Solar Energy Systems

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Abstract

Different variables affect the maximum output power and electrical conversion efficiencies of photovoltaic solar panels. In this experiment, the tilting, shading, and temperature of photovoltaic solar panels were examined in order to observe how each altered the maximum output power and efficiency levels. It was determined that the solar panel exhibited its highest value of irradiance and maximum power output at a tilt angle of 50° with a zenith angle of approximately 45.5°. With respect to shading of the PV solar panel, an increase in vertical shading resulted in a decrease in current and demonstrated a nonlinear relationship to power output and a decrease in efficiency due to the panel's inability to convert DC power to AC power. On the other hand, an increase in horizontal shading lead to a decrease in voltage and demonstrated a more direct linear relationship to power output as well as a higher efficiency in comparison to vertical shading. The temperature of the PV panel varied due to diffuse solar irradiance. As the initial irradiance of 765.0 W/m^2 increased to 823.3 W/m^2, the efficiency of the PV panel decreased by 7.71% from its initial efficiency of 0.04%. This demonstrated that when irradiance increased, the panel temperature will also increase which will result in a decrease in the panel's efficiency. In general, it is vital to analyze the variables that may affect the efficiency of photovoltaic solar panels in order to optimize design and location with respect to implementation at either commercial, residential, or utility levels.

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Introduction

Around the world, there is a movement towards renewable energy. As developing countries are growing and develop countries are looking to reduce their greenhouse gas emissions, solar energy is becoming a popular alternative to traditional energy sources. Currently there are two main methods to produce electricity and heat from solar energy: photovoltaics (PV) and solar thermal.[1] The PV method utilizes panels made of semiconductor wafers to convert solar energy to electricity. When light shines on a PV cell, it may be transmitted, absorbed, or reflected. When the light is absorbed the photons from the sun excite the electrons in the semiconductors causing them to move to a higher state and produce an electrical current.[2] However, due to the semiconductor only reacting to absorbed sunlight, PV cells cannot be 100% efficient. In fact, the market average PV cell has an efficiency of 12-18%.[3]

As the demand for renewable energy grows, there must be an understanding of the performance characteristics of PV cells. Other than the material of the semiconductor, there are several factors that influence the PV output. These include seasonal sun angle changes, atmospheric effects, and panel orientation. Factors that influence the DC conversion are shading and panel temperature.[4] In order to understand to what extent these influence the performance of the PV panel, two different panels (Unisolar and Kyocera) were tested at various tilt angles. Next, one panel was placed flat and used to analyze to effects of shading. Finally, the effect of temperature was tested by covering the panel with ice and letting the panel temperature stabilize. Using the results from these tests parameters, conditions can be set to optimize the power output and therefore efficiently implement PV panels for commercial and domestic use.

Theory

Solar PV was directed in this lab through manipulating the following factors: Tilt Angle, Shade, and Temperature. Our first method of altering the photovoltaic panel's performance was through tilting.

Tilt Angle

Earth receives its energy from the sun via solar irradiance. This is measured as two different variables, diffused horizontal irradiance [DHI] and direct normal irradiance [DNI]. DNI is the energy directly from the sun per unit area while DHI is the horizontal irradiance that has been diffused by the atmosphere. In order to find the total radiation the Earth obtains from the sun, global horizontal irradiance [GHI], the sum of DHI and DNI must be taken.

A solar panel's maximum input of irradiance comes when it is perpendicular to the incoming solar irradiance. This maximum value is characterized by the Solar Zenith Angle [α_0]. The Zenith Angle is measured when the absolute center of the sun's disc is perpendicular to the solar panel, which is found through tilting. In all, we calculate GHI by the following:

$$GHI = DNI + DHI * \cos(\alpha 0) * \tau \qquad (1)$$

τ is defined as atmospheric transmissivity which is the ratio between incoming and outgoing light. Since solar irradiance is a max when $\alpha_0 = 90$, it is shown that GHI can be maximized or minimized by the tilting of the panel.

Shading

Power generated by the PV panel is defined as:

$$P = V * I \qquad (2)$$

V is the voltage and I is the current. When V = 0, a short circuit current occurs [I_{SC}]. This is the maximum current. Maximum voltage [V_{OC}] occurs when I = 0. Because of this, the maximum power point occurs when the voltage and the current are both at a max.

When portions of the panel are shaded, the expected power output of the panel P_{shade} is found through finding the average irradiance:

$$Ir_{avg} = (A_{us}/A_T)(Ir_{us}) + (A_s/A_T)(Ir_s) \quad (3)$$

Where Ir_{avg} is the average irradiance, A_{us} is the area unshaded and A_s is the area shaded. Now that average irradiance is determined, P_s can be solved.

$$P_s = (P_{us})(\frac{Ir_{avg}}{Ir_{us}}) \quad (4)$$

Solar panels utilize inverters to output the optimal voltage for power. This is problematic when the PV panel is shaded. When shaded, only the diffusive irradiance is able to reach the panel where the inverter struggles to choose the optimal voltage across the covered and the uncovered cells. This causes a loss in power that is much greater than the loss dedicated to simply the covering of the cells. Because voltage and current share a linear relationship, there is a greater loss when the unshaded cells are in series versus parallel. This is because of the increase in resistance across the shaded cells which greatly reduces the current.

Temperature

The efficiency of the PV panels increases at lower temperatures and decreases as the temperatures rise. The open current voltage is most affected by the rising temperature whereas the current is only slightly increased. From equation 2, power decrease will coincide with the decrease in voltage. Overall, as temperature increases, power output decreases. However, cooling the physical temperature of the panel will increase the output of power.

Experimental Procedure

In order to maximize results, a open spot in full sunlight was chosen in the center of EBU2. The first week of the lab used two solar panels, the Kyocera and the Unisolar. They were placed next to each other on the wooden tilt board next to MP-170 in the powered off mode. Then, the leads (black and red) were connected to the wires on the panel and the ports of the MP-170. Thermocouples were then attached to the proper ports Temp 1 and Temp 2, and on the backside of the Sensor Unit. Thermocouple, Temp 1 was connected to the back of the panel with conductive tape while Temp 2 was kept in the shade and away from the other equipment. Next, connect the MP-170 to the Sensor Unit via the RS-485 cable. Finally, the Sensor unit was placed on a level surface in range of the PV panel. Now that the system is wire, it was time to orient it to the panel to 0 tilt. This was done by removing the shadow level from the Sensor Unit and placing it on top of the PV panel. At this point, you must record the location of the shadow's dot on the instrument for calculating the Zenith Angle. After data is recorded, remove the shadow level and replace it on the Sensor Unit.

Now that the system is set up accordingly, it is time to power on the devices. First the Sensor Unit is powered on, followed by the MP-170. On the MP-170 hit "config" on the home screen of the device. Then, press "measpar" and "enter". Next, highlight the "select" option and once again hit "enter" button. Based on the brand of PV panel, highlight the measurement protocol from the "parameter list" and press "enter". For accurate data to the time and day, select "config" then highlight "system" and press enter. Here you can set "date & time set" to enter to correct information. It is also important to erase previous data from past groups. From the home screen, hit "data" and then "erase. In order to take measurements, from the home screen press "measure". Once the device is done reading, use the right and left arrow keys to scroll through the data and ensure that data is saved after each measurement. These steps were repeated at both 0 and 30 degrees.

While repeating just the measurement steps, more data was taken at 10, 20, 40, 50, and 60 degree tilt angles as follows:

(1,1) (2,1)	(1,2) (2,2)
(3,1)	(3,2)
⋮	⋮
(11,1)	(11,2)

Figure 1: Solar Panel Matrix Layout

The next test used the 10W Unisolar PV panel on a flat surface, and the same general procedure for operation and measurement with the MP-170. Once set up, take one measurement to test if the set up is correct. Fill a cooler with ice and all of the plastic bags in order to cover the entire surface of the PV panel. Wait 10-15 minutes for the panel to fully cool. Then remove the ice and place back in the cooler and begin taking measurements with the MP-170 as frequently as the program allows. Continue taking measurements until the panel reaches a steady state temperature. Repeat these steps to get two complete sets of data. Make sure to wait 10-15 minutes between tests to allow the PV reset.

Results

Week 1 - PV performance and Tilt

The first part of the experiment involves observing the direct correlation between tilt angle and the amount of power generated. When increasing the tilt angle, the panel receives a larger amount of solar irradiance causing the current to increase at a given voltage. As seen in Figure 2, the highest curves are Unisolar at 30 degree tilt angle and Kyocera at 30 degree angle. Given to the position of the I-V curve at the same tilt degree, the Unisolar solar panel seems to be more efficient than the Kyocera solar panel.

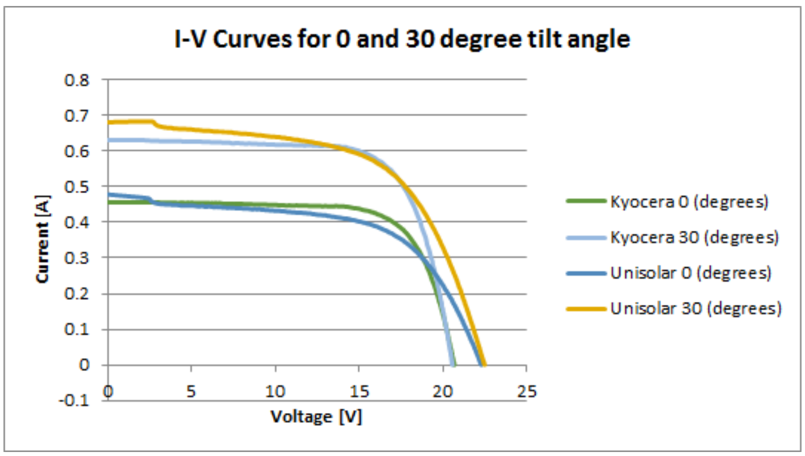


Figure 2: I-V Curves at 0 and 30 degree tilt angle for Unisolar and Kyocera Model Panels

This correlation between the tilt angle and the resulting increase of current is further analyzed with angles ranging from 0° to 60° tilt angle for the Kyocera model. As seen in Figure 3, the graph shows a general positive linear relationship, ranging from 0.457 to 0.712 Amp, which indicates that the short circuit current increases as the tilt angle increases.

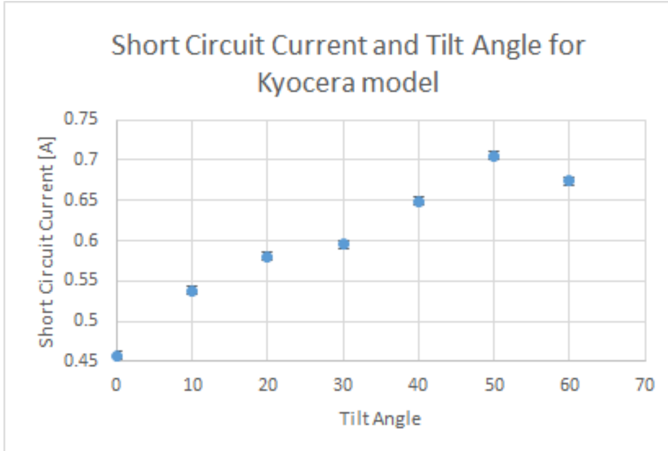


Figure 3: Short Circuit Current as a function of the tilt Angle for Kyocera Solar Panel.

On the other hand, the relationship between the open circuit voltage and tilt angle shows otherwise, another relationship. The data shows a negative linear relationship ranging from 20.7 V at a 10 degree tilt angle to the 20.2 V at a 60 degree tilt angle.

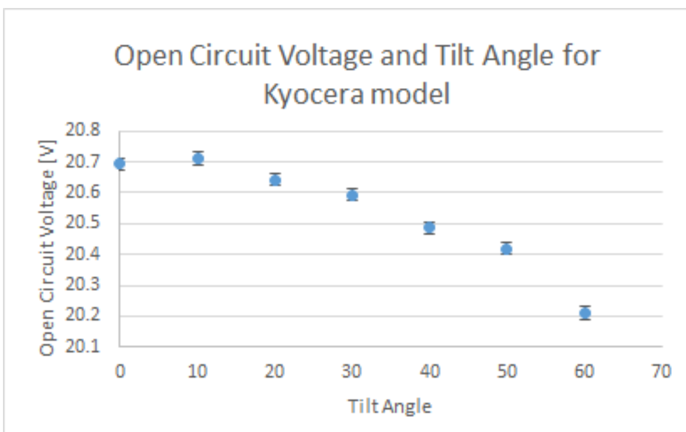
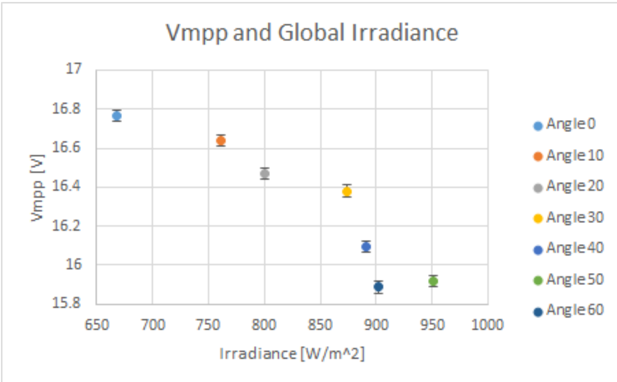


Figure 4: Open Circuit Voltage as a function of tilt angle for Kyocera Solar Panel

The voltage at the maximum power point in Figure 6 shows a similar negative linear relationship with a trend line of y = -0.0033x + 19.068. As seen in Figure 5, the highest maximum power point voltage is 16.77 ± 0.01 V at the 0 degree tilt angle, where it has a low value irradiance of 668.1 ± 1.0 W/m^2 and the lowest maximum power point voltage is 15.89 ± 0.01 V at the 0 degree tilt angle, where it has an irradiance of 901.4 ± 1.0 W/m^2.



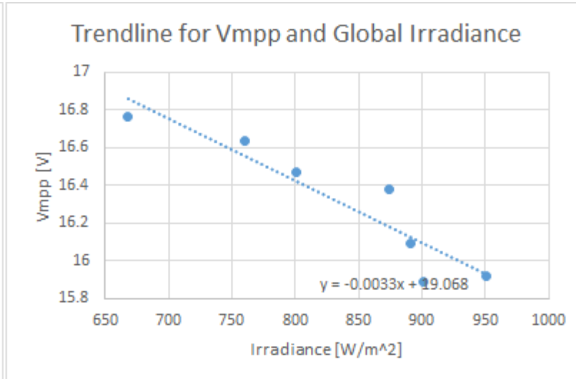
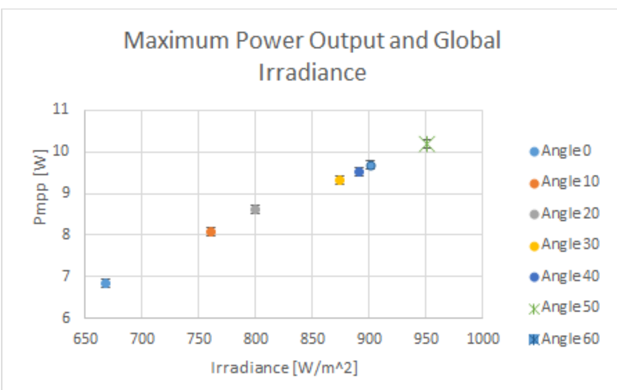


Figure 5: Maximum power point voltage as a function of tilt angle for Kyocera Panel

Figure 6: Trend line for the maximum power point voltage as a function of tilt angle for Kyocera Panel

As seen in Figure 7 and 8, the maximum power point power output shows a strong positive linear relationship with a trend line of y = 0.0117x - 0.8561. The data points are relatively precise and follow the trend line closely. The lowest maximum power point power output was 6.86 W at 0 degree angles and the highest maximum power point power output was 10.20 W at 50 degree angle. This indicates that the power output is more correlated with the irradiance rather than the tilt angle.



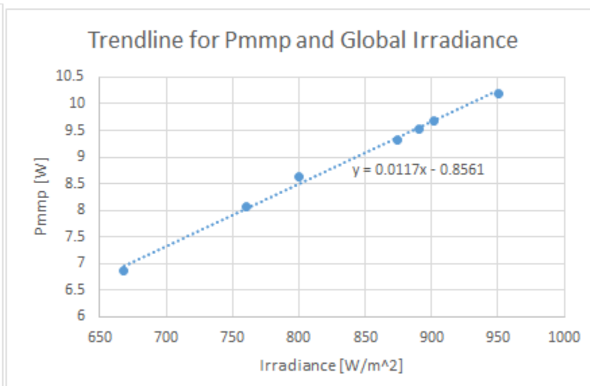


Figure 7: Maximum power point power output as a function of tilt angle for Kyocera Panel

Figure 8: Trendline for the maximum power point power point output as a function of tilt angle for Kyocera Panel

Week 2- Effect of Shading on the PV Panel Performance

The second part of the experiment explores the effects of shading on the performance of the PV panel. As expected the performance decreases as the shading area increases. Figure 9, shows the effect of shading area on a half side of the Unisolar model solar model. The baseline, which meant no cells shaded, the 1 cell shaded and the 3 cells shaded have very close short circuit current around 0.63 Amps, and as the amount of shaded cells increases, the short circuit current decreases. Nevertheless, the curves decrease at different voltages and rates for each shaded cell. As the shaded cells increases, the curves exhibit a sharper drop at lower voltages, until it reaches to 9-11 cells shaded, where the drop reaches a plateau and the performance has reached minimum efficiency, given that that only half of the area is shaded.

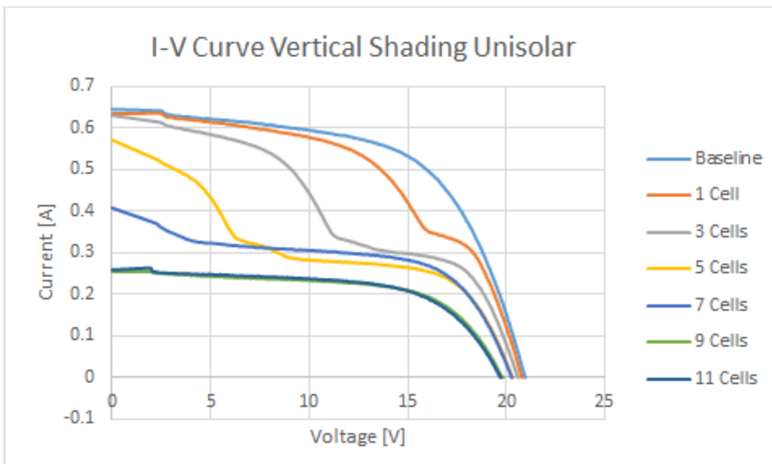


Figure 9: I-V Curve for Vertically Shaded areas on the Unisolar Panel

Similarly, when horizontally shading the area, as seen in Figure 10, the curves drop at a sharper angle and at a lower voltage as the shading area increases. The curves show a ladder like drop with the baseline having one step and the rest of the curves with two steps, each reaching 0 Amp current at a lower voltage as the number of shaded cells increases.

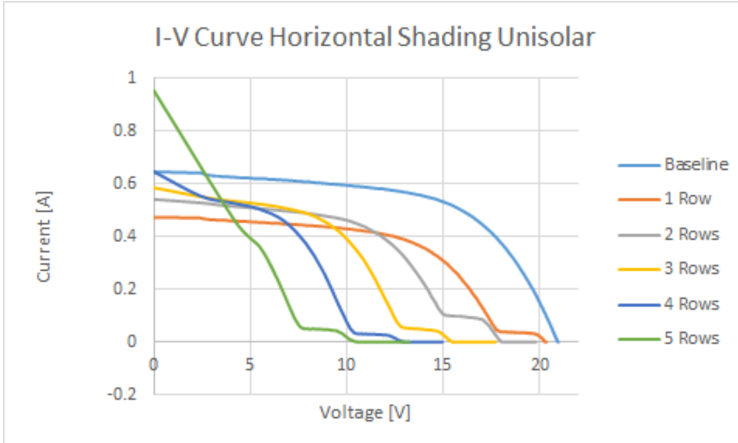


Figure 10: I-V Curve for Horizontally Shaded areas on the Unisolar Panel

The vertically shaded panel power output as a function of the voltage load in Figure 11 shows a trend similar to its respective I-V curve in which the curve shows a sharp drop at some point of the curve before it resumes to decrease as the voltage increases. The drop happens at earlier voltages as the amount of shaded cells increases. At "7, 9 and 11 cells shaded," there is no initial drop, but it appears to be a shape similar to the baseline with a much lower power output. The highest maximum power output was 8.03 ± 0.1 W at the baseline and the lowest maximum power output was 3.13 ± 0.1 W when 5 rows are shaded.

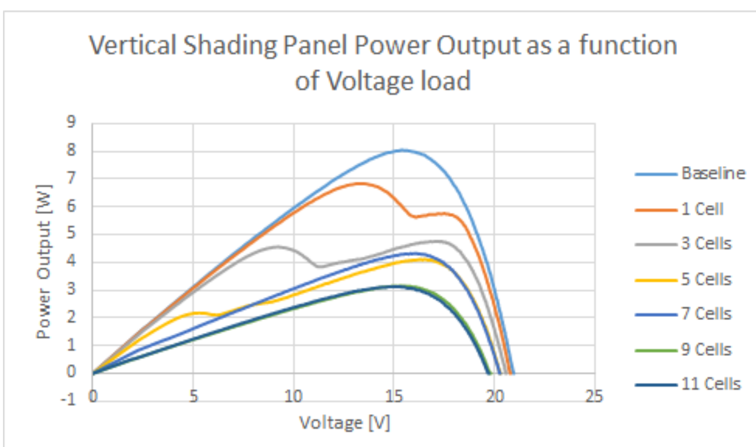


Figure 11: Power Output of Vertically Shaded areas as a function of Voltage on the Unisolar Panel

The horizontally shaded panel shows a different pattern. As seen in Figure 12, although the power output still shows a general decrease in relation to the increase of shaded area, the maximum power output shows a more visible and positive linear relationship. At more shaded areas the maximum power output happens at a lower voltage than when the panel is not shaded. Furthermore, the curves still show the "ladder" trend mentioned before in its respective I-V curve. The highest power output, 8.03 ± 0.1 W, occurs at the baseline and the lowest power output, 3.12 ± 0.1 W at "5 rows shaded."

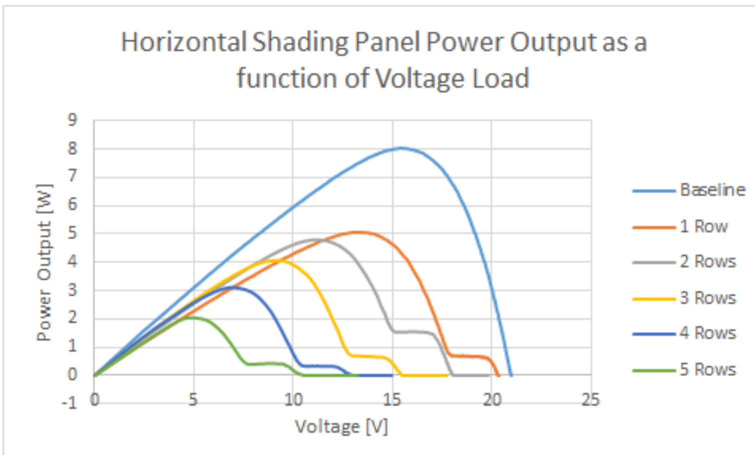


Figure 12: Power Output of Horizontally Shaded areas as a function of Voltage on the Unisolar Panel

Figure 13 shows the relation between the maximum point power output to the ratio of shaded area. As expected, both the horizontally and vertically shaded area show a decrease of maximum point power output as the ratio of shaded area increases. Nevertheless, the horizontally shaded areas show a slightly steeper decrease than the vertically shaded. The linear relationships and least square regressions of both vertically shaded and horizontally shaded are $y= -9.1434x + 7.0435$ with an R^2 of 0.8404 and $y = -10.42x + 7.1323$ with an R^2 of 0.9065.

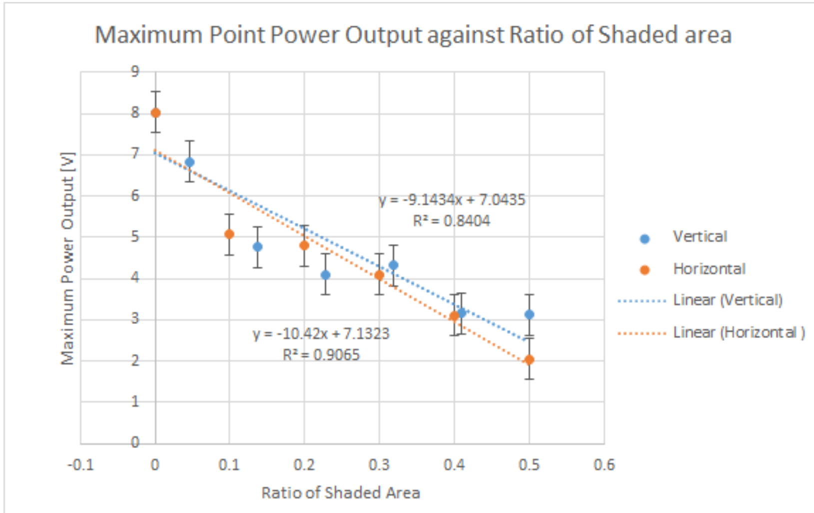


Figure 13: Power Output at Maximum Power Point as a function of Shaded Area Ratio for Unisolar Solar Panel.

Similarly, to Figure 13, Figure 14 shows a negative linear relationship between the conversion efficiency and the shaded area ratio. Therefore, as the ratio of shaded area increases, the conversion decreases. The horizontally shaded area still show a steeper decrease than the vertically shaded area. The linear relationships and least square regressions of both vertically shaded and horizontally shaded are y = -0.0615x + 7.0435 with a R^2 of 0.7806, and y= -0.0974x + 0.067 with a R^2 of 0.9968.

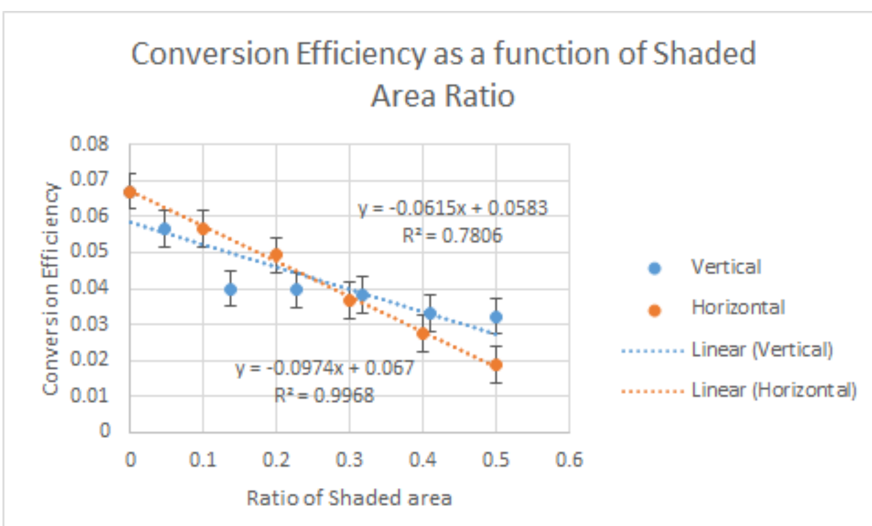


Figure 14: Conversion Efficiency as a function of Shaded Area Ratio for Unisolar Solar Panel.

Week 3- Effect of Temperature on PV Panel Performance

The third part of the experiment involves observing the effect of temperature on the panel performance. Figure 15 shows the relationship between the electrical conversion efficiency and the panel temperature where up until 10□ shows very low conversion efficiency of around 0.04%, after 10□ the data points increase up to 7.75% efficiency. The linear trend line was y = 0.1399x + 1.1822 with a least-square regression of 0.5332. However, while exploring other models, the most fitting one was the polynomial trend line, as seen in Figure 16, which gave y = -0.0095x^2 + 0.6199x - 2.2818 with a least-square regression of 0.8298. Therefore, once it has reached around cutting point, about 10□ , the efficiency starts decreasing. Looking at the GHI labels, the two sets of measurements have different values of GHI with an average of 823.3 ± 0.1 W/m^2and 765.0 ± 0.1 W/m^2 for the respective measurements.

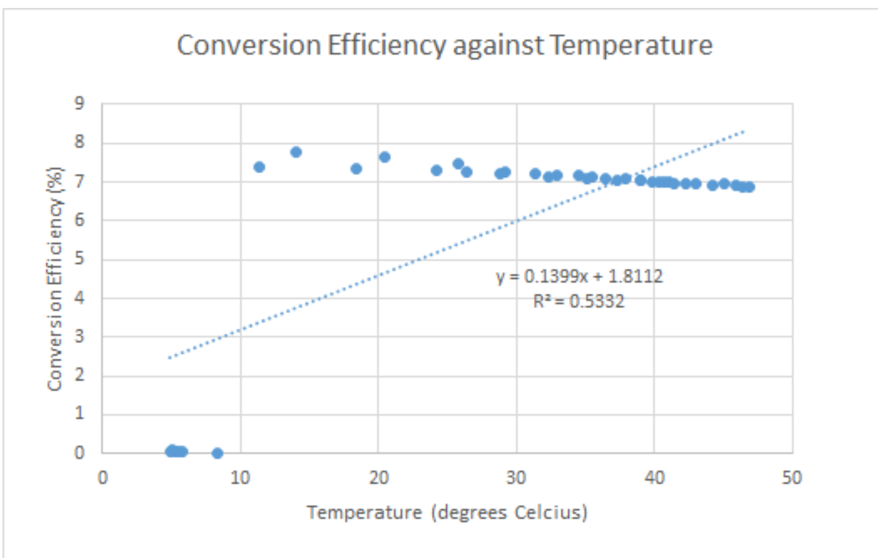


Figure 15: Electrical Conversion Efficiency as a Function of Panel Temperature of Unisolar Solar Panel

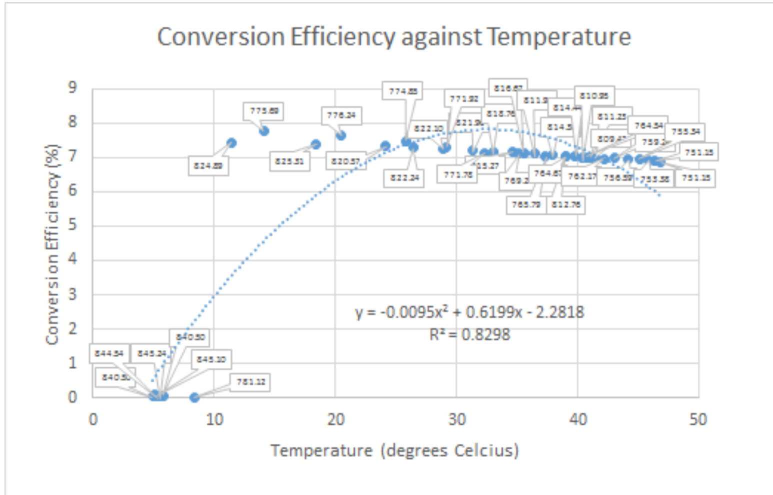


Figure 16: Electrical Conversion Efficiency as a Function of Panel Temperature of Unisolar Solar Panel with GHI labels and Polynomial fitting.

Similarly, Figure 17 shows the relationship between the maximum point power output and the panel temperature where, up until the 10□ cutting point shows very low maximum power point power output of about 0.06 W , after 10□ the data points increase up to 9.30 ± 0.01 W. The linear trend line was y = 0.163x + 2.3536 with a least-square regression of 0.4928. When fitting it into a polynomial trend line, as seen in Figure 18, it gave the relationship y = -0.0123x^2 + 0.7854x - 2.9549 with a least-square regression of 0.8328. Therefore, once it has reached around cutting point, about 10□ , the power output at maximum power point starts decreasing as the panel temperature increases.

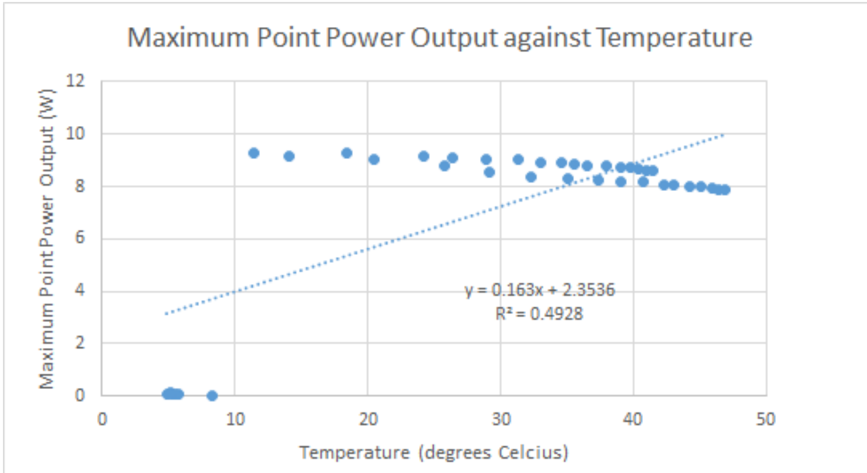


Figure 17: Power Output at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel

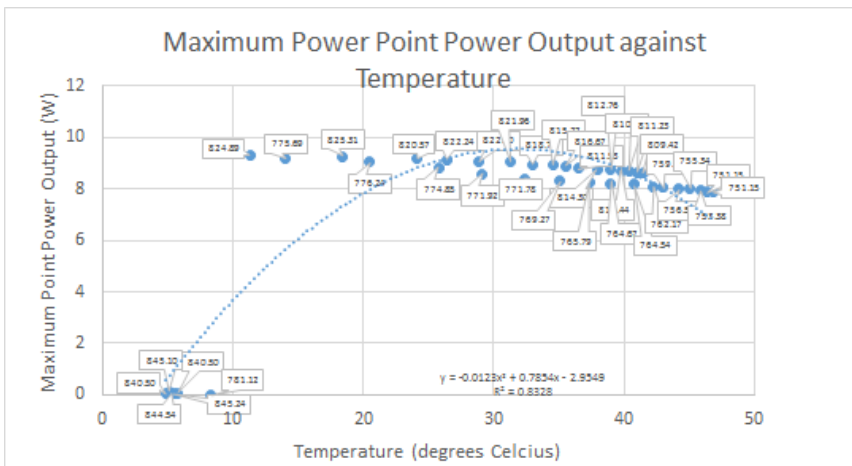


Figure 18: Power Output at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel with GHI labels and Polynomial fitting.

The voltage at the maximum power point from both measurements in Figure 19 exerts a similar trend to the previous graphs, nevertheless one can argue that the relationship looks closer to an I-V curve. The polynomial trend line is y = -0.0124x^2 + 0.7917x + 4.4285 with the least-square regression of 0.6066. The curve reaches its highest point at 14.06℃ with Vmpp of 17.32 ± 0.01 V and the voltage decreases as the temperature increases. When looking for the voltage temperature coefficient, in order to acquire a precise result, the linear trend line was found without including the outliers before the 10□ , as seen in Figure 20. The resulting voltage-temperature was -0.0533 V/□ .

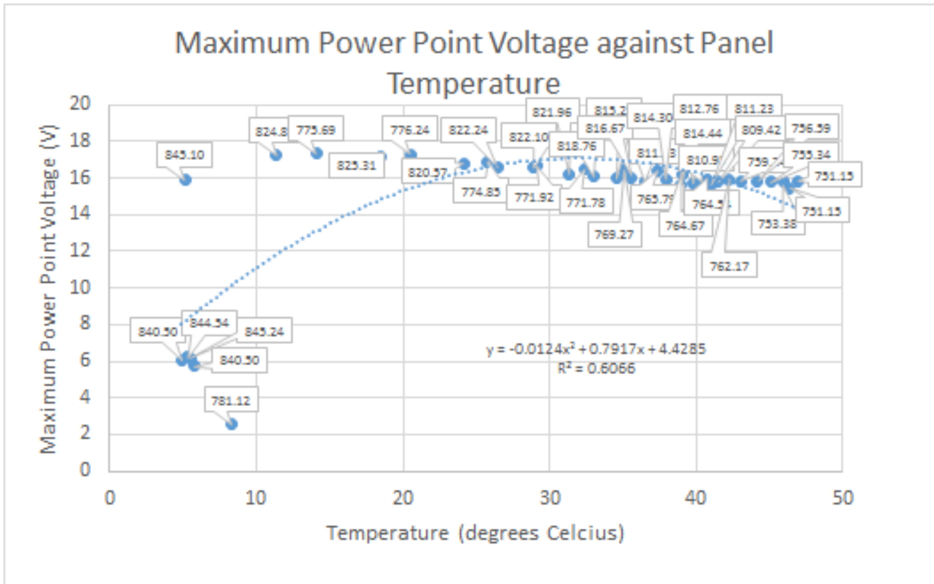


Figure 19: Voltage at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel with GHI labels and Polynomial fitting.

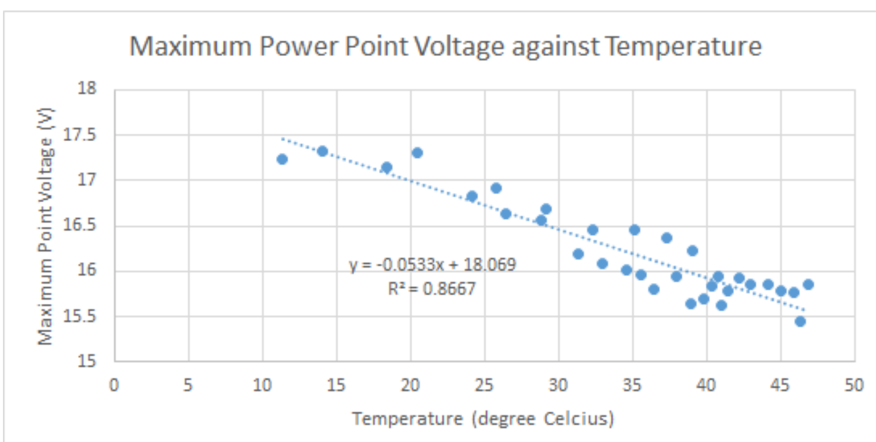


Figure 20: Voltage at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel and linear fitting without outliers.

The current at the maximum power point as a function of panel temperature in Figure 21 exerts a similar relationship to the voltage at the maximum power point as a function of panel temperature. The polynomial trend line is y = -0.0007x^2 + 0.0457x - 0.1706 with the least-square regression of 0.857. The curve reaches its highest point at 14.06□ with Impp of 0.529 ± 0.001 V and the current decreases as the temperature increases. The GHI for both the voltage and current graph fluctuates between the averages of 823.3 ± 0.1 W/m^2 and 765.0 ± 0.1 W/m^2 according to the measurements and are scattered throughout the graph. Nevertheless there is a correlation of decrease of GHI as the temperature rises, the voltage and the current decreases within their respective group sets.

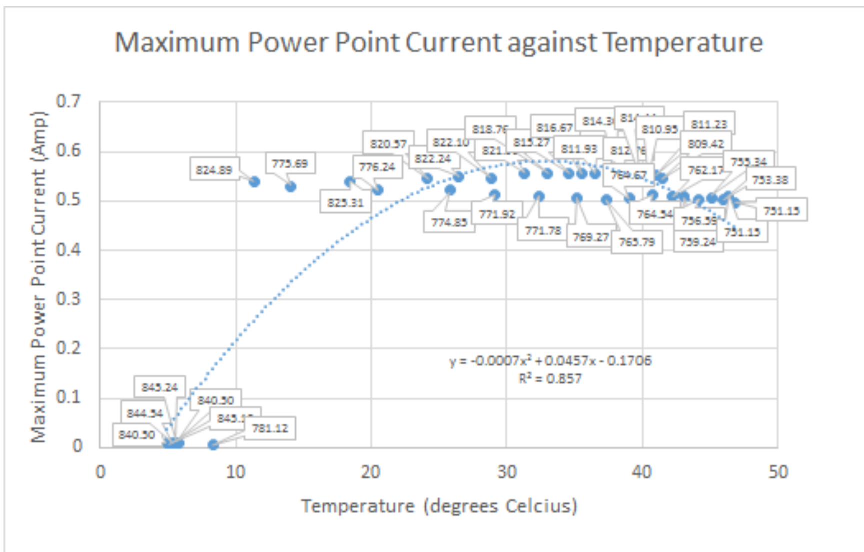


Figure 21: Current at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel and polynomial fitting.

Given the effect of GHI observed from the previous graphs, the two data sets were individually analyzed. As seen in Figure 22, the two measurements show a slight discrepancy between their respective polynomial trends. Nevertheless, the R^2 in the first run is 0.9141 as opposed of the R^2 in the second run, 0.6314. This discrepancy can be further seen when fitting both data sets in a linear trend line without the outliers. As seen in Figure 23, the first run has a trend line of y = 0.0004x - 0.536, while the second run has a trend line of y = -0.0007x + 0.5365. As mentioned before, the average of the GHI for the respective measurements were 823.3 ± 0.1 W/m^2 and 765.0 ± 0.1 W/m^2. Consequently, the ΔGHI was 58.3 ± 0.1 W/m^2. The averages of the maximum power point current were 0.421 ± 0.001 A and 0.480 ± 0.001 A respectively. The ΔI was calculated to be -0.059 A. The linearized Impp to GHI coefficient was -0.00101.

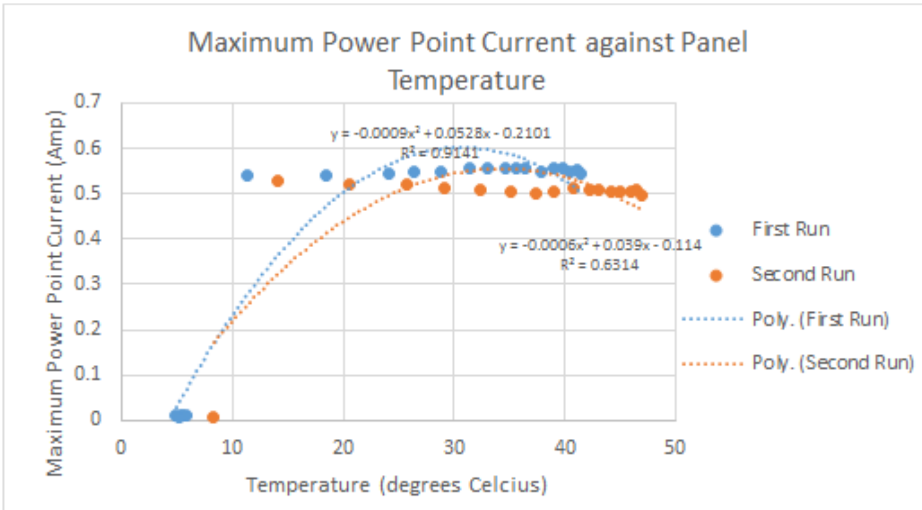


Figure 22: Current at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel and polynomial fitting for First Run and Second Run.

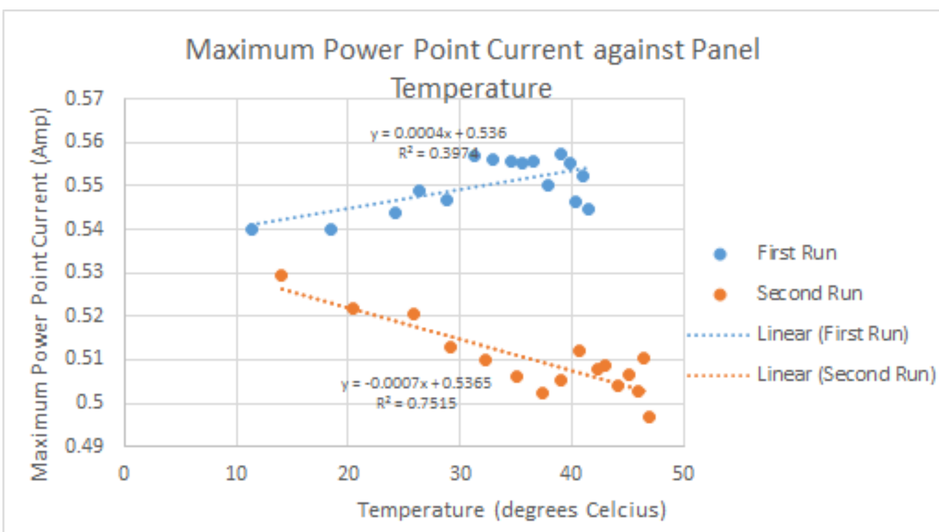


Figure 23: Current at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel and linear fitting without outliers for First Run and Second Run.

A linear trend line was fitted to corrected maximum power point current as a function of panel temperature. The corrected current- temperature coefficient in Figure 24 was 0.0106 A/□ with a R^2 of 0.6088, but when taken the outlier it had a much smaller result of 0.0002A/□ with a R^2 of 0.0438, as seen in Figure 25. Regardless of the higher R^2, Figure 24 already shows fewer variations within the two measurements than in Figure 25.

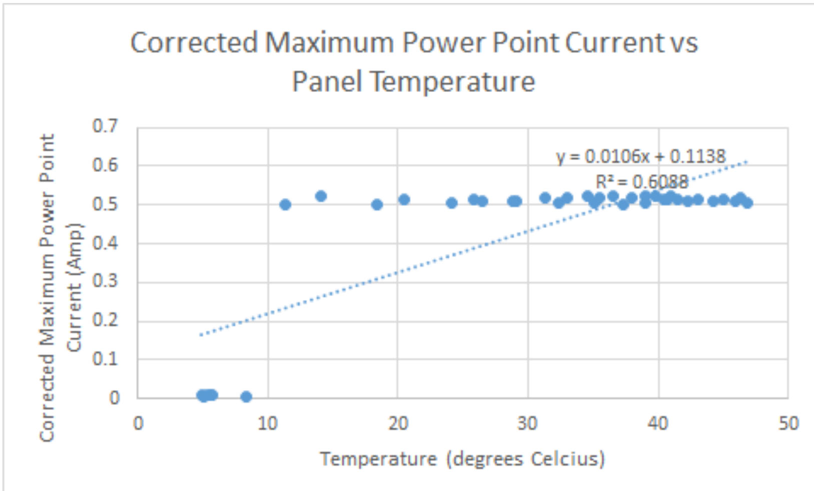


Figure 24: Corrected Current at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel and linear fitting.

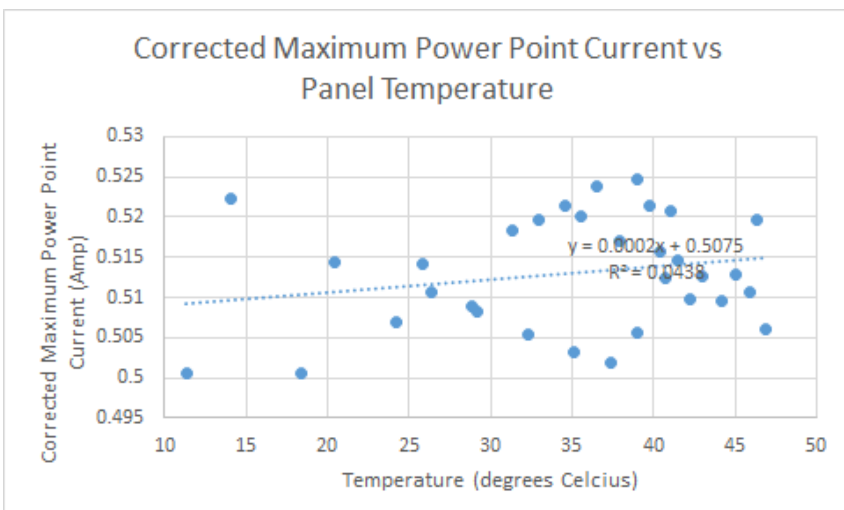


Figure 25: Corrected Current at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel and linear fitting without outliers.

The corrected conversion efficiency as a function of panel temperature shows a very similar trend to the previous graphs. As shown in Figure 26, after the 10□ cutting point, the corrected conversion efficiency decreases as the panel temperature increases. Compared to the non-corrected conversion efficiency as a function of panel temperature graph in Figure 16, the data points look less linear and more divided between the two data sets. Nevertheless, the polynomial fittings, which are $y = -0.0095x^2 + 0.6199x - 2.2818$ and $y = -0.0102x^2 + 0.61465x - 2.2432$ respectively, show great similarity.

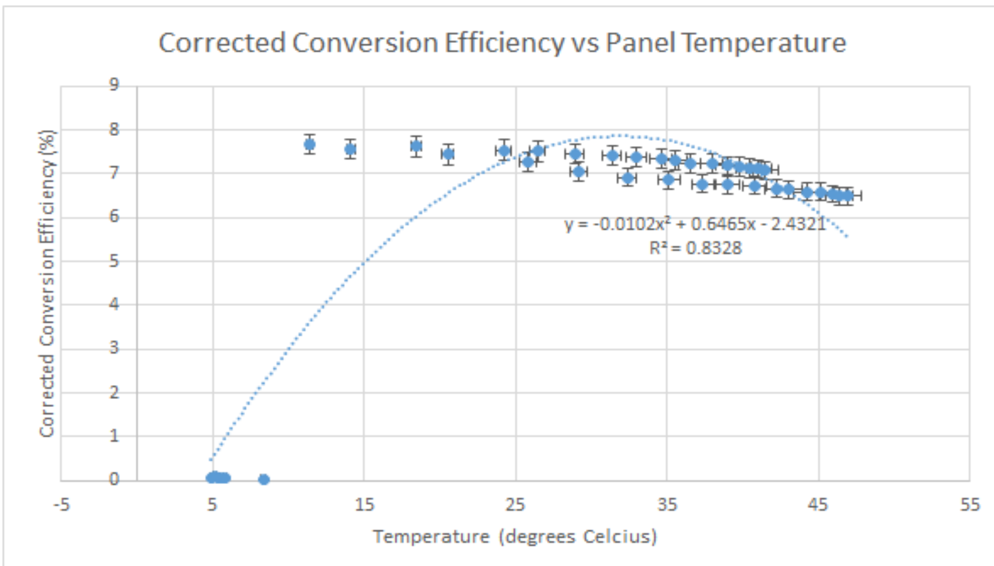


Figure 26: Corrected Electricity Conversion Efficiency at Maximum Power Point as a Function of Panel Temperature of Unisolar Solar Panel and polynomial fitting.

Error Analysis

In this lab, the largest source of random error was a result of weather variations. During repeated samples, varying cloud coverage and random shading resulted in fluctuation in solar irradiance and thus lead to random errors in our data. Additionally, as measurements were taken a considerable amount of time passed between trials resulting in a repositioning of the sun. For example, during the week 3 experiment, the first trial was taken at 12:56pm while the last data point was 1:52pm. This difference in the position of the sun may have also accounted for variances in the data.

As many of the measurements were taken from the MP170, there were uncertainties for the data based on the resolution of the readings. These uncertainties were then carried through the calculations. The voltage-temperature coefficient was calculated to be -0.0533 V/□ , while the rated value was nearly 20 times smaller at -0.0027V/°C. The calculated current-temperature coefficient was 0.0002 A/°C. This is double the rated value of 0.0001 A/°C. As previously mentioned, these higher than expected values may be a result of the climate during the test day. The sunny day would increase the horizontal irradiance causing an increase in the temperature.

The uncertainties in this experiment were calculated from error propagation equation

$$\delta = \sqrt{(\frac{\delta X}{X})^2 + (\frac{\delta Y}{Y})^2}$$

Using this equation, the uncertainty in the corrected current would be found using

$\delta I = I\sqrt{(\frac{\delta P}{P})^2 + (\frac{\delta V}{V})^2}$, where $\frac{\delta P}{P}$ was found using $\frac{\delta P}{P} = \sqrt{(\frac{\delta ETA}{ETA})^2 + (\frac{\delta GHI}{GHI})^2 + (\frac{\delta A}{A})^2}$. The corrected conversion efficiencies were calculated using

$\delta\eta = \eta\sqrt{(\frac{\delta P}{P})^2 + (\frac{\delta ETA}{ETA})^2 + (\frac{\delta GHI}{GHI})^2}$. These calculated uncertainties were then plotted as error bars of each point on the Corrected Conversion Efficiency Vs Panel Temperature Plot.

Discussion

Tilt Angle Discussion

As seen in Figure 2, there is, notably, a minor increase in voltage and a much larger increase in current when the panels were tilted from 0° to 30°. For both the Unisolar and the Kyocera photovoltaic panels, the voltage readings, when tilted at 30°, were measured at slightly below their rated performances. The rated performance, in terms of voltage readings, for the Unisolar photovoltaic panel was 23.8V and the rated performance, also in terms of voltage readings, for the Kyocera photovoltaic panel was 21.7V. Therefore, the Unisolar photovoltaic panel's voltage reading was 12.18% lower than its rated value; while, the Kyocera photovoltaic panel's voltage reading was 12.90% lower. This is within the expected ranges for each panel since there are several factors which could contribute to the relatively small variance between the actual and expected values. Furthermore, also seen in Figure 2, the current values for each panel also fell within their expected ranges. The Unisolar photovoltaic panel's current was rated at 0.78A and the Kyocera photovoltaic panel was rated at 0.62A. The Unisolar reading was 8.98% lower and the Kyocera panel was 4.84% lower than their rated specifications for current. Additionally, the power ratings were evaluated for both panels. The Unisolar panel had a maximum power rating of 10.3W and the Kyocera panel had a maximum power rating of 10.0W. At a tilt of 30°, the Unisolar panel displayed a power rating of 10.58% lower than the rated maximum, while the Kyocera displayed a power rating of 8.87% below its rating. The conclusion was made that the Kyocera panel was more efficient based upon the I-V curves, found in Figure 2. These curves show a similar trend for both panels; moreover, the Kyocera panel occupies 48% less area so it was determined to be the more efficient of the two. Additionally, the maximum power points were analyzed to determine performance differentials between the two panels.

Next, the effects of increasing the tilt angle, from 0° to 60° in increments of 10°, were measured based on the changes in current or voltage. Shown in Figure 3, there is a direct correlation between the short circuit current and the tilt angle for each panel; neglecting some minor outliers. As the tilt angle increases, the panel absorbs increasing irradiance and that results in an increase in temperature. Excited electrons, as a result of the increase in temperature, lead to an increased flow of electrons. As expected, the opposite phenomena occurred when the tilt angle decreased from 30° to 60°; the voltage readings decreased slightly in a linear trendline. This is also related to the excitement of electrons; only this time, the electrons are excited into the ground wire which decreases the voltage drop. There was an observed change in voltage readings between irradiance values, seen in Figure 5, which was noted to be approximately 10%. As expected, the trend line has a negative, linear slope caused primarily by the excitement of electrons as a function of the change in irradiance.

As seen in Figure 7, there is a clear proportionality between increasing power and increasing irradiance; again, neglecting minor outliers. For example, when the Unisolar panel was tilted at 10°, the maximum power output was 6.86W; however, when it was tilted to 50°, the maximum power output was 10.20W. This increase in power as a function of increasing irradiance is actually a result from an increase in current which can be seen in Figure 8; shown by the nearly constant voltage outputs. Again, this clearly demonstrates that an increase in temperature and/or in irradiance results in an increased current, or flow of electrons. Furthermore, from Figure 7, the highest value for irradiance and maximum power output occurs at 50°.

Another method used in determining this angle of maximum irradiance and power output utilizes the zenith angle and the elevation angle equation. A shadow compass was used for this experiment to determine the zenith angle; also, to cross reference the US Department of Commerce's website for the solar position calculator was also used at the time of the experiment. This calculation is important because it relates the solar noon to the local time; in other words, the solar noon varies depending on the exact location and the time of year. The zenith angle was determined to be approximately 45.5°.

Vertical and Horizontal Shading Discussion

Next, the effects of vertical and horizontal shading on the power output were examined. As the vertical shading increased the current decreased, as seen in Figure 9. This I-V curve is nonlinear which demonstrates that the resistors were in series for this setup; also, as the shading increased vertically across the panel, the diffuse irradiance began to dominate the total incoming irradiance in comparison to the direct irradiance. This is important because it shows that the inverter had a difficult time determining the optimized voltage for all cells; clearly, this inability resulted in a decreased efficiency, seen in Figure 14, which shows the change in shading versus the change in efficiency. Furthermore, the decreased efficiency is directly related to a decrease in the panel's ability to convert DC to AC power; and, this explains Figure 13, which demonstrates a decrease in power as a function of shading across the panel. As the horizontal shading increased across the panel, the voltage also decreased, significantly. This I-V curve very closely resembles a linear trend which is to be expected from a set of resistors in parallel. This relationship is essentially representative of several different panels, of varying sizes, in which the horizontal shading merely represents the decrease in panel area which, naturally, corresponds to a decrease in voltage without affecting the inverter's ability to optimize which voltage output to select across the cells for each panel. The horizontal shading had a higher efficiency than the vertical shading, seen in Figure 14; the horizontal shading efficiency was 5.413% and the vertical shading efficiency was 5.312%. Moreover, since the vertical shading of the panel resulted in a variable, unstable power output and efficiency, it is important to determine cloud velocities and directions of travel when installing such panels to best avoid vertical shading for the greatest amount of time throughout each day, in order to maximize efficiency per panel. If shading must occur, which is less desirable than a purely sunny day, it is greatly preferred to shade in the horizontal direction of the panel, as opposed to the vertical shading since horizontal shading causes a steady change in power output.

Temperature Discussion

Additionally, temperature plays an important role in the efficiency of photovoltaic panels as it affects the conversion of energy within the panel. Shown in Figure 15, an increase in panel temperature results in a decrease in electrical conversion efficiency. The increase in temperature causes additional excited electrons which flow to the ground wire; thereby, decreasing the voltage difference.

Next, the maximum power point voltage was compared to the temperature at which the computed voltage-temperature coefficient was -0.0533V /°C which exhibits an inverse relationship between voltage and temperature. The rated value was -0.0027 V/°C. On the other hand, seen in Figures 21 and 22, current generally increases with temperature as a direct result of additionally excited electrons. Voltage decreases and current increases with increasing irradiance; similarly to how these parameters would respond to an increasing temperature. The prolonged exposure to the relatively high magnitude of irradiance throughout the experiment was the result of an increasing temperature, not the other way around. In Figure 25, the computed current-temperature coefficient was determined to be 0.0002 A/°C. The rated value was 0.0001 A/°C . This higher than expected value was probably a direct result of the sunny nature of the day on which this experiment took place. Again, this would have been because the sunny day had an increased horizontal irradiance which caused in increased temperature which caused an increase in current throughout the circuitry.

As irradiance increased, the efficiency decreased for the panel as a result of an increased temperature. When the GHI was 765.0 W/m^2, the efficiency was determined to be 0.04%; and an increase in GHI to 823.3 W/m^2 caused a decrease in efficiency by 7.71%. Therefore, in an ideal situation, a high irradiance that does not cause an increase in the panel's temperature is preferred. The slope of the corrected efficiency versus temperature clearly shows an increase from that of the raw efficiency versus temperature plot. Essentially, since there was little to no fluctuation in efficiencies or GHI throughout the experiment, this trend shows that the day was constantly sunny.

Conclusion

From examining the Unisolar and Kyocera photovoltaic solar panels, a variety of information was obtained that aided in our understanding of how tilt angle, shading, and temperature altered the efficiency and performance of a photovoltaic solar panel. While examining, the tilt angle, a direct correlation between irradiance and power output was observed. As the tilt angle was increased, it was determined that the maximum power output occurred at a tilt angle of 50°. When testing the shading of the PV panel, an increase in vertical shading resulted in a decrease in current and efficiency. Vertical shading also demonstrated a nonlinear relationship between current and voltage which is a result of the connection of the resistors in series. On the contrary, an increase in horizontal shading caused a decrease in voltage and demonstrated a more linear relationship between current and voltage due to the panel's resistors being connected in parallel. The orientation of the resistors also resulted in a representation of decreased panel area and therefore did not affect the inverter's ability to select the optimal voltage output. Overall, horizontal shading resulted in higher efficiency in comparison to vertical shading. In the case of the temperature of the PV panel, the computed voltage-temperature coefficient was -0.0533 V/°C and the computed current-temperature coefficient was 0.0002 A/°C. With relation to the panel's efficiency, it was shown that as the temperature increased, the efficiency decreased. Thus, the ideal situation would be for the panel's temperature to be unaffected by high irradiance. Overall, this analysis allowed for a better understanding of the specific factors that affect the performance and efficiency of photovoltaic solar panels. However, it is important that more experimentation continues to be done in order to gather more information concerning these factors that limit panel efficiency and performance so that photovoltaic solar panels continue to improve and make a larger impact in the renewable energy market.

Appendix and Raw Data

Raw Data, notes, and Excel Spreadsheets are available upon request.

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