SANDIA REPORT
SAND2017-7962
April 2017

Performance Comparison of Four SolarWorld Module Technologies at the US DOE Regional Test Center in New Mexico: November 2016 – March 2017

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Preliminary Performance Comparison of Four SolarWorld Module Technologies at the US DOE Regional Test Center in New Mexico

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ABSTRACT

This report provides a preliminary (three month) analysis for the SolarWorld system installed at the New Mexico Regional Test Center (RTC.) The 8.7kW, four-string system consists of four module types): bifacial, mono-crystalline, mono-crystalline glass-glass and polycrystalline.

Overall, the SolarWorld system has performed well to date: most strings closely match their specification-sheet module temperature coefficients and Sandia's flash tests show that Pmax values are well within expectations. Although the polycrystalline modules underperformed, the results may be a function of light exposure, as well as mismatch within the string, and not a production flaw. The instantaneous bifacial gains for SolarWorld's Bisun modules were modest but it should be noted that the RTC racking is not optimized for bifacial modules, nor is albedo optimized at the site.

Additional analysis, not only of the SolarWorld installation in New Mexico but of the SolarWorld installations at the Vermont and Florida RTCs will be provide much more information regarding the comparative performance of the four module types.

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1. INTRODUCTION

SolarWorld Americas, a leading manufacturer of solar cells and modules headquartered in Hillsboro, Oregon (near Portland, Oregon), joined the US DOE Regional Test Center (RTC) program in 2015 to have the performance of its modules analyzed under multiple climatic conditions and validated by the national labs. SolarWorld installed its first RTC system at the NM RTC in 2016 and by mid-2017 will have installed almost identical systems at the Colorado, Florida, and Vermont.

This preliminary report describes the performance of SolarWorld's modules based on the first three months of their operating history in Albuquerque, New Mexico. While by no means equivalent to a standard comprehensive RTC report that spans multiple seasons and multiple sites, this document—produced at the request of SolarWorld—nevertheless serves a valuable purpose: it allows for early review of one site's data and opens up a discussion between Sandia and SolarWorld that could result in improvements at the system and/or module level and in a more impactful study overall.

Performance data for the SolarWorld installations at other RTC sites are forthcoming and will be included in the October 2017 performance report, and all subsequent reports delivered to SolarWorld.[1]

2. SYSTEM DESCRIPTION

The SolarWorld installation at the New Mexico RTC, like the SolarWorld systems at other RTC sites, is a 30-module, four-string 8.7kWdc photovoltaic (PV) system. Designed collaboratively by Sandia and SolarWorld, the system consists of four module types (one type per string):

1. Sunmodule Bisun SW 270 Duo (B14)
2. Sunmodule Protect SW 270 Mono Black (MB2)
3. Sunmodule Plus SW 290 Mono (MC1)
4. Sunmodule Pro-series SW 260 Poly (PB3)

All modules are installed in landscape orientation on a fixed rack at latitude tilt (35˚) facing due south (*see Figures 1 and 2.)* One spare of each type is stored on site.

[1] The inclusion of data from the Nevada RTC in this report is predicated on SolarWorld's timely installation of their modules on the fast-track racking system.

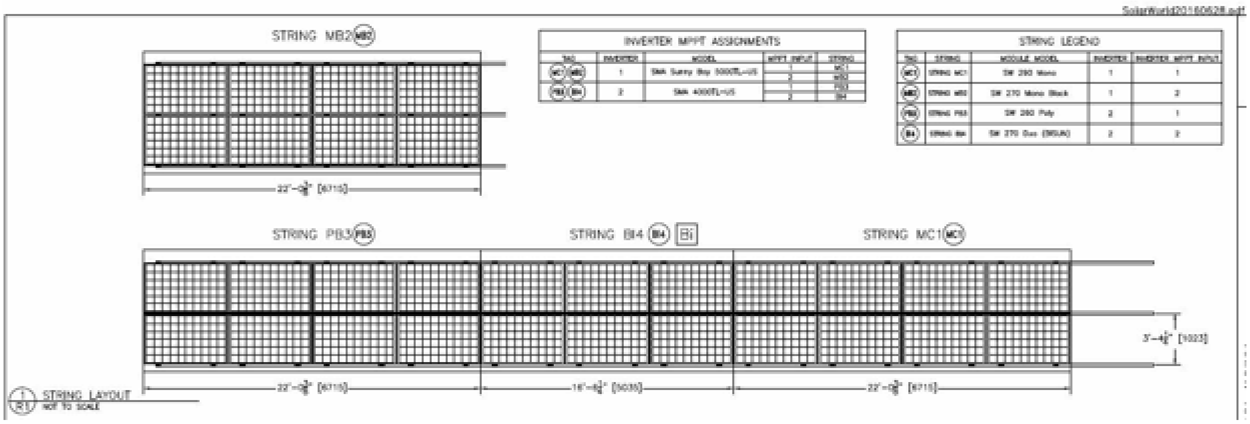


Figure 1. Layout of the SolarWorld system at the NM RTC. Note that the MB2 modules are on a section of rack just to the north of the other modules.

Figure 2. Photograph of the SolarWorld system at the NM RTC

Table 1: String Descriptions

String Short Name	Module Type	Spec Sheet Module Pmax	Spec Sheet Module Imp	Spec Sheet Module Vmp	Modules per String	Total kW
BI4	SW 270 Duo (Bisun)	270W (front-side)	8.68A (front-side)	31.3V (front-side)	6	1.62
MB2	SW 270 Mono Black	270W	8.81A	30.9V	8	2.16
MC1	SW 290 Mono	290W	9.33A	31.4V	8	2.32

PB3	SW 260 Poly	260W	8.37A	31.4V	8	2.08

3. MODULE CHARACTERIZATION

Module characterization prior to installation provides data against which future changes in performance and/or reliability can be referenced. In accordance with the SolarWorld validation plan, Sandia flash tested all the SolarWorld modules, selected a random sample of monofacial modules for outdoor testing on a dual-axis tracker and subjected multiple modules to EL imaging, the number commensurate with the extent of electrical performance anomalies detected. Complete details of the characterization and per-module results can be found in SolarWorld Commissioning Report [1].

3.1. Flash-Testing of Modules

All SolarWorld modules were flash tested on Sandia's class AAA solar simulator (Spire 4600 SLP) at Standard Test Conditions (STC -1000 W/m2, 25°C, AM 1.5). Before flashing the Bisun modules, we masked the opposite side using an opaque, non-reflective double-layer black felt cloth that fully covered the solar cells, thus ensuring no ambient light could reach that side. Our flash test results for all four modules show that measured Pmax values varied slightly from the spec sheet values (see Table 2.)

In general, the PB3 modules had a lower (-2.7 percent) power output compared with the nameplate rating but the results are within absolute flasher tolerances from factory measurements to Sandia's AAA solar simulator. The MB2 modules on average had a 3.4 percent lower power output than their nameplate rating; the MC1 modules were similarly about 4 percent lower, both drops attributable to lower current output. The average "bifaciality" of the BI4 modules was estimated at ~58%, with front side power output measuring an average current that was 8.329 percent lower than their nameplate rating.

Table 2: Comparison of SolarWorld spec sheet characteristics with Sandia's flash test results

String	Spec Sheet Module Pmax	Test Mean Pmax	Spec Sheet Module Imp	Test Imp	Spec Sheet Module Vmp	Test Vmp
BI4	270W (front-side)	261W (front side)	8.68A (front-side)	8.49A (front side)	31.3V (front-side)	30.79V (front side)
MB2	270W	261W	8.81A	8.54A	30.9V	30.54V
MC1	290W	278W	9.33A	8.92A	31.4V	31.18V
PB3	260W	253W	8.37A	8.44A	31.4V	29.99V

As depicted in Table 2, SolarWorld's spec sheet values and Sandia's subsequent flash test results differ. These differences, which are to be expected, reflect slight performance degradation, such as the light induced degradation that takes place when modules are exposed outdoors; they also reflect variation attributable to different flash test equipment, reference modules and procedures. Within this context, all Pmax values measured at Sandia (after light soaking) were lower than SolarWorld's spec sheet values. The most notable differences are the ~5 percent drop in Vmp for the PB3 modules and the ~8 percent lower Imp value for the BI4 modules.

3.2. Outdoor Module Testing

We randomly selected two modules of each monofacial type for light soaking and outdoor characterization on our dual-axis tracker. Although the tracking accuracy of Sandia's trackers is specified to be within 2°, they are typically accurate to well below 1°. IV curves were measured with Digital Multimeters that are accurate to 6.5 digits and are calibrated at Sandia's ISO-accredited calibration laboratory. Module temperatures were measured using T-type thermocouples that were adhered to the back of the modules in modified IEC 61853 configurations. Irradiance was measured with calibrated global pyranometers with traceability to the World Radiometric Reference. Nominal electrical performance values at STC were generated using Sandia Array Performance Model (SAPM) regressions, and were normalized using a local global pyranometer. These values are considered the most accurate when compared to nameplate and indoor testing results.

Figure 3. Sandia's advanced thermal-testing solar tracker with an MC1 module under evaluation.

4. PERFORMANCE MONITORING

4.1. Data-Acquisition System

The high-resolution data-monitoring system, which we custom designed for the RTC program, collects data at no less than five-second-intervals and averages the data at one-minute intervals (see Table 2.) Data collected includes DC voltage and current at the string level (multiplied together to calculate total DC power); module temperature (measured by thermocouples placed on the backside of multiple modules); and plane-of-array (POA) irradiance sensors. At least one RTC team member reviews the data daily for quality and availability; twice a year the team produces a confidential, in-depth performance report that is shared with SolarWorld.

Table 3: Data-Monitoring System for the SolarWorld Installation

Performance Measurement	Types	Sensor Type
Irradiance	Global horizontal (GHI); plane-of-array (POA)	Kipp & Zonen CMP-11
PV Reference Cell	POA front-side; also backside high and backside low	EETS cell
Temperature	Ambient; backside of module (2 per string)	Omega Type-T thermocouples
DC voltage	String	Resistive voltage divider with accuracy of 0.1%.
DC current	String	Empro current shunts with accuracy of 0.1%

Figure 4. Backside irradiance cells, mounted in both high and low positions (*left image*); irradiance sensors mounted in the plane-of-array (*right image*.)

4.2. Data Availability

This preliminary report presents data from a representative three-month period (November 18, 2016 through January 31, 2017). Data availability during this period was very good (*see Figure 5*), indicating that both the PV and monitoring systems were fully functional.

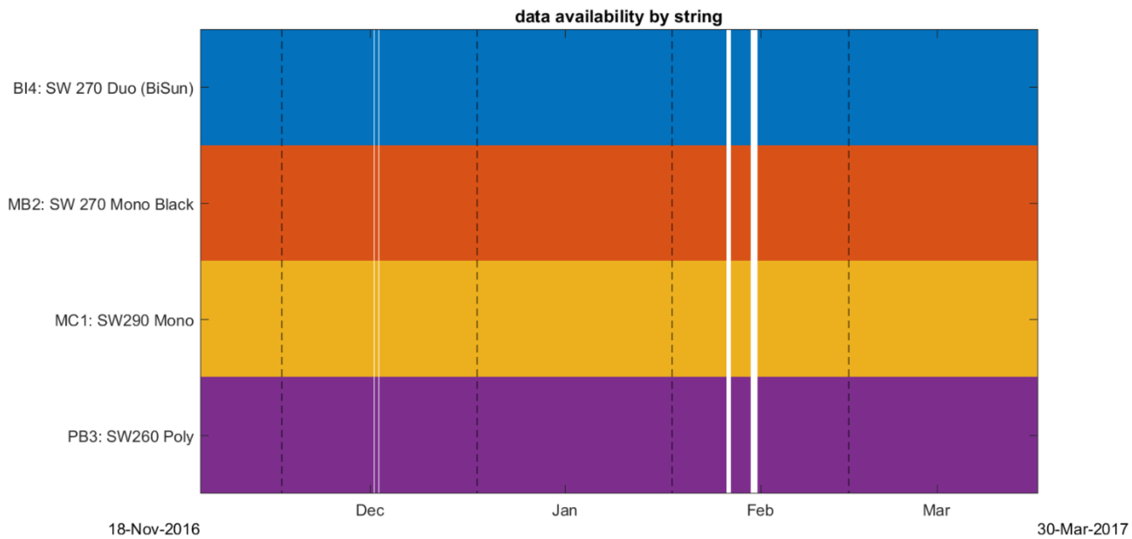


Figure 5: Data availability for the four strings, with each string represented by a distinct color.

4.3. Data Quality Control

To ensure the meaningfulness and quality of data analyzed, Sandia filtered the performance data collected from the SolarWorld array to include only the irradiance and power measurements made when the sun was above the horizon, that is, at an altitude angle greater than 10°, as seen in Figure 6.

By eliminating data from the beginning and end of each day, when the irradiance values are small and low sun-angles can produce differential shadowing among strings, we could generate a more accurate performance profile. In addition, note that the filtered-out data for all four strings represents a negligible amount of energy: less than 3.5 percent of the system's total energy production.

4.3.1. Solar-Angle Filter

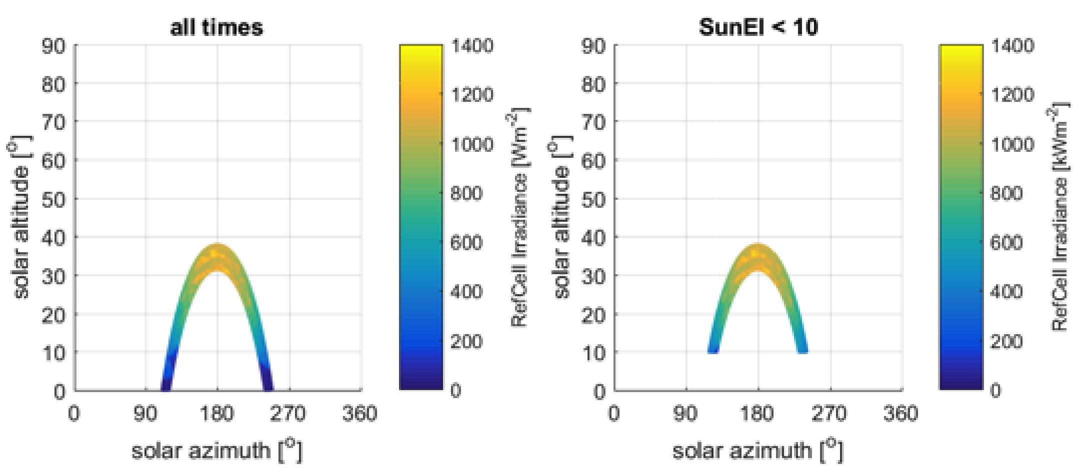


Figure 6: Comparison of unfiltered performance data (*left*) with filtered data (*right*) compiled for all four SolarWorld strings. In both graphs, the reference cell irradiance measurements (*colors*) are plotted as a function of solar azimuth and solar altitude.

4.3.2. Current-Irradiance Filter

In addition, we applied a current-irradiance filter to capture the relationship between the dc current generated by each string, or module type, and the POA irradiance, as measured by the EETs reference cell. Using this filter, we could eliminate any measured-current data points that deviated by more than 30 percent from the current predicted by the equation:

$$I = I_{mpp,\ STC} \times Irr_{ref\ cell}$$

where $I_{mpp,\ STC}$ is the STC maximum power point current (*see Table 1*) and $Irr_{ref\ cell}$ is the reference cell irradiance, expressed in kWm^{-2}. As indicated in Figure 7, the filtered data represents periods of low irradiance, typically when the sun is at a low angle in the sky.

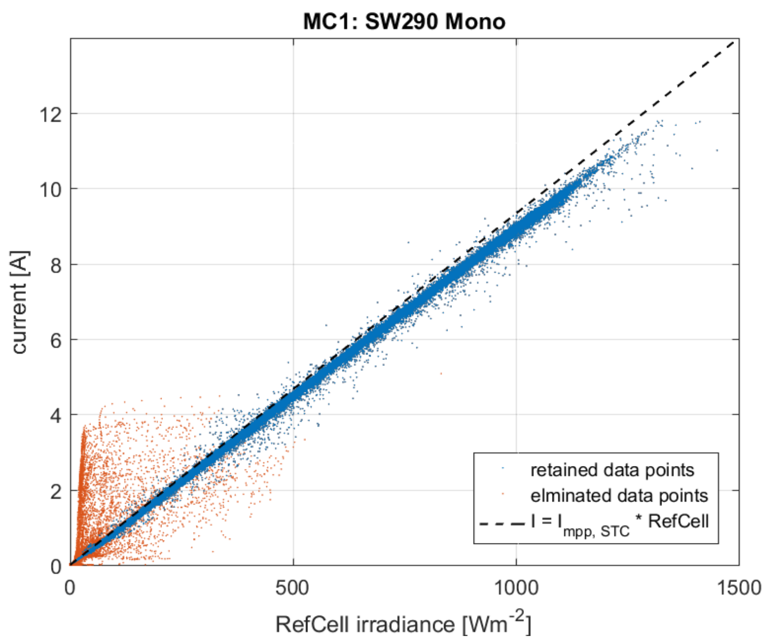


Figure 7: Current-irradiance scatterplot for string MC1 (*blue*), showing data points filtered out from the analysis (*orange*). The intent of this filtering was to eliminate data collected during low irradiance levels, generally near the beginning and ending of each day.

5. PERFORMANCE RESULTS

An important aim of this ongoing study is to quantify the energy yield of each module technology and to understand how climatic variables impact that yield. The following analysis of the performance of the four module technologies includes calculations of 1) relative efficiencies, with irradiance and temperature treated as both separate and coupled variables; 2) monthly module efficiencies (although the period covered is too short to be conclusive); 3) the bifacial gain in energy of the Bisun modules relative to the three monofacial technologies; and 4) relative performance under intermittent conditions (cloudy and clear periods during one day). Taken as whole, this performance report provides an interesting snapshot into the relative performance of modules but the data are too preliminary and too geographically limited to draw over-arching conclusions.

5.1. Weather Over the Test Period

During the period of performance analysis (November 2016-March 2017), the temperatures at the NM RTC were generally cool and consistent (nearly always between 0°C and 20°C). As depicted in Figure 8, irradiances were close to uniformly distributed, representing a range from 50 to 1050Wm^{-2}, with only a slight bimodal shape showing preference for high and low irradiances, presumably caused by fully clear or fully overcast days.

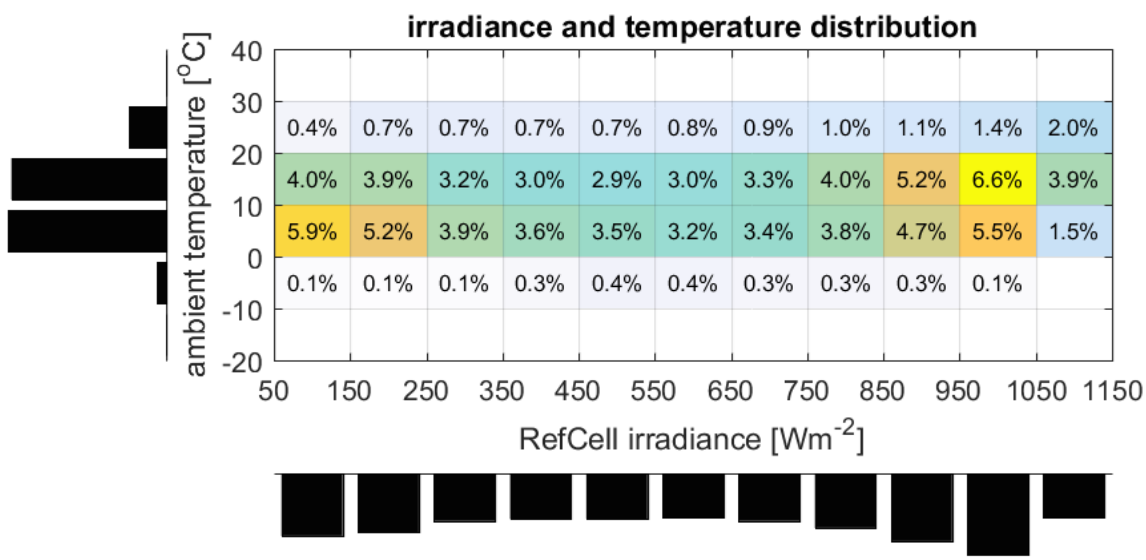


Figure 8: Two-dimensional histogram shows the percent of values that pass the solar-time filter, binned by irradiance/ambient temperature. For example, 6.6 percent of minutes passing the solar time filter had irradiances between 950Wm^{-2} and 1050Wm^{-2} and ambient temperatures between 10˚C and 20˚C.

5.2. Cell Temperatures

Omega Type-T thermocouples placed on the backside of select modules in each string provide module temperature measurements. Sandia converts the module temperatures to cell temperatures using the follow equation from the Sandia Array Performance Model [2]:

$$T_c = T_m + \frac{E}{1000\ Wm^{-2}} \times \Delta T, \qquad (1)$$

where T_c is the cell temperature, T_m is the module temperature, E is the reference-cell-measured irradiance, and ΔT is the temperature difference between the cell and the module at 1000 Wm^{-2}. We use the suggested value of $\Delta T = 1°C$ [1] for glass/cell/polymer layouts for MC1 and PB3 and of $\Delta T = 3°C$ for glass/cell/glass layouts for BI4 and MB2.

Table 4 shows mean cell temperatures for the four different strings. For both the BI4 and MB2 modules, which are glass-glass, we mounted thermocouples between the cells, which may explain the lower average temperatures, as this location is likely slightly cooler than the back of the cells themselves. Thermocouples mounted over the MC1 and PB3 cells generally registered higher cell temperature, with temperatures for the MC1 string exceeding those of the PB3 string.

Table 4: Mean cell temperatures measured by thermocouples on the backside of the SolarWorld modules

String	Mean Cell Temperature
BI4*	25.9 °C
MB2*	25.6 °C
MC1**	29.3 °C
PB3**	27.0 °C

* Thermocouples placed between cells on these glass-glass modules so the readings are lower than if directly behind the cell.
** Thermocouples placed directly behind the cell.

5.3. DC Efficiency

String-level DC performance efficiency is a value similar to the module-level efficiency listed on PV module spec sheets, but is a more realistic value because it takes into account string-level variations such as mismatch between modules or errors in inverter maximum power point tracking that negatively impact string-level efficiency.

In this section, string-level DC efficiencies are presented as relative efficiencies, $rEff_{DC}$,

$$rEff_{DC} = \frac{string\ DC_{power}}{\frac{irradiance}{1000\ Wm^{-2}} \times string\ Pmax}, \tag{2}$$

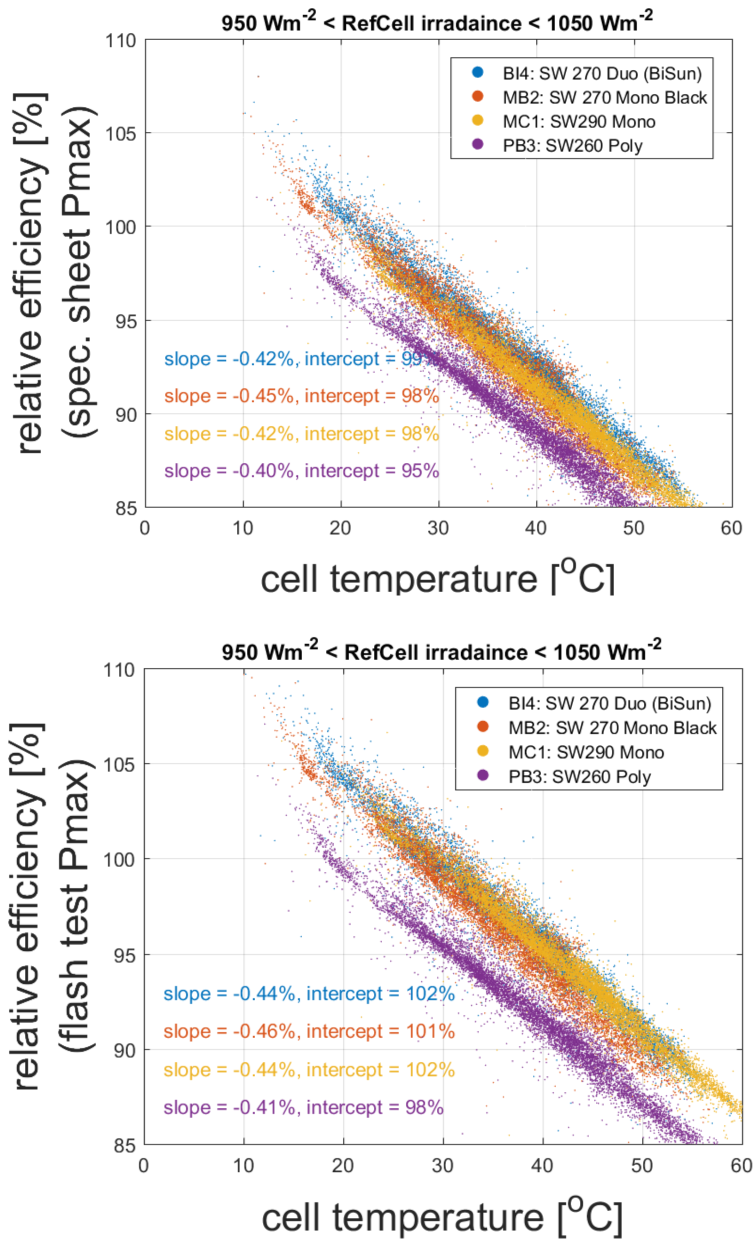
where string Pmax is determined by multiplying the module Pmax by the number of modules per string (*see Table 1*). Irradiance measurements are obtained from the POA pyranometer for the PV system.

We also calculated efficiency under parameters of constant irradiance and constant temperature to better understand how corresponding variable impacted performance.

5.3.1. Efficiency at Constant Irradiance

The relative DC efficiency for each string, as a function of temperature for relatively constant irradiances around 1000Wm^2, is shown in Figures 8a and 8b. Efficiencies based on the Pmax value provided on SolarWorld's module specification sheet are depicted in Figure 8a; efficiencies calculated from Sandia's flash test results are shown in Figure 8b (*see Table 2*). As expected, both plots show a decline in efficiency as cell temperature increases, with all strings having similar slopes. The slopes, which range in value from -0.40 to -0.46 percent, are similar to the temperature coefficients listed on the module specification sheets, which provide values ranging from -0.41 to -0.43 percent.

The intercepts of the efficiencies through 25°C, i.e., under standard test conditions (STC), show that most strings *slightly underperform* (by <3 percent) the Pmax value listed on SolarWorld's specification sheets, a finding consistent with most modules that have been sun-exposed and have expected de-rates (e.g., soiling, mismatch, spectral, angular losses, etc.) But three of the four strings *outperform* when compared with the flash-test Pmax values, with intercepts that exceed 100 percent at STC conditions. The one exception is string PB3, which underperforms the rest of the modules by about 3 percent. Sandia will continue to monitor the PB3 data but may have to investigate further to identify and understand the cause of the discrepancy.



Figures 9a and b: Relative DC efficiency (y-axis) is represented as a function of cell temperature, filtered to show times when the irradiance was between 950Wm^{-2} and 1050Wm^{-2}. Figure 9a (*top*) depicts string-level efficiency calculated using the specification sheet Pmax; Figure 9b (*bottom*) shows the efficiency calculated using flash test Pmax. Slope and intercept values (through 25°C) of the best-fit lines are shown for each plot.

5.3.2. Efficiency at Constant Temperature

When temperatures are nearly constant (between 20˚ and 30˚C), the relative DC efficiencies of each string decrease slightly as a function of irradiance (*see Figure 10.*) This finding is consistent with other c-Si modules Sandia has evaluated. As with the constant irradiance findings (*see Figure 9)*, string PB3 consistently demonstrates lower efficiencies than the other strings. We suspect the explanation is that the modules' actual Pmax values are lower than those listed on SolarWorld's specification sheet but we will have to investigate further to be certain.

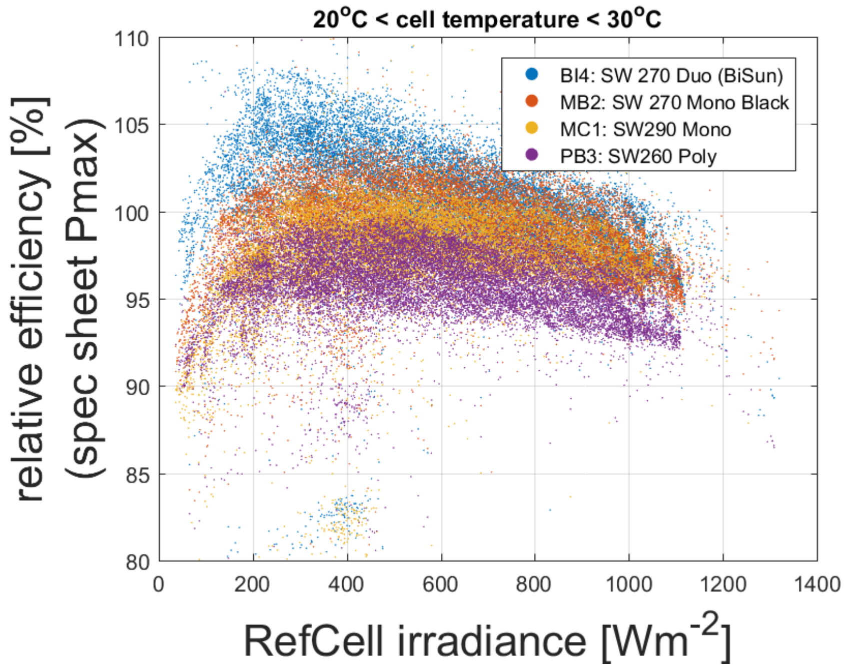


Figure 10: DC efficiency (y-axis) as a function of reference-cell irradiance with cell temperatures between 20˚C and 30˚C for the SolarWorld modules.

5.3.3. Efficiency's Joint Dependence on Irradiance and Temperature

Module efficiency also depends on the coupling of irradiance and temperature.
Figure 11 shows the median values for each irradiance/temperature bin as two-dimensional color plots. The coupled irradiance and temperature dependence of efficiency can be seen, as can the distribution of irradiance and cell temperatures for each location.

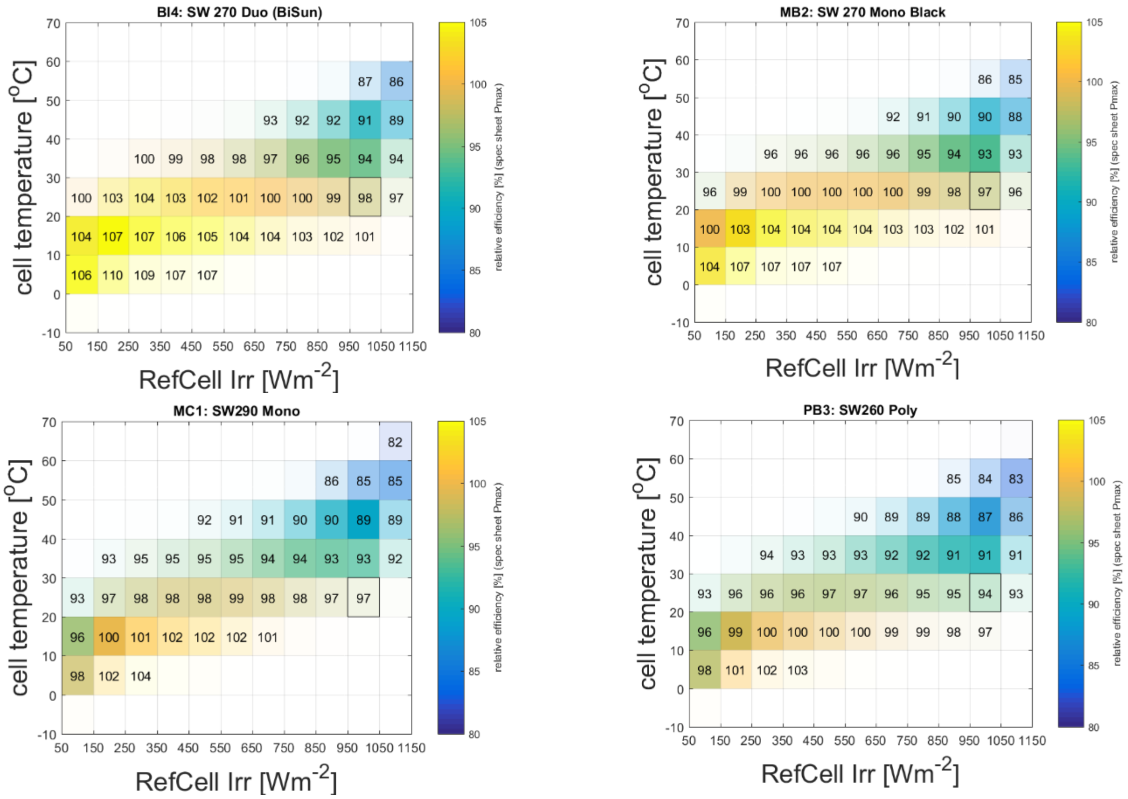


Figure 11: Relative DC efficiency of each SolarWorld string is represented as a function of reference-cell irradiance (*x-axis*) and module temperature (*y-axis*) bins, using spec sheet Pmax. Colors (*blue to yellow*) show efficiencies, with blue representing the lower, and yellow the higher, values. Color intensities (*strong vs. faded*) indicate the relative number of data points in each bin: stronger colors indicate more data points. The square outlined in black indicates the bin containing STC conditions.

5.3.4. Monthly Efficiency

String-level DC efficiency is typically represented as an instantaneous value. But one can also average DC efficiencies for periods of one to several months to show how efficiencies are affected by seasonal differences and examine how the latter impacts system performance. Monthly DC efficiencies are similar to monthly performance ratios, except that they do not account for DC to AC conversion losses, and are calculated using the following equation:

$$monthly\ rEff_{DC} = \frac{\sum_{month} string\ DC_{power}}{\frac{\sum_{month} irradiance}{1000\ Wm^{-2}} \times string\ Pmax}, \tag{3}$$

As shown in Figure 12, string-level efficiencies in December are higher than they are in either previous or subsequent months, likely due to the colder temperatures in December. We also observed that the BI4 string consistently delivered the highest efficiency relative to the other

SolarWorld modules, though these results are to be expected given the bifaciality of the BI4 modules. Because efficiency values are computed based on the Pmax of the front of the modules, the power generated from backside irradiance will always boost the perceived efficiency of a bifacial module. The MB2 modules also have monthly efficiencies above 1, likely due to cell temperatures often being below the STC condition of 25°C. In any case, we will be able to bring greater clarity to our analysis of such seasonal trends with as we acquire longer-term data.

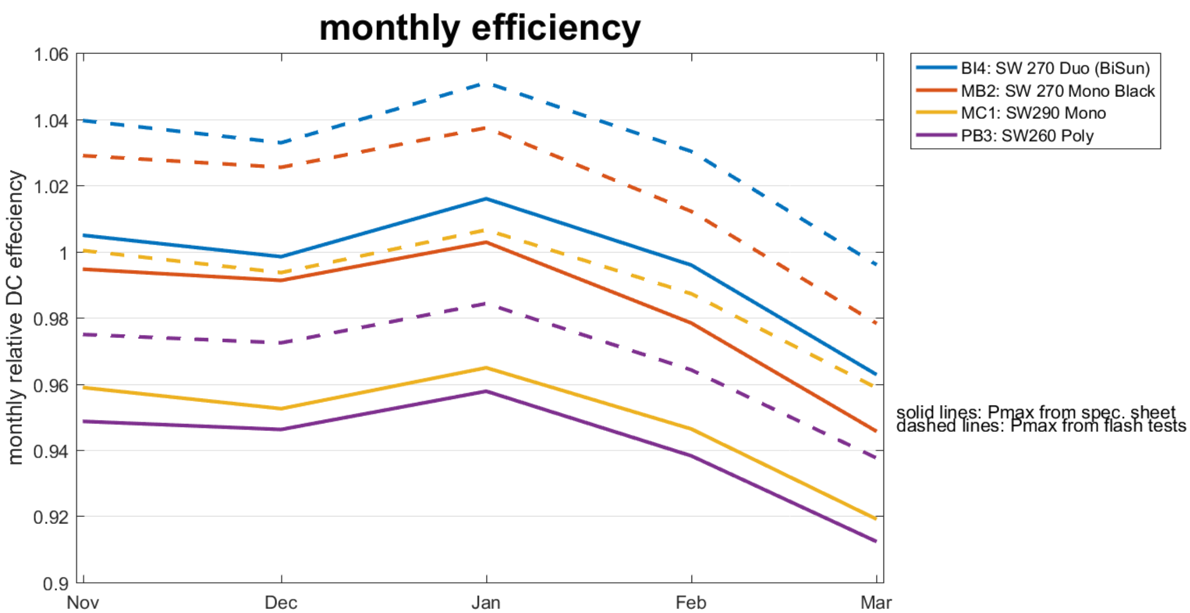


Figure 12: Monthly efficiency for each string. Note the high efficiency of the bifacial (BI4) modules (*blue dashed line*) and the MB2 modules (*dark-orange dashed line*), which are glass-glass and therefore tend to have cooler cell temperatures (*see Table 4*.) Even so, all modules show a decrease in efficiency in the early part of 2017, likely attributable to rising temperatures.

5.4. Measured Bifacial Gain of Bisun Modules

Instantaneous bifacial gain (BG_i), that is, the increase in energy yield from a bifacial module relative to a monofacial module under the same conditions, can be readily quantified using the following equation: BG_i

$$BG_i(t) = 100\% \times \left(\frac{P_{bifacial}(t) \;/\; Pmax_{bifacial}}{P_{monofacial}(t) \;/\; Pmax_{monofacial}} - 1 \right), \qquad 1$$

When we plotted the monthly bifacial gain of the SolarWorld BI4 modules against the energy output of the other three SolarWorld modules, we found the monthly bifacial gains to be between -1 and 6 percent. When we looked at three months of performance, we found a similar range of values for the BI4 modules of from -0.62 to 4.95 percent (*see Figure 13*.)

The range of values reflects the three-way comparison of the BI4 modules with the MB2, MC1 and PB3 strings, each of which has different performance characteristics. But the results are nonetheless surprising because the overall bifacial gain is relatively small and actually negative when compared with the MB2 modules. For that reason, and because the low results remain even when using flash test Pmax values, we plan to investigate further.

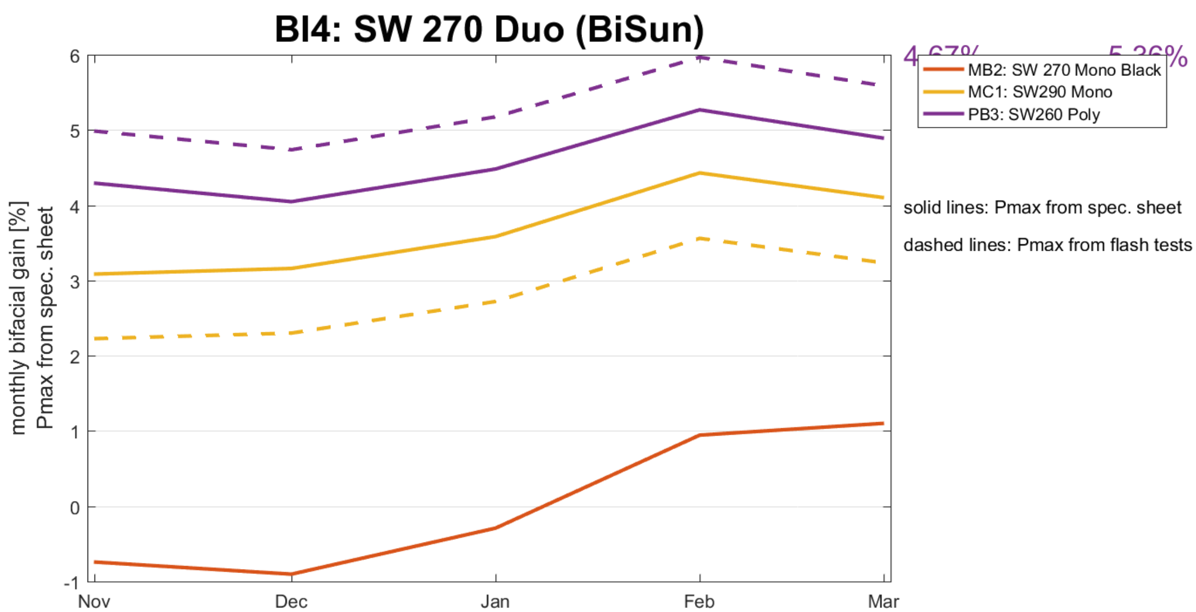


Figure 13: Monthly average bifacial gain for SolarWorld's Bisun (BI4) modules, compared with three SolarWorld monofacial modules. The above calculations are based on Pmax values provided by SolarWorld (*solid lines*) and measured by Sandia (*dashed lines*.)

5.5. Efficiency on a Clear and Cloudy Day

To investigate the impact of clouds on instantaneous string-level DC efficiencies, we measured the changes in the relative efficiency of each string over an eight-hour period on November 27, 2016, a day with both clear and cloudy periods. We also plotted irradiance measurements from the system's EETs reference cell against cell temperatures for modules from each string (*see Figure 14.)* As seen in Figure 14, and noted in Table 4, the cell temperature measurements for string MC1 are higher than for the other three strings and the relative efficiency of string PB3 is consistently less than the other strings.

The behavior of bifacial string BI4 on this day shows that bifacial gain (as seen here through a higher relative efficiency than the monofacial modules) is much larger during cloudy periods (10:00 to 13:00) than during clear periods (13:00 to 16:00).

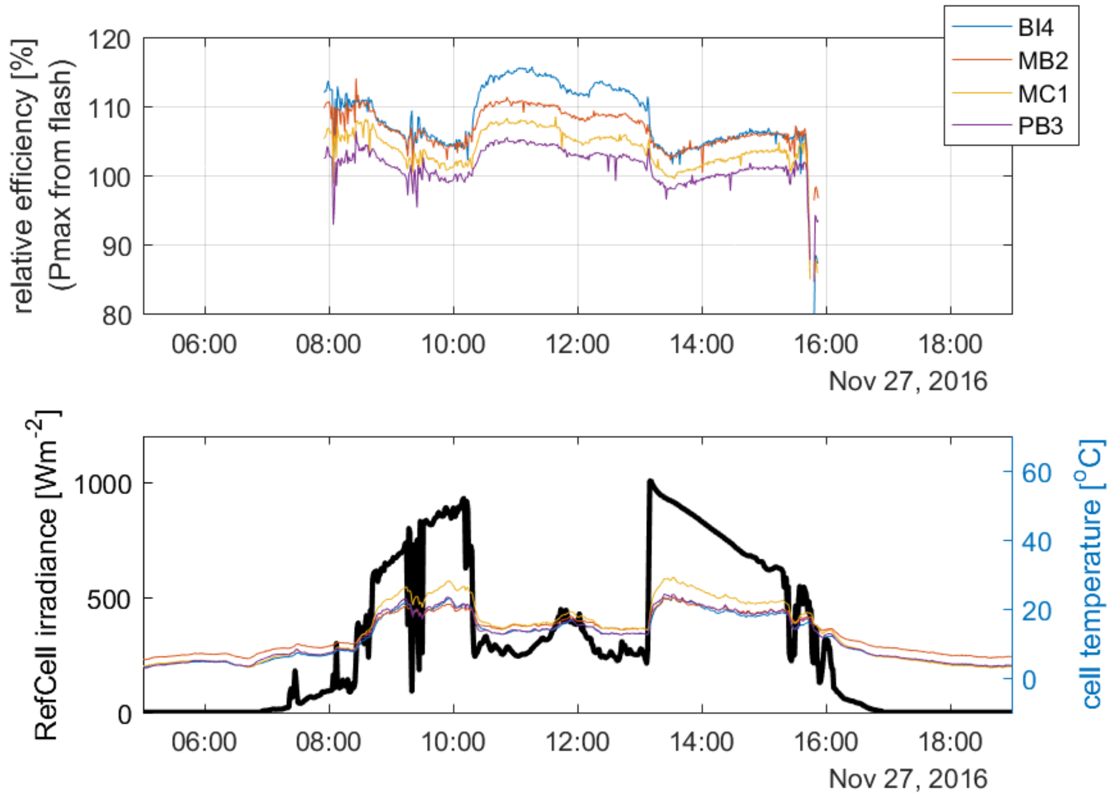


Figure 14: Relative DC efficiency for each of four strings (*top*), reference cell irradiance (*bottom, black line*), and cell temperature for each string (*bottom, colored lines*) on November 27th, 2016.

6. CONCLUSIONS

- Overall, the four-string SolarWorld system in New Mexico has performed well and shown no signs of premature failure, although not all strings perform equally.
- Most SolarWorld strings closely match their specification sheet module temperature coefficients, with modules measuring within 3 percent of their expected efficiency under standard test conditions.
- When Pmax values from Sandia's flash tests are used, three of the four strings produce slope intercepts that exceed 100 percent at STC conditions, showing they are performing well within expectations.
- The one string that consistently underperforms is PB3, which is made up of polycrystalline cells. String PB3 ran about 6 percent below its expected STC relative efficiency. Although these results may be affected by light exposure, as well as mismatch within the string, and not a production flaw, Sandia will likely investigate further if the discrepancy persists.
- Strings PB3 and MC1 operate with slightly higher cell temperatures than the other strings, although these differences may not be statistically significant.
- Monthly efficiencies show a slight seasonality, with relative efficiencies increasing as ambient air temperatures drop, as would be expected, but these differences need to be supported by a longer data record and with performance data from other RTC sites.
- Instantaneous bifacial gains for SolarWorld's Bisun modules (string BI4) were modest, ranging from 0 to 10 percent, although the racking was not optimized for bifacial modules, the installation site was not optimized for albedo and the study data represent only six months. The gains were smallest during clear periods, suggesting that bifacial modules might offer greater relative value in cloudier regions of the country. But more data, not only from New Mexico but also from the other RTCs, is needed to better understand the impact of cloudiness on bifacial energy gain.

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