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Sunpower Shading Study on P-Series and Conventional Solar Panels

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1 **Project Summary:** CFV Solar Test Lab conducted outdoor performance testing on two strings of SunPower (P-Series) modules and two strings of conventional solar panels on behalf of Sunpower Corporation. The arrays were tested in landscape and portrait orientation at 30 degree tilt to quantify the effects of row-to-row shading on maximum power (Pmp). Electroluminescence and indoor flash tests were done during the initial inspection. The indoor testing was done according to the IEC 61215 and IEC 60904 standards.

2 **Executive Summary of Results:** The measured effect of row-to-row shading on array level Pmp matched closely with the predicted results from Sunpower modelling. The Sunpower P-Series shaded array showed significantly less power loss than the conventional solar panel shaded array in the side by side testing. The detailed test data is documented in an Excel workbook titled "16012 CFV Project Workbook Sunpower Shade Study.xls". Any opinions and interpretation of data in this report are those of CFV Solar Test Laboratory.

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3 Procedures:

3.1 Incoming Inspection and Labeling: The modules were unpacked and labeled according to CFV Solar convention. The module IDs and the manufacturer's serial numbers were recorded in the Excel documents. Sunpower provided 23 P-Series modules and CFV Solar purchased 20 conventional solar panels for the study.

3.2 Outdoor Array IV Testing: Four arrays were assembled in the test yard at CFV Solar Test Lab to allow for landscape and portrait installation. The arrays were configured to face due west in order to maximize shade length for this time year. Figure 3.2.1 shows the portrait installation with the conventional solar panel arrays in the foreground and the P-Series modules in the background. The modules were mounted with the positive jbox downward during portrait. Each array consisted of 8 active modules. The front rows had a dummy module on either end in order for the back row to be fully shaded when the sun was not perpendicular to the array orientation. Any gaps between the modules on the unshaded array were covered with tape so the shade line on the back row would be continuous. One module in each array was configured with five thermocouples. Two plane of array irradiance sensors (CMPs) were also installed.

Figure 3.2.1 West-facing, portrait configuration of conventional solar panel and P-Series arrays

The arrays were connected to two 6 kW Power One ABB inverters with dual MPPT capability. One inverter was used to MPP track the conventional solar panel arrays and the other was used to MPP track the P-Series. The startup voltage on the inverter was reduced to 120 V, the minimum allowed, on each string so that the inverter would continue to operate as the row-to-row shading reduced the output voltage. The operating voltage for the ABB inverter is a function of the startup voltage. Specifically, the operating voltage is 70% of the startup voltage. An ACUDC 240 meter by Accuenergy was installed between the arrays and the inverters to monitor DC current, voltage, and power from each array. The sensors were connected to a Campbell Scientific CR1000 via RS485 and logged at one minute intervals. The module temperatures and the irradiance sensors were simultaneously logged by the Campbell Scientific, as well. Figure 3.2.2 shows the installation of the electronics inside a shed adjacent to the arrays. The two inverters are mounted on the wall to the right. The four Accuenergy DC meters are installed in the two boxes mounted on the wall in the center. The Campbell Scientific was installed in the white box shown in the bottom left corner, which was placed outside under the arrays during testing.

Figure 3.2.2 Power electronics and monitoring equipment

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The Pmp loss function was calculated as the ratio of the Pmp of the shaded array over the Pmp of the unshaded array for each module type. The ratio was normalized to 1 by the ratio of the Pmp from unshaded array to the shaded at the start of each test period before the shading occurred. The normalization constant was calculated for each day.

The shade length was monitored with a ruler taped directly to the frame of the last module on the shaded array (Figure 3.2.3). Still shots were made at one minute intervals, and the shade length was estimated visually every 10 minutes. An interpolation routine was used to fill in between the 10 minute intervals. The shade length data was then joined to the IV data using the time stamp. Ultimately, the Pmp loss function was plotted versus shade length for each array.

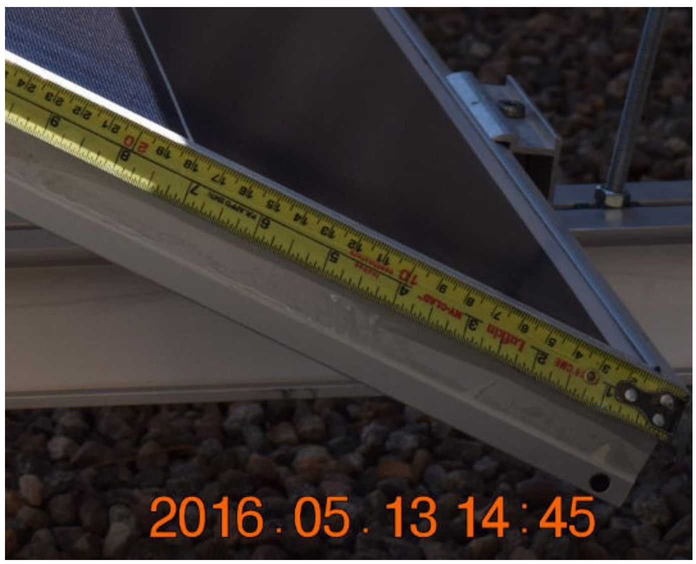

Figure 3.2.3. Shade length on a P-Series module as measured on 5/13/16.

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4 Discussion of Results:

4.1 Outdoor Array Power Monitoring: Figure 4.1.1 and 4.1.2 show the normalized Pmp loss functions for landscape and portrait. These curves were generated for two clear sky days in landscape and two clear sky days in portrait. The results were nearly identical from day to day. These curves match the Sunpower modelled results, except for the unexpected dip in the curve for conventional solar panels in landscape and P-Series in portrait. The scan interval parameter was reduced from 15 minutes to 5 minutes on the ABB inverter after the testing was complete. That data suggests that the second dip seen on P-Series in portrait mode was less severe under the short interval scan. The landscape orientation was not monitored with the new scan interval, so the effect on the dip in the conventional solar panels was not characterized.

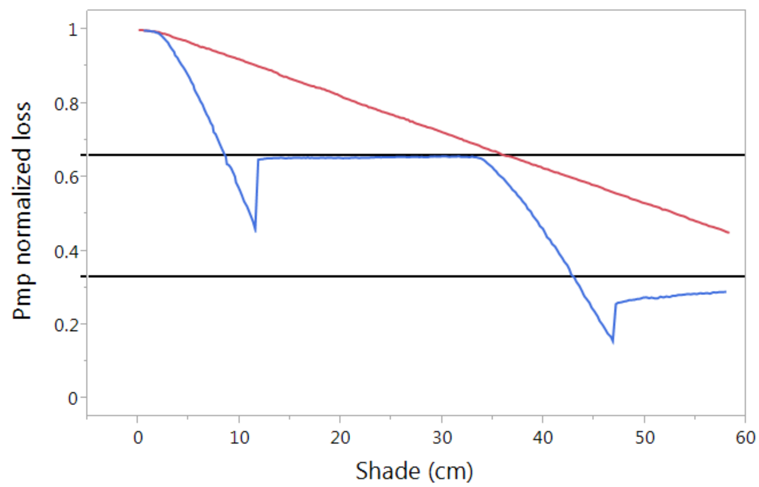

Figure 4.1.1 Normalized loss function in landscape, P-Series (red) and conventional solar panel (blue)

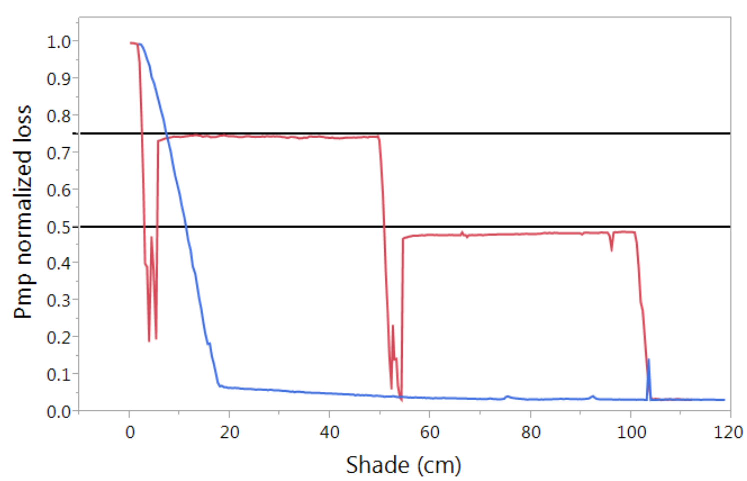

Figure 4.1.2 Normalized loss function in portrait, P-Series (red) and conventional solar panel (blue)

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Figure 4.1.3 shows the 20 temperature profiles from May 12, 2016 when the modules were mounted in landscape at 30 degree tilt. One module in the center of each array was instrumented with 5 TCs each. The figure on the left represents the P-Series modules, which shows how the shaded area of the module cools as the shade increases and the active area decreases. The two black curves represent TCs attached to the cells in the bottom row of the module in the shaded array, and the red curve represents the temperature at the center of the module in the shaded array. The figure on the right represents the conventional solar panels. The black curve represents the bottom row of the module in the shaded array. The second TC installed on the bottom row was not functional, so it's not included in the plot. The red curve represents the center of the module in the shaded array. The remaining curves represent areas of the modules that were unshaded throughout the test.

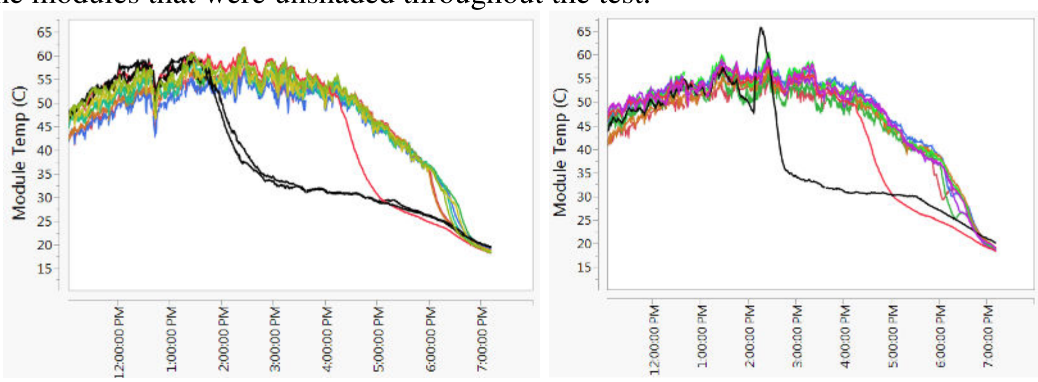

Figure 4.1.3 Module temperature trends for P-Series (left) and conventional solar panel (right) in landscape

Figure 4.1.4 shows the spike in temperature on the conventional solar panel from Figure 4.1.3 above. The spike occurred around 2:20 PM (MST), and corresponds to the moment when the normalized loss function reached the low point. This is likely when the bypass diode activated.

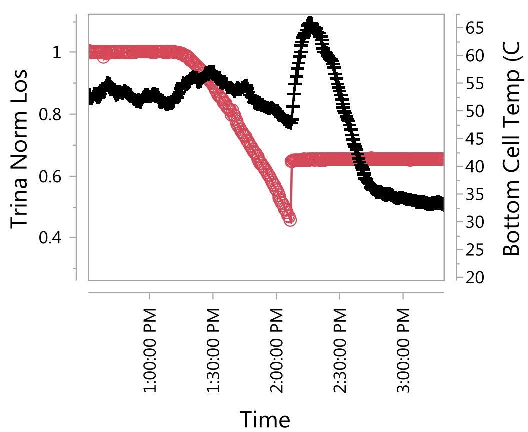

Figure 4.1.4 Overlay of conventional solar panel loss function and bottom row shaded module temperature

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Figure 4.1.5 shows the 20 temperature profiles from May 23, 2016 when the modules were mounted in portrait at 30 degree tilt. The figure on the left represents the P-Series modules, which shows how the shaded area of the module cools as the shade increases and the active area decreases. The two solid black curves represent TCs attached to the cells at the bottom row of the module in the shaded array, and the red curve represents the temperature at the center of the module in the shaded array. The dashed lines represent the diode temperature and dashed-dot line represents the temperature inside the jbox. The figure on the right represents the conventional solar panels. The 2 black curves represent the bottom row of the module in the shaded array. The red curve represents the center of the module in the shaded array.

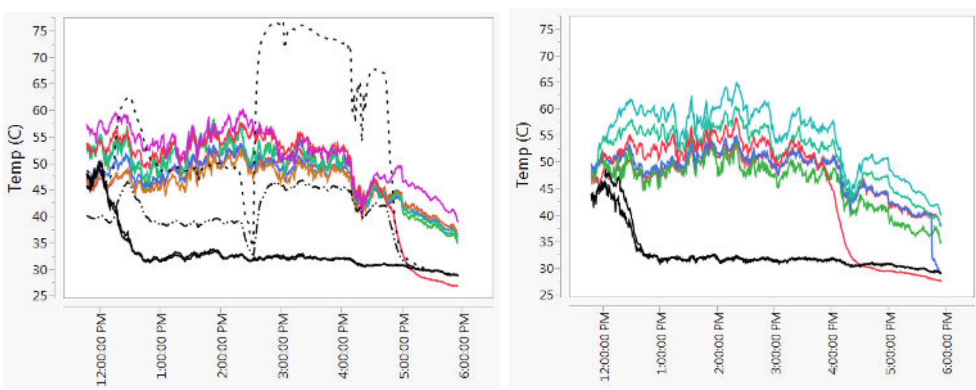

Figure 4.1.5 Module temperature trends for P-Series (left) and conventional solar panel (right) in portrait

Figure 4.1.6 shows the P-Series loss function overlaid with the diode temperaure. The modules were mounted with the positive jbox facing down, so this temperatture profile represents the diode temperature inside the positive jbox as the shade increases.

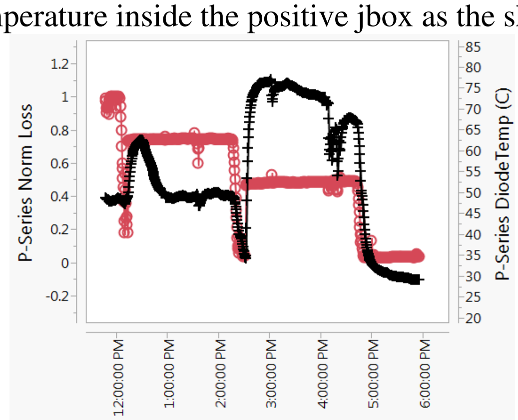

Figure 4.1.6 P-Series loss function (red) and bypass diode temperature (black) in portrait