HOLOGRAPHIC CPV FIELD TESTS AT THE TUCSON ELECTRIC POWER SOLAR TEST YARD

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ABSTRACT

Holographic concentrators incorporated into PV modules were used to build a 1600 W grid-tied PV system at the Tucson Electric Power solar test yard. Holograms in concentrating photovoltaic (CPV) modules diffract light to increase irradiance on PV cells within each module. No tracking is needed for low concentration ratios, and the holographic elements are significantly less expensive than the PV cells. Additional advantages include bi-facial acceptance of light, reduced operating temperature, and increased cell efficiency. These benefits are expected to result in higher energy yields [kwh] per unit cost. Field tests of the holographic concentrator system are reported here. A performance ratio greater than 1 was observed. The field tests include comparison with other flat plate non-tracking PV systems at the same test yard. Predicted yields are also compared with the data.

HOLOGRAPHIC CONCENTRATOR

The optical physics of holographic concentrators is described in more detail elsewhere [1-3]. The present study reports field tests of a holographic CPV system shown in Figure 1 that was designed and constructed by Prism Solar Technologies Inc. [4]. The system was commissioned in October 2010 at the Tucson Electric Power solar test yard, where 20 other grid-tied PV systems are operating for comparison purposes [5].

Our main finding is that the holographic CPV system produces larger final yields [kwh/kwp] than traditional flat plate PV systems [6]. Based on preliminary data we predict an annual final yield of 2240 kwh (ac) per kwp (dc) for a fixed-tilt (32^{o}) holographic concentrator system in Tucson as compared to 1700 kwh/kwp for more traditional flat-plate systems. Explanations for these high yields include bi-facial acceptance of light, reduced operating temperature, and increased module operating efficiency in the field.

The holographic CPV system developed by Prism Solar Technologies contains 32 modules, each rated under STC conditions to produce 50 Watts dc. The STC rating was done with a SunSim module testing apparatus made by Pasan and operated at Prism Solar Technologies. To

Figure 1. The holographic concentrator PV system made by Prism Solar Technologies, Inc. The modules are 20 x 32 inches, and feature holographic diffraction gratings embedded within each module between strips of PV cells.

understand the high performance ratios found in the field, it is important to note that the STC ratings were determined with the modules in front of a black background. However, the modules are made with Hitachi bifacial cells and were observed to produce 15% to 19% more power at mpp when flash tested with a white background. It is also possible that the effectiveness of the holograms for concentrating light is higher in the field conditions than in the flash test conditions.

In the field the modules are positioned above a white-painted mock roof. An SMA-4000 inverter was used. Power data are acquired by three independent methods: a revenue-grade kwh meter digitally reports Watt-hour increments of energy, a Hall probe measures dc current and dc voltage with a resistor network, and the commercially available data logging system that accompanies the SMA inverter reports both dc and ac measurements. Results from the three measurements of power are consistent within 5%.

COMPARISON SYSTEMS

Data from three comparison photovoltaic systems are also shown in this paper. The comparison systems, like the Prism Solar Technologies system, are all held at a fixed angle, facing south at 32-degrees. The four PV systems in this study are listed in Table 1. The output every minute on November 8, 2010 from four PV systems is shown in Figure 2. The data are normalized by the STC kwp ratings in order to better compare the PV systems of slightly different sizes.

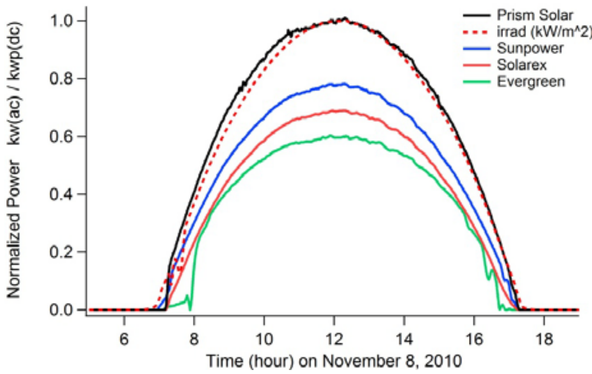

Figure 2. Normalized AC-power (kw/kwp) on November 8, 2010, plotted every 1-minute for four PV systems. Irradiance (kw/m^2) is also plotted (dashes).

Table 1: PV Systems compared in this study.

Prism Solar Technologies (holographic concentrators) 32 modules each rated at 50 W. Total DC rating: 1600 Watts. System Commission date: 10-20-2010. SMA 4000 inverter. Yield on 11-08-2010: 7.2 kwh/kwp. Performance Ratio on 11-08-2010: 1.04
SunPower (SPR-215-WHT-U) 9 modules of x-Si each rated at 215 W. Total DC rating: 1935 Watts. System commission date: 07-2009. SMA 3000 inverter. Yield on 11-08-2010: 5.5 kwh/kwp. Performance Ratio on 11-08-2010: 0.78
Solarex (MST-43MV) 60 modules of thin film a-Si each rated at 43 W. Total DC rating: 2580 Watts. System commission date: 05-2004. Xantrex inverter. Yield on 11-08-2010: 4.7 kwh/kwp. Performance Ratio on 11-08-2010: 0.68
Evergreen Solar (EC-115-GL) 17 modules of px-Si each rated at 115 W. Total DC rating: 1955 Watts. System commission date: 04-2009. Soleil inverter. Yield on 11-08-2010: 4.1 kwh/kwp. Performance Ratio on 11-08-2010: 0.59

The total radiant energy per area on November 8, 2010 was 6.9 kwh/m^2. The daily final yield (kwh/kwp/day) and performance ratio (PR) for each of the systems is listed in Table 1.

TESTING AN HYPOTHESIS ABOUT LOW-LIGHT LEVEL PEROFRMANCE

Holographic concentrators are predicted to enhance performance under low-light conditions because cell efficiency generally increases with irradiance, if the cell temperature is held constant. For example, theoretical cell efficiency vs. irradiance curves are shown in Figure 3 along with a histogram of irradiance. The increased cell efficiency associated with a concentration factor of 2 is shown in solid red. The histogram (black bars) summarizes a year of measurements every 1-minute during 2010 of the global irradiance at 32-degrees in Tucson, AZ.

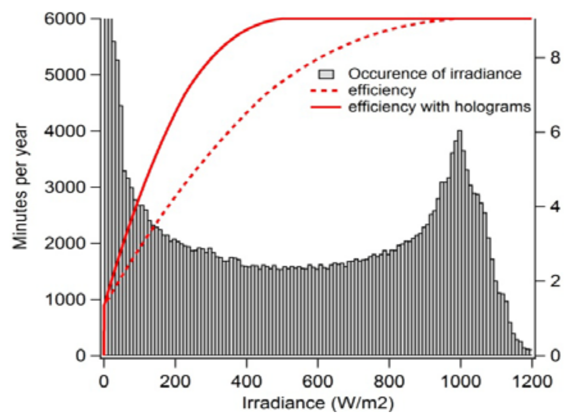

Figure 3. The occurrence of various irradiance levels (bars) compared with cell efficiency without concentration (dashed) and with a concentration factor of 2 (solid curve).

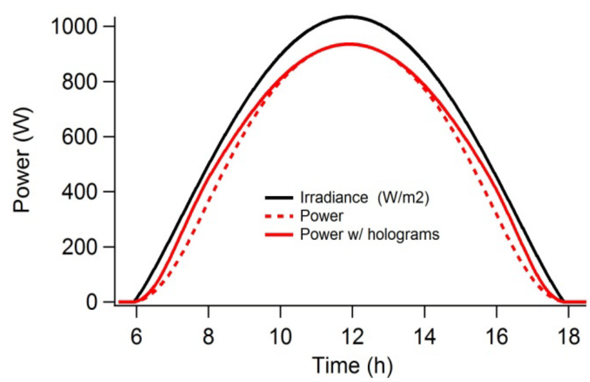

Figure 4. PV output models highlighting how concentration improves cell efficiency, especially at low light levels, and hence can increase annual energy yields by 7%.

The claim that concentration increases the low-light performance is a testable hypothesis with the system-to-system comparison. A model developing predictions based on this hypothesis is put forth, as shown in figures 3 and 4. The main result of the model is to increase the relative performance of a CPV system during hours of low irradiance, for example near 8:00 and 16:00. Preliminary system-to-system comparison data shows this effect is weaker than predicted in Figure 4. Explanations for this discrepancy include inhomogeneous concentration on cells within a string (analogous to a shade impact factor). This discrepancy could also be explained if the cell efficiency does not depend so strongly on irradiance.

EFFECT OF DIFFUSE LIGHT ON BIFACIAL MODULES

The 20% to 40% higher performance ratio of the Prism Solar system compared to traditional flat-plate PV systems can be partly explained by the bifacial acceptance of light of the Prism modules. STC flash testing only rates photovoltaic modules based on light incident on one module face and not both. Two experiments testing the effect of light incident on the back face of the module were conducted. In the first experiment, the white-painted mock roof behind the system was covered with black painter's plastic, as shown in Figure 5. This absorbed most of the light that would normally be reflected by the white roof. This experiment did not result in a significant temperature increase (<1°C). The second experiment blocked all light incident upon the back face of each module by directly covering the back with black fabric, as shown for two strings in Figure 6. The white roof was left uncovered. This shading method increased the module back surface temperature by 5°C.

Figure 5. Shading experiment covering mock white roof with black plastic that reflects light onto backside of modules.

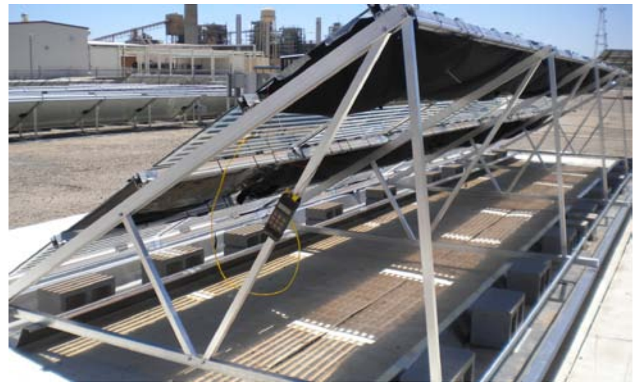

Figure 6. Shading experiment covering back of module with black canvas that blocks all albedo and diffuse light that would otherwise be accepted by bifacial modules.

Current loses due to both shading experiments for all four system strings are shown in Figure 7 and Table 2. It is important to note that string current losses were measured for unshaded strings when adjacent strings were covered directly with black canvas fabric. String 1 is the row of eight modules closest to the ground and string 4 is the row furthest from the ground. Because the top row recieves the most diffusely reflected and scattered light, String 4 was expected to demonstrate the most power loss due to shading. Strings 1 and 3 do not show as large a current loss due to direct shading as expected. This could be due to either the normal presence of cinder blocks (as mounting hardware) under the strings, which do not reflect as much light as the white mock roof, or to the time of day in which these measurements were taken, i.e. shading the back surface might make a greater impact at solar noon.

Table 2. Current losses due to shading experiments that block albedo and diffuse light incident upon the back face of CPV modules.

	Current loss due to ground shading of black plastic	***Current loss due to direct string shading of black canvas***
String 1	8.9%	3.9%
String 2	5.2%[1]	9.3%
String 3	8.8%	5.1%
String 4	8.8%	11.0%

[1] It is expected that current loss due to ground shading for String 2 is actually closer to 8.8%, but noise present on the sensor during experiment results in a low averaged value of 5.2% loss. This error reduces the total system current loss due to shading reported later.

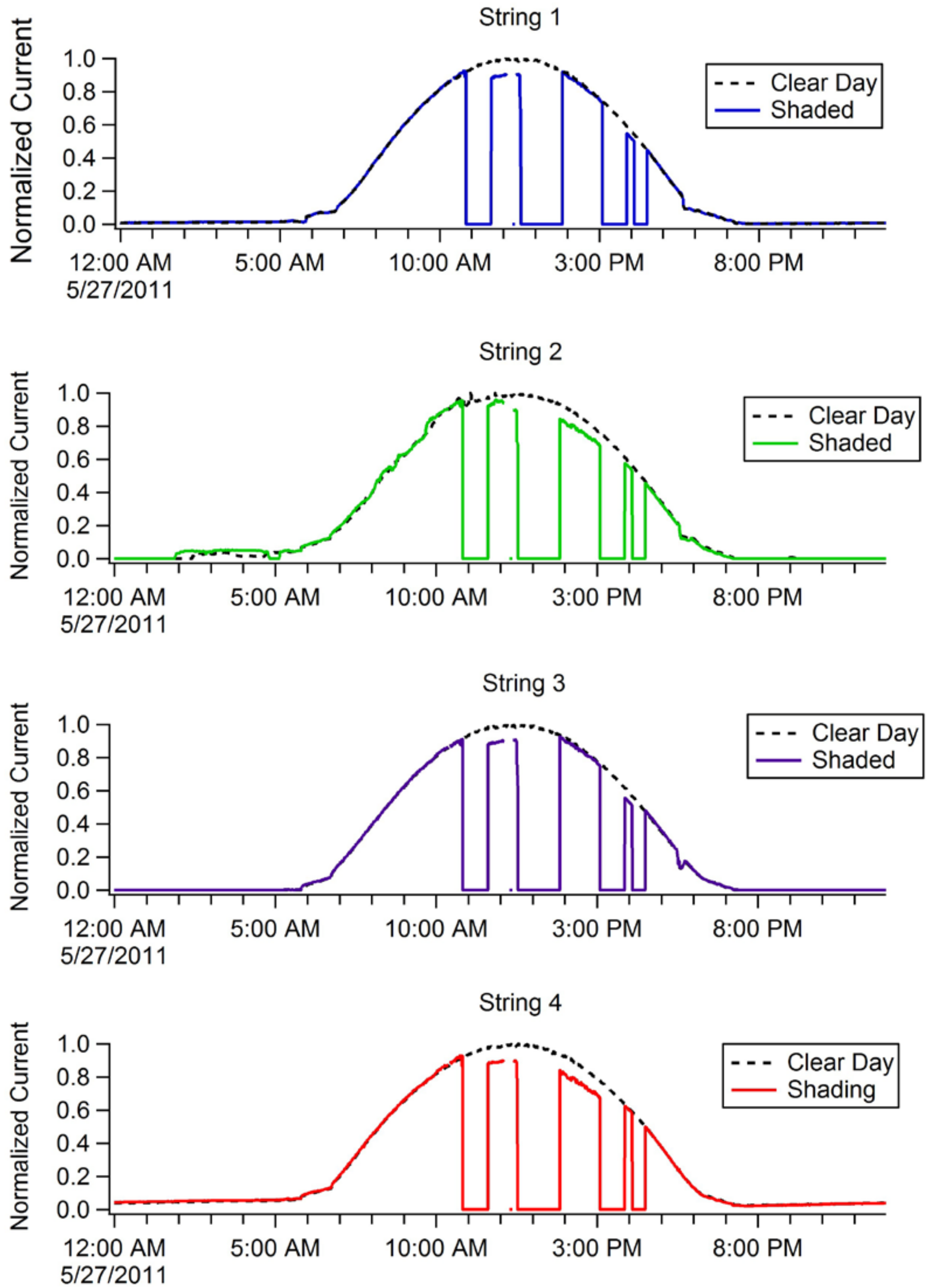

Figure 7. Normalized current response to shaded back face of Prism modules. Shaded strings are shown separately for clarity. The dashed black line is string output for unshaded system measured the day following shading experiments. System is unshaded from 5:00 to 10:45am and again from 4:30 to 8:00pm on May 27, 2011. The white mock roof was shaded from 11:35am to 12:30pm with a few minutes of data loss around 12:15pm. The back face of strings 2 and 4 were directly shaded from 1:45 to 3:15pm and strings 1 and 3 were shaded in the same manner from 3:50 to 4:10pm.

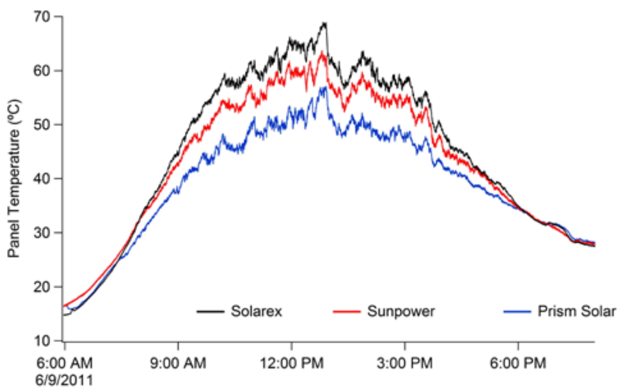

Figure 8. Operating temperatures for three systems on June 9, 2011 showing a maximum temperature difference of 10°C between Prism Solar and Solarex.

DISCUSSION

To explain the 20% to 40% higher performance ratio compared to traditional flat-plate PV systems, bifacial acceptance of light is proposed to be the dominant factor. Blocking the white-painted mock roof under the CPV system with black plastic reduces the system DC current by 7.9% (while the system DC MPP voltage remained constant). Blocking all light reaching the back face of each individual string with black fabric produces string current losses between 3% and 11%. These significant amounts of electrical output due to illumination of the back surface are not accounted for in the STC power rating for the modules.

Other contributing factors to the high performance ratio of the holographic CPV system include a low operating temperature compared to flat plate systems, the higher albedo of the mock roof in front of the CPV system, and increased performance of the holograms in the field compared to the STC flash test.

The operating temperature of the cells is predicted by quantitative models to be cooler than traditional (non-concentrating) flat-plate modules operating temperatures [7]. Figure 8 shows the holographic CPV modules operate an average of 8±2°C cooler than Sunpower modules and 10±2°C cooler than Solarex modules at high noon on a summer day. Given a temperature coefficient of -0.45%/°C for the cells, the cooler operating temperatures can explain only a 3.6% to 4.5% increase in performance ratio over flat-plate systems.

The cooler operating temperature is expected due to the spectral-selectivity of the holographic concentrators and the proportionately larger surface area available to dissipate heat by the modules containing the thin strips of PV cells (see Figure 1). The heat dissipation has been studied in laboratory experiments and simulations [7] used to design the Prism Solar Technologies modules. In a future study the operating temperature of the holographic CPV module and cells will be compared to other PV systems (listed in Table 1) as they operate side-by-side in the field at the Tucson Electric Power solar test yard.

CONCLUSION

This study found the performance ratio of the Prism Solar Technologies holographic CPV system to be 20% higher than a system with Sunpower modules, and 40% more than a system with Evergreen modules. A contributing factor to this high yield is the acceptance of light on the back side of the CPV modules. Selective shading experiments we performed in the field indicate that illumination of the back face of modules explains approximately 10% increase in performance ratio. The contribution of diffuse light illuminating the module front face has not yet been determined. Preliminary studies of operating temperature suggest that the holographic CPV modules operate between 8°C and 10°C cooler than comparable flat-plate systems, explaining nearly a 5% increase in performance ratio over flat-plate systems. The remaining few percentage points of higher performance ratio could be explained by increased effectiveness of the holograms in full sun compared to the STC flash tester.

REFERENCES

[1] J. M. Castro, D. Zhang, B. Myer, and R. K. Kostuk, "Energy collection efficiency of holographic planar solar concentrators", *Applied Optics*, 2010, Vol. 49, pp. 858-870.

[2] R.K. Kostuk, J. Castillo, and J.M. Russo and G. Rosenberg "Spectral-shifting and holographic planar concentrators for use with photovoltaic solar cells" Proc. of SPIE Vol 649, 64901 (2007).

[3] R.K. Kostuk and G. Rosenberg "Analysis and Design of Holographic Solar Concentrators", Proc. SPIE 7043, 70430I (2008).

[4] http://www.prismsolar.com/

[5] http://www.uapv.org/

[6] B. Marion, J. Adelstein, K. Boyle, H. Hayden, B. Hammond, T. Fletcher,B. Canada, D. Narang, A. Kimber, L. Mitchell, G. Rich, and T. Townsend, "Performance Parameters for Grid-Connected PV Systems" IEEE PVSC 2005.

[7] J. E. Castillo, J. M. Russo, R. K. Kostuk, G. A. Rosenberg, "Thermal effects of the extended holographic regions for holographic planar concentrator", Journal of Photonics for Energy 1(1), 015504 (2011).