maybe can compare which pattern and which percentage leads to minimal performance dropped

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