Photovoltaic Array Field Characterization Report: University of Toledo R1 Arrays

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National Renewable Energy Laboratory

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Technical Report
NREL/TP-5J00-64998
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Contract No. DE-AC36-08GO28308

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Prepared under Task No. SS13.5510

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Photovoltaic array field characterization report University of Toledo R1 arrays

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November 26, 2014

1 Introduction

As part of the Photovoltaics (PV) Service Life Prediction agreement, we visit and characterize PV systems that have been in service for several years. This allows us to assess the condition and performance of PV modules after extended field exposure but before they are decommissioned.

The University of Toledo is a public university with high research activity in Toledo, Ohio. The University was an early collaborator with the company that later became First Solar, Inc, which has major manufacturing and R&D facilities in nearby Perrysburg, Ohio. The Research and Technology Complex 1 or "R1" building continues to be a center of PV research and an incubator for renewable energy companies.

Four ground-mounted PV arrays are situated on the south side of R1 (Figure 1). The systems were installed in two phases: the two southernmost systems in 2006 and the two northernmost systems in 2014. The systems installed in 2006 are the subject of this report. We visited the site from 2014-09-22 through 2014-09-25.

Figure 1: Four ground-mounted CdTe arrays at the University of Toledo R1 building. The two systems in the foreground are the subject of this report.

Each system is a single rack of 108 First Solar model FS-57 CdTe modules. This series of modules is informally called “Series 1” although at the time of its production it was not designated as such. The modules are the 600 mm $\times$ 1200 mm frameless form factor that is typical for First Solar modules. This generation of modules has no edge seal other than the encapsulant in the margin of the laminate. The modules’ nameplate power is 57 W, making each system’s nameplate capacity $\sim$6.2 kW.

The systems are located at 41.6531° N, 83.6060° W. Their azimuth is south and their tilt is 35° above horizontal. The southern edge of the modules is approximately 2.3 m above the surrounding ground, which is an actively maintained turf lawn.

The southern system (“row 1”) has been connected to a Sunny Boy SB6000U 6 kW inverter since its installation. Series strings of six modules each are all connected in parallel. At some point prior to 2008, a single module in this system was replaced with a newer product.

The northern system (“row 2”) was initially wired completely in parallel with a 2 kW MPP system configured to power an electrolyzer load. When the system’s maximum power point exceeded 2 kW, this system clipped it to 2 kW. When the electrolyzer load was less than 2 kW, a dummy load was switched in to dissipate the extra energy [2]. This configuration was used until approximately 2010, when the electrolyzer was disconnected. There are no records indicating the configuration of the array between 2010 and 2014. The MPPT and dummy load resistor were still located on the site during our visit, but the system might have been at open circuit during this period. In April 2014 this system was reconfigured and connected to a Sunny Boy SB 7000US-12 7 kW inverter.

2 Method

We performed a formal visual inspection of the modules [4], photographing features of interest. With the system energized, we collected thermal images of every module’s front surface and detailed images for areas of interest. Finally, we chose a sample of 42 of the 216 modules and collected I-V characteristics for each.

3 Results

3.1 Visual inspection

3.1.1 Nameplate

Every module’s nameplate was nearly illegible because the black text had been bleached white. The chalky texture of the labels had some contrast where lettering once was, enabling the reading of serial numbers at certain angles. The chalky residue appears to have washed down the backs of the modules, leaving streaks behind (Figure 2).

3.1.2 Soiling

Immediately before our visit, the site received enough rain to clean the modules. We cleaned a small area of one module to visualize the extent of the soiling that was not washed away by substantial rainfall (Figure 3). On subsequent days, dew on the modules trapped considerable additional soil from a construction site across the street.

Figure 2: Degraded nameplates on this system left streaks of chalky residue on the backs of modules. Text on the labels was nearly illegible.

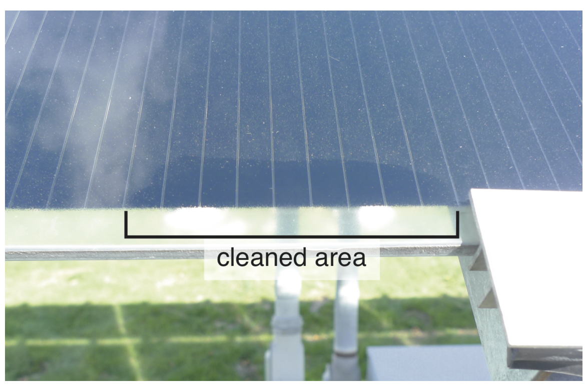

Figure 3: Light soiling present even after substantial rainfall is evident when a small area is cleaned completely.

3.1.3 Delamination and discoloration

The modules use metallic bus tape to connect the junction box to the terminals of the first and last cells. On about 75% of the modules, a small area of delamination was visible near the serial number, at the intersection of the bus tapes at the junction box end of the module (Figure 4). On some specimens, this delamination extended to areas of the bus tape beyond this intersection, but was always most visible at the intersection. On modules having this delamination, minor discoloration of the encapsulant was visible at the bus tape intersection (Figure 5). Series 3 First Solar modules use a substantially different bus tape design.

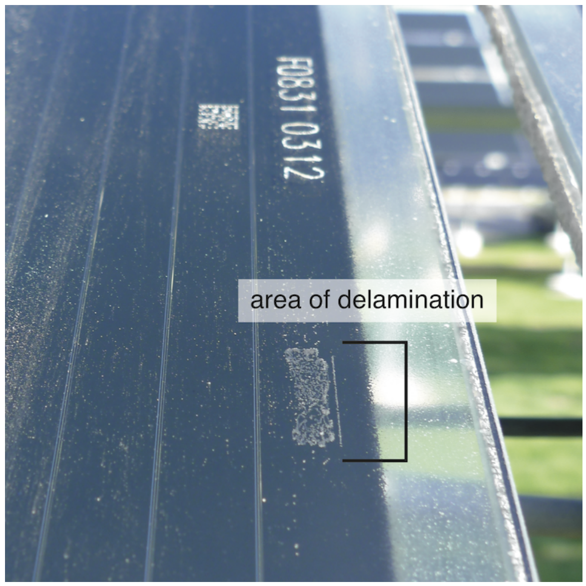

Figure 4: A small area of delamination was present in the same location on about 75% of modules. This location is the intersection of one pair of bus tapes.

3.1.4 Encapsulant extrusion

Most modules had a ring of extruded encapsulant around the periphery of the laminate (Figure 6). This extrudate contained many gas bubbles which, in some cases such as in Figure 6, continued into the margin of the encapsulant. The extrudate was gray in color, presumably due to trapped soil. The out-of-plane thickness of the extrudate was nearly the full thickness of the module and in many cases the outside edge of this extrudate was artificially flat (Figure 7), suggesting that it had been extruded against a form during manufacture and not in the field.

3.1.5 Glass

Two modules had broken front glass and one had broken back glass. The modules with broken front glass had visible impact sites and were both located on the array nearest the

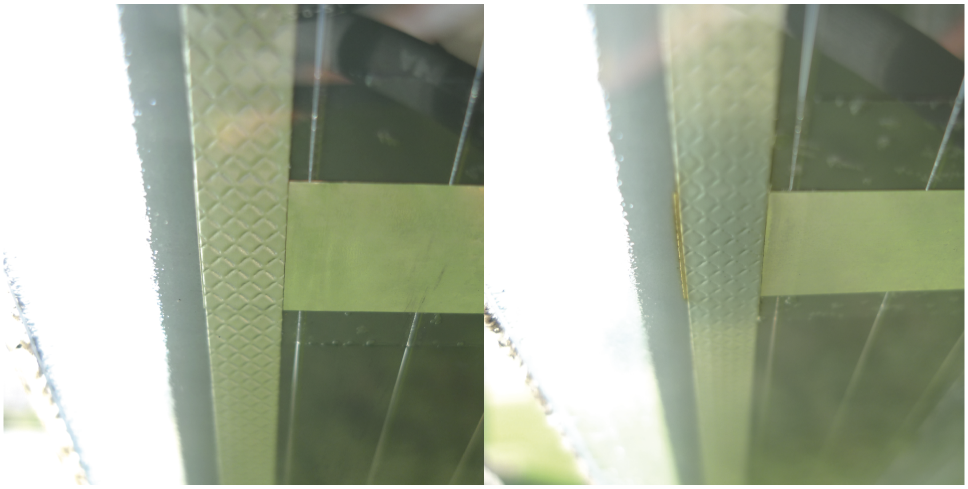

Figure 5: On modules without the type of delamination shown in Figure 4, there was no discoloration at the bus tape intersection (left) but those with the delamination showed brownish discoloration of the encapsulant at this intersection (right).

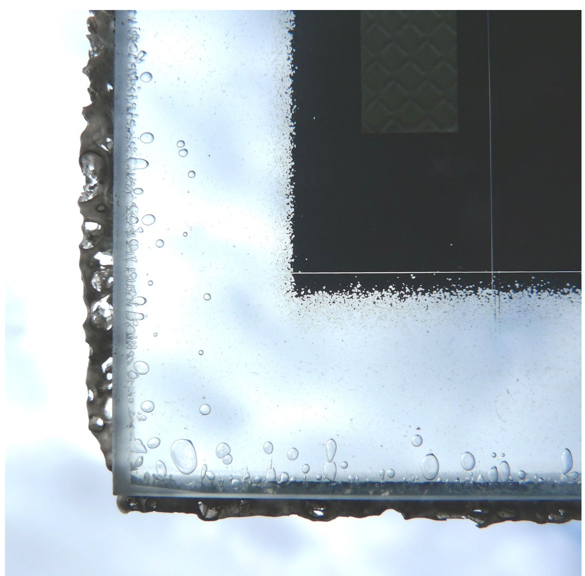

Figure 6: Every module had a porous band of extruded encapsulant around the edge.

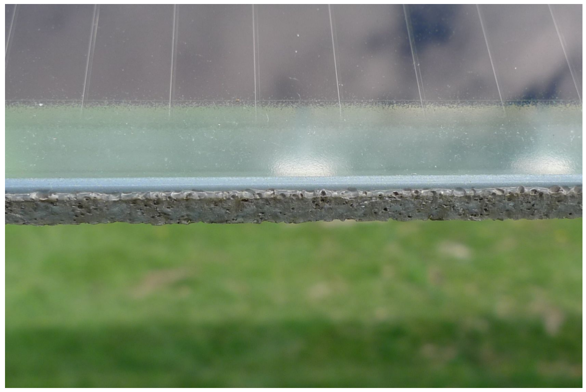

Figure 7: The encapsulant extrudate was nearly the entire thickness of the module and, in many cases, it was artificially flat, suggesting that it did not extrude in the field.

street and sidewalk. The most extreme example is shown in Figure 8. Visible from the back side of the module was brown discoloration presumably due to locally high temperature at areas where the broken glass disturbed interconnection or allowed water ingress.

3.2 Thermal imaging

A temperature map of the systems is shown in Figure 9. The map is composed of images collected of each north-south pair of modules. The northernmost modules in each system were necessarily imaged at a shallower angle than the southernmost modules. No correction has been made for sky reflection, so these rows are artificially cooler in the map.

The map shows the bus tape defect on 75% of modules. Typical modules with bus tape heating show a single spot (Figure 10), while some, such as s4 and h8 (shown in detail in Figure 11), have multiple hot spots along the bus tape. One string of six modules (p7–u7) is hotter than the surrounding modules because the broken module t7, shown in Figure 8, places the entire string at open circuit.

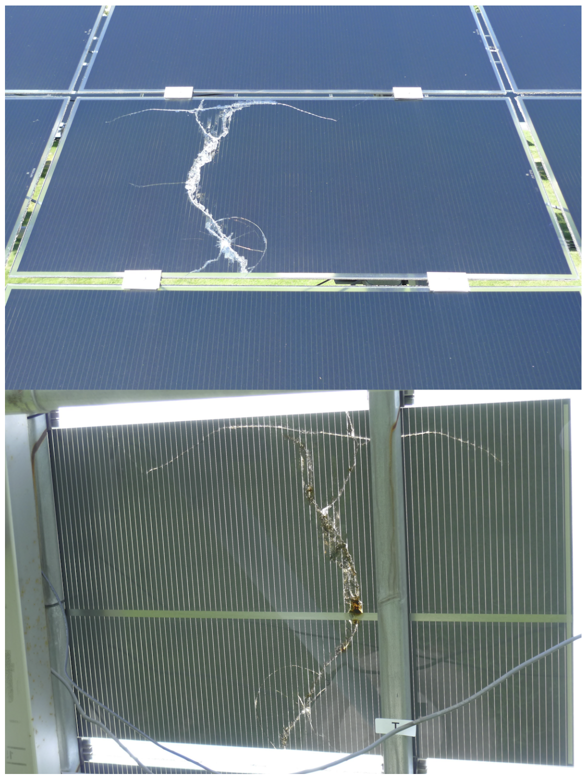

Figure 8: The front (upper image) and back (lower image) sides of a module with broken front glass.

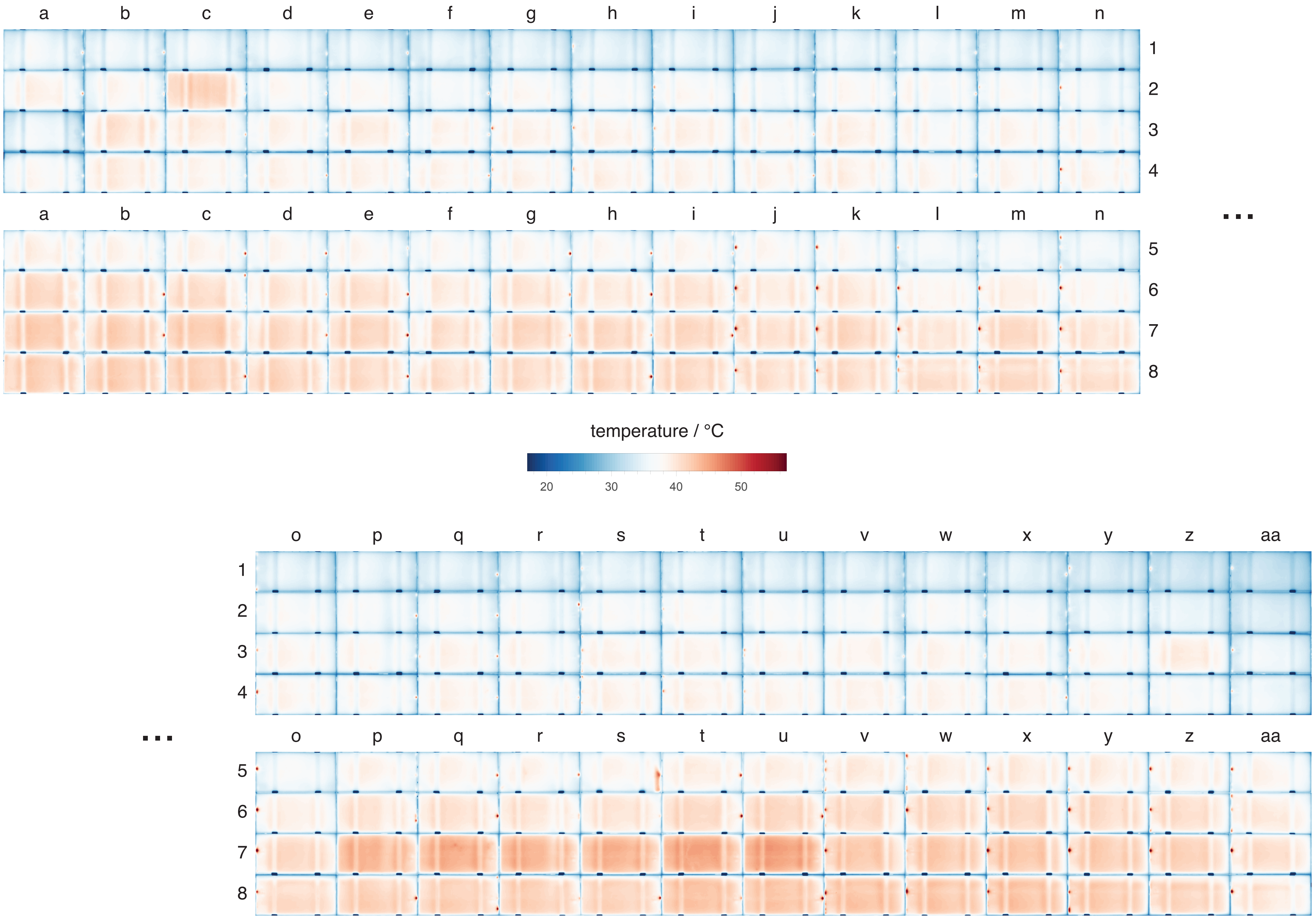

Figure 9: An uncorrected temperature map of both systems. Note that modules n1–n4 and n5–n8 are physically adjacent to o1–o4 and o5–o8, respectively. The upper rows appear cooler because their images were collected at a shallower angle.

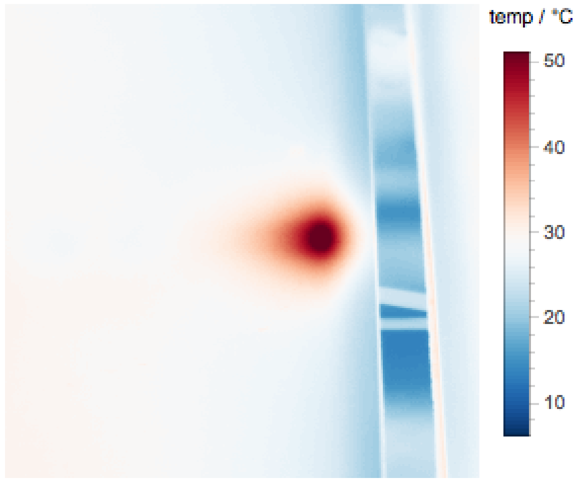

Figure 10: Most modules with bus tape heating show only a single hot area at the intersection of the bus tape. This is over the same area indicated in Figure 4.

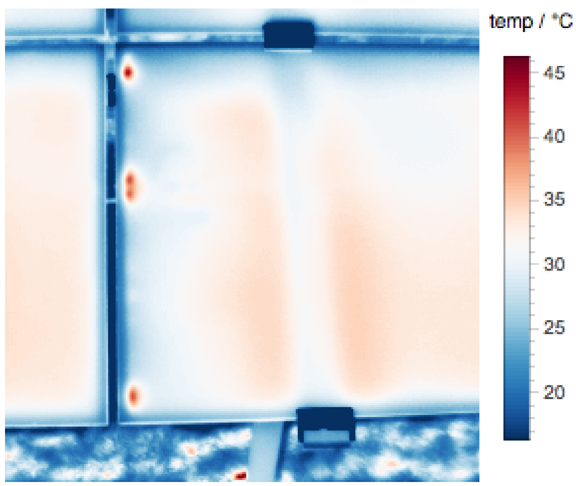

Figure 11: Module h8 is a specimen with multiple hot areas along the bus tape.

3.3 Electrical characterization

The performance specifications for model FS-57 are shown in Table 1. We collected light I-V curves outdoors on 42 modules, including one with broken glass which was excluded from further analysis. 24 of the selected modules had bus tape heating and 18 did not; 21 were in the "row 1" system and 21 in the "row 2" system.

Table 1: Performance specifications for First Solar model FS-57 [1].

P_{mp}	57 W	P_{mp} temp. coeff.	-0.25%/K
V_{oc}	89 V	V_{oc} temp. coeff.	-0.29%/K
I_{sc}	1.13 A	I_{sc} temp. coeff.	0.04%/K
V_{mp}	63 V	number of cells	116
I_{mp}	0.9 A		
FF	0.56		

We corrected measured power for irradiance and temperature using

$$P_{mp,0} = \frac{E_0}{E} \frac{P_{mp}}{1 + \gamma(T - T_0)},$$

where $P_{mp,0}$, E_0 and T_0 are maximum power, irradiance and temperature, respectively, at standard test conditions (STC) of 1000 W/m^2 irradiance and 25°C. P_{mp}, E and T are the observed maximum power, irradiance and temperature.

A histogram of corrected power is shown in Figure 12. The median power was 54.8 W, about 4% below the nameplate power rating, but the sampled population contains a higher fraction of modules free of bus tape heating than the array. Weighting the with-heating power measurements by 0.75 and the without-heating measurements by 0.25, the mean corrected power was 53.6 W, about 6% below the nameplate power rating. The median corrected P_{mp} values for the "row 1" and "row 2" systems were not significantly different.

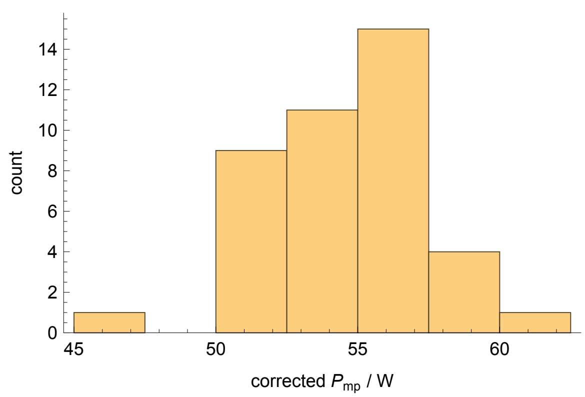

Figure 12: Median corrected P_{mp} for the 47 sampled modules is about 4% below the nameplate rating.

A paired histogram of corrected P_{mp} for modules with and without bus tape heating is shown in Figure 13. The medians were 52.6 W and 56.7 W, respectively, suggesting the bus tape delamination was responsible for a 4.1 W (7%) reduction in power. The median values of P_{mp} for the two populations were significantly different according to a Mann-Whitney test ($p < 0.001$).

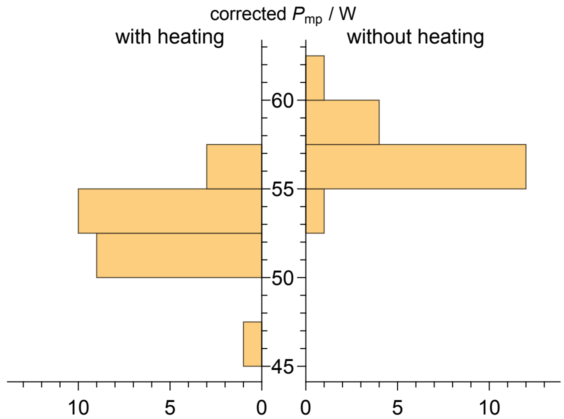

Figure 13: Corrected P_{mp} for modules with (left) and without (right) bus tape heating. The median P_{mp} values from these two populations were significantly different.

We fitted each I-V curve using the single diode model [3] to determine each module's series resistance, R_s. A paired histogram of R_s for modules with and without bus tape heating is shown in Figure 14. The medians were 18.3 Ω and 12.7 Ω, respectively, suggesting that the bus tape delamination was responsible for a 5.6 Ω (44%) increase in series resistance. The median values of R_s for the two populations were significantly different according to a Mann-Whitney test ($p < 0.001$).

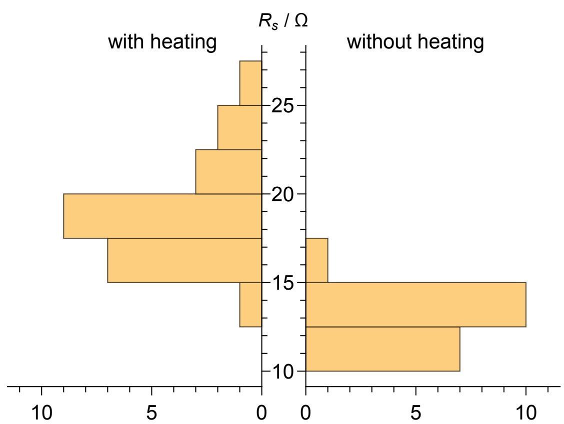

Figure 14: Series resistance (R_s) for modules with (left) and without (right) bus tape heating. The median R_s values from these two populations were significantly different.

Table 2 summarizes the performance of the highest- and lowest-power modules we measured. The parameters are temperature- and irradiance-corrected. The $\sim 22\%$ loss in P_{mp} is due almost entirely to a loss in FF.

Table 2: Comparison of irradiance- and temperature-corrected performance parameters from the highest- and lowest-power modules we measured.

id	P_{mp} (W)	V_{oc} (V)	I_{sc} (A)	FF
h1	47.2	88.4	1.2	0.45
f5	60.2	88.9	1.2	0.58

4 Conclusion

We inspected two 6.2 kW systems of CdTe modules that had been deployed for approximately eight years. Every module displayed some benign defects such as illegible nameplates and extruded encapsulant. Three modules had broken glass and produced little or no power. Approximately 75% of modules had localized heating at a bus tape intersection near the junction box. This heating was correlated with delamination visible from the front of the module and minor encapsulant discoloration visible from the back. Modules with bus tape heating produced significantly (7%) less power than those without heating due to significantly (40%) higher series resistance. The design of the bus tape has changed substantially in Series 3 First Solar modules, so this problem may have been eliminated. The weighted average corrected P_{mp} was 53.6 W, 6% below the nameplate rating. Despite never being loaded at P_{mp} for almost all of the first eight years of its deployment, the "row 2" system's median P_{mp} did not differ significantly from that of the "row 1" system.

Acknowledgments

We gratefully acknowledge the assistance of Randy Ellingson, Mike Heben and Ngalula Sandrine Mubenga at the University of Toledo.

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