Presented at Solar 2004 Conf., July 9-14, 2004, Portland, OR

PERFORMANCE MEASUREMENTS OF A SLAT-ARRAY PHOTOVOLTAIC CONCENTRATOR

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ABSTRACT

In this paper we discuss the progress made in the development of a novel slat-array photovoltaic concentrator. The rationale of the new concentrator concept is in replacing a large parabolic trough mirror with an array of simple cylindrically shaped slats in order to gain additional optical, operational and cost advantages over the traditional concentrators.

A small concentrator PV prototype has been built and tested. The prototype is designed to provide about 40-suns single-stage concentration with relatively uniform illumination of solar cells. A very low weight to aperture ratio is obtained for the reflector and its support frame.

Different types of concentrator cells were used to measure the electrical output per unit collector aperture and estimate the actual concentration and system efficiency. The irradiance distribution across the focal line was studied using a digital CCD camera. The comparison of model estimates based on raytracing and experimental data is presented.

1. INTRODUCTION

Parabolic mirrors have been well known as sunlight collectors ideally suited for the parabolic trough thermal power technology. In the recent years, there has been an increased interest to the use of parabolic troughs in conjunction with photovoltaics. As the cost of large-area PV panels is very high, concentrators can be used to substitute a substantial part of PVs with less expensive optics.

However, the two major obstacles have been limiting the progress and adoption of concentrating photovoltaics involving conventional parabolic troughs: the still high cost of large-aperture mirrors and their support structures and the performance and reliability issues of PV cells exposed to highly non-uniform concentrated fluxes.

In our earlier work (1), we discussed an alternative approach for concentrating the sunlight efficiently and inexpensively using a novel slat-array concentrator (SAC) and described the initial progress in developing a concentrator photovoltaic (CPV) prototype module.

The concentrator is based on an array of relatively narrow concave strips of reflective material (slats) aligned to reflect the incident radiation through spaces between the adjacent slats downward to a common linear focus. The slats replace a continuous-surface mirror of the parabolic trough with a sort of self-supporting reflective lattice which can be fabricated more easily and at a lower cost.

An additional opportunity existing in the non-imaging slat-array approach is the ability to tailor the concentrated flux for obtaining either maximum concentration in the focal spot or a uniform illumination of the target receiver by selecting a suitable arrangement of individual slats. This feature not found in traditional optics was used to optimize the concentrator for irradiating PV cells more uniformly while keeping the concentration ratio at relatively high levels of 40 suns and above.

2. THE PROTOTYPE

A small pilot-prototype CPV based on PV-adapted SAC was fabricated. In order to simplify testing and facilitate the access to the receiver disposed below the concentrator, an asymmetric design of SAC was implemented (see Fig. 1).

2.1. Mirror

The concentrator mirror includes 10 reflective slats which dimensions, positions and shapes were calculated from raytracing. The slats were fabricated from 3″-wide strips of solar-grade reflective aluminum coil and secured between two side walls having laser-cut slots for precise slat positioning. The specular reflectivity of this material is between 88% and 91% (2). The longitudinal rigidity for each slat was ensured by attaching a non-reflective aluminum coil stiffener to the slat's back side in the shadow zone so that neither incident nor concentrated fluxes were intercepted.

In order to depart from using rather complex parabolic profiles all slats have been curved to simple cylindrical shapes. It was possible due to the unique concentrator's optical configuration employing a segmented mirror composed by almost planar slats. Obviously, at a large radius of curvature much exceeding the length of the transversal slat profile, the circular shape is almost indistinguishable from the corresponding parabolic one, which allowed to make this transition without impairing the overall sunlight collection ability.

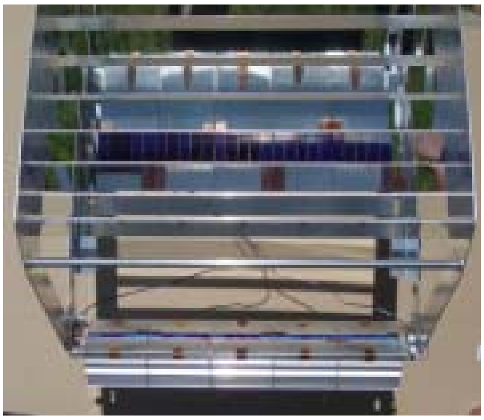

Fig. 1: Top view of the experimental slat-array CPV

The prototype CPV was mounted on a commercially available two-axis solar tracker customized for a bit higher tracking precision. The tracker's gear drive provides azimuth and elevation sun tracking both in automatic and manual modes with the accuracy in elevation of 0.1 to 0.3 angular degrees.

The prototype concentrator has the active aperture of about 1.7 ft^2 and designed to collect the sunlight to a centimeter-wide (0.4″) linear receiver with approximately 38:1 concentrator to receiver aperture ratio.

2.2. PV receivers

A selection of experimental PV receivers was fabricated for testing the concentrator as a CPV device. Each receiver module incorporated a strip of five series-connected concentrator silicon cells from SunPower Corp. of Sunnyvale, Calif. The backside point contact cells were bonded to an extruded aluminum heat sink with a thermal conductive adhesive tape. Fig. 2 shows one of the passively cooled experimental PV receiver modules.

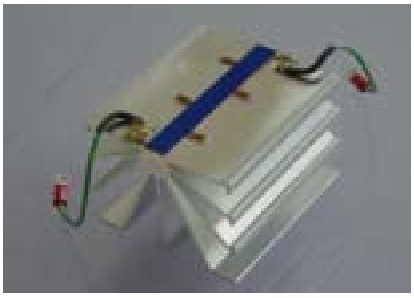

Fig. 2: A five-cell PV receiver module with passive cooling

Another test receiver with known characteristics was ordered from Spectrolab of Sylmar, Calif. The receiver is based on a single triple-junction cell having 1 cm × 1 cm active area and mounted on a cooling plate (Fig. 3). An active pumping water chiller shown in Fig. 4 was assembled to improve heat dissipation and keep the cell temperature low.

Fig. 3: A single-cell reference PV module based on a triple-junction cell.

Fig. 4: A water-carrying chiller for reference PV receiver

3. TEST SETUP

The test setup included optical and electrical parts each aimed at independent verifying the concentrator efficiency and optical performance.

The optical part was based on a digital CCD camera for imaging the concentrated flux visualized by a uniformly scattering target. Light profiles of the captured digital images were used for tracing the energy distribution across the focal line and estimating the amount of light that reached the target after being reflected from the concentrator.

We used a scientific-grade monochrome CCD camera to capture digital images of the focal spot with the spatial resolution of 1360 x 1024 pixels and 10-bit dynamic range. A set of neutral density optical filters was used to control the amount of light entering the CCD and prevent its overexposure.

The digital camera was installed on the tracker's torque tube at a distance of about 1ft from the concentrator focal line (see Fig. 5) and pointed to the light scattering target. The target was a thin glass plate having a layer of compacted barium sulphate powder deposited on its receiving surface. This type of target is a good approximation of the ideal Lambertian surface isotropically scattering the incident light and which visible brightness depends linearly on the illumination level only in a wide range of orientations. A reference scale was attached to the glass plate to assist in measuring the size of the focal spot.

Focal images were captured as individual frames of the live video stream using the software interface supplied with the camera. The images were encoded with a lossless format and stored on the computer hard drive for further processing.

A complete set of images for each exposure included one or more pictures of the concentrator-illuminated target, a series of pictures capturing the irradiance background on the target with and without direct sunlight illumination, one-sun illuminated target, two and three suns when appropriate, and a closed-diaphragm background (dark current of the CCD).

The natural illumination level was measured by exposing the target to the direct normal solar radiation. An alternative method for estimating the one-sun irradiance level was based on the use of flat mirrors laminated with a silvered, 95%-reflective film and positioned to reflect the sunlight to the target and provide uniform illumination of 1 to 3 suns.

The electrical part of the test setup was based on measuring I-V curves for different PV receivers placed in the concentrator's focus and comparing their electrical current and power output under concentration with the corresponding parameters of the same receivers exposed to the ambient (non-concentrated) sunlight.

The level of direct solar irradiance was measured with a normal incidence pyrheliometer (NIP). The cell temperature was measured with a J-type thermocouple having the accuracy of 1° C. The sensitive end of the thermocouple was attached to one of the electrical contacts of PV cells close to the cell's edge. Relative humidity and ambient air temperature were measured and recorded for each set of measurements.

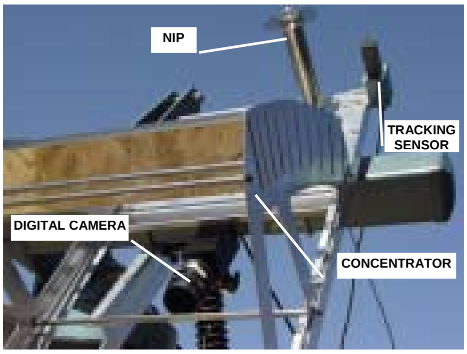

Fig. 5: The prototype concentrator under testing

The I-V curves for different PV receivers were traced by simultaneous capturing the magnitudes of ADC, VDC, cell temperature, and the level of direct incident solar radiation by a multi-channel multiplexer/datalogger. The successful scans were downloaded to a PC for further processing.

4. RESULTS AND DISCUSSION

4.1. Receivers based on silicon cells

Table 1 shows the peak values of short circuit current I_{sc} measured at normal operating temperatures for different test receivers in August-September, 2003. The measurements were normalized for 1,000 W/m^2 direct incident power assuming the direct component of solar irradiance for clear sky conditions and for relatively small zenith angles of the sun at Sacramento's latitude being 95% of global radiation. The table also shows the corresponding values of concentrator optical efficiency adjusted for the optical losses due to the off-normal incidence of the concentrated sunlight onto the cells.

Table 1. Concentrator optical efficiency estimated from short circuit current measurements.

Receiver	I_{sc} , A	η_{opt} ,%
#1	1.85	84.9
#2	1.83	85.6
#3	1.85	83.6
#4	1.84	84.7

The estimated optical efficiencies shown in Table 1 vary only slightly from 83.6% to 85.6% thus exhibiting a good consistency for different receivers and sunlight conditions. The experimental data are also in a good agreement with the targeted concentrator efficiency of 85% for the small prototype.

Fig. 6 shows normalized averaged I-V curves obtained for different receivers, and Fig. 7 shows the corresponding power curves.

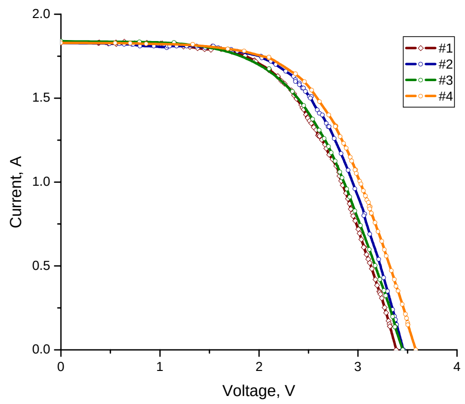

Fig. 6: Measured I-V curves for different receiver modules

Despite the data were averaged for a series of measurements taken at different dates and for slightly varying zenith angles of the sun, the behavior of generated electrical current is consistent for all receivers indicating similar normalized illumination levels for the cells.

The absolute magnitude of open circuit voltage V_{oc} showed a 3-4 per cent difference between the receivers. However, its variation was also within the anticipated range. According to the manufacturer's specifications for the concentrator cells, their temperature coefficient for V_{oc} is about 0.22% per degree which corresponds to a 2.2% drop in voltage at the temperature increase by 10°C. The average cell operating temperature was varying from about 55°C to 65°C depending on test conditions where the temperature differences in individual measurements between the receivers were sometimes 15°C and above.

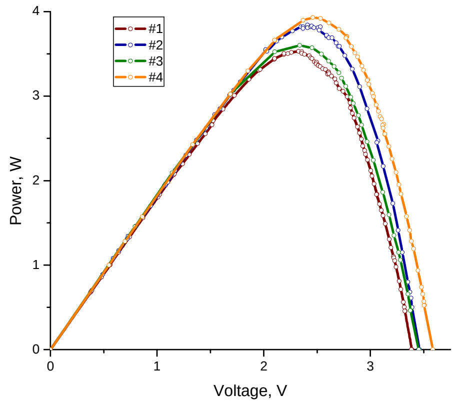

Fig. 7: Power curve comparison

The total power output from test receivers under the variable resistive load was somewhat below the expectations, however. This indicates that the overall solar to electric efficiency of the system was affected by some imperfections in the photovoltaic receiver design.

The individual concentrator cells that we used are optimized for concentrations of about 100 suns are designed to have the fill factor value of about 0.76 at 25 W/cm^2 illumination level and about 0.81 at 9.6 W/cm^2 (100 suns).

The fill factor obtained from the measurements of test receivers incorporating five series-connected cells was about 0.69-0.70 for the ambient direct sunlight and about 0.60 for 40-suns concentrated flux, both values being well below the expectations based on the characteristics of a single cell. The reason for such degradation of the fill factor can be a mismatch in series resistance of the cells within each 5-cell module, insufficient thermal conductivity of cell/heat-sink interface and even possible partial damage of the extremely fragile cells during soldering at the time of receiver fabrication.

As a result, the solar to electric efficiency of the CPV prototype based on in-house fabricated PV receivers was also somewhat lower than we expected for these cells. For example, at the efficiency of a single concentrator cell of about 22% at 40 suns, the peak power output by test receiver #4 was 3.93 W which corresponds to a peak CPV system efficiency of 14.3% versus projected 16% to 18%. Nevertheless, the measured efficiency is still well comparable to the efficiencies reported for other linear focus CPVs employing silicon solar cells.

4.2. Test receiver based on a triple-junction cell

Figs. 8 and 9 show measured I-V and power curves for the reference receiver based on a single triple-junction cell. As it can be seen from the plotted data being normalized to 1kW/m^2 direct irradiance level, the factory-manufactured receiver performed significantly better than any of the in-house fabricated receivers. Different runs of measurements conducted at different time produced very close results. The cell temperature was kept nearly constant at about 25 ºC to simulate normal test conditions.

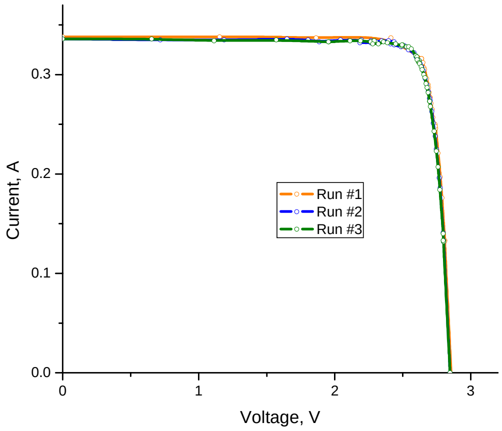

Fig. 8: Experimental I-V curves for the single-cell receiver

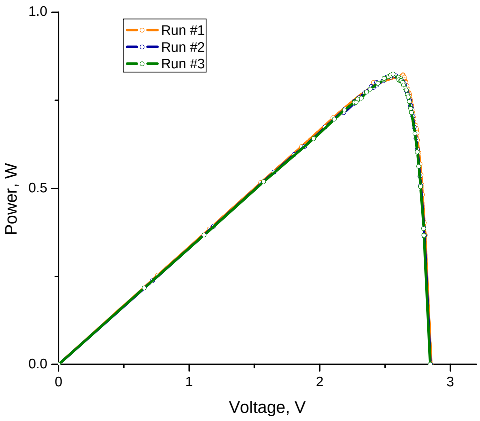

Fig. 9: Power curves obtained for the reference receiver

Table 2 shows the comparison of CPV-measured electrical parameters with the corresponding reference data for the triple-junction cell. The reference data were obtained by the interpolation of corresponding cell characteristics for V_{oc}, fill factor FF, and the cell efficiency at different concentration levels available from Spectrolab and based on solar simulator measurements at NREL.

Table 2. Comparison of measured and reference cell parameters

Parameter	CPV module (prototype)	Reference cell (30-40 suns)
I_{sc} , A	0.34	N/A
V_{oc} , V	2.85	2.83
FF	0.87	0.87-0.88
Max power, W	0.84	N/A
Efficiency, %	22.0	28

The measured V_{oc} and FF values are very close to those derived from manufacturer's data. The total solar to electrical efficiency of the prototype CPV obtained from the measured I-V curves is 22% which makes 78.6% of the cell rated efficiency (28%).

The optical efficiency of the concentrator alone was more difficult to estimate from these measurements since no data on I_{sc} and power output of the reference cell was available at the time of experiments. However, taking into account the anticipated optical losses due to the presence of off-normal incident rays and possible mismatch between the cell spectral response and the spectrum of concentrated beam, we estimate the optical efficiency of concentrator prototype to be about 84% – 85%. This estimate is consistent with that based on the ratio of short circuit currents for the receivers employing concentrator silicon cells (see above).

4.3. Flux mapping

Fig. 10 shows a raw focal image of the prototype SAC. The corresponding irradiance distribution in the concentrator focus is shown in Fig. 11 where the concentration level was calculated relatively to the level of direct solar radiation after subtracting the background and dark current noise.

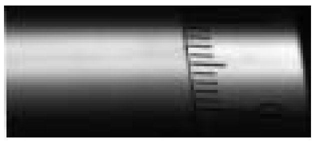

Fig. 10: Focal image of the concentrator focal spot. The scale is graduated in 1-mm increments.

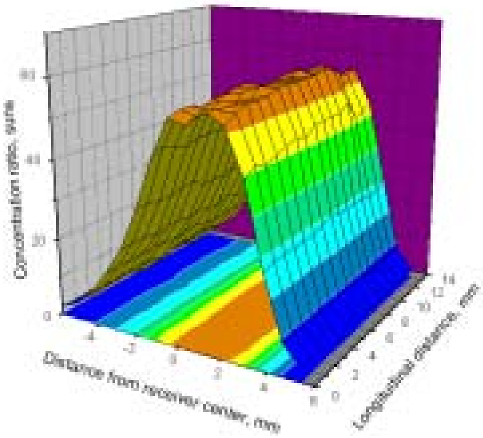

Fig. 11: Measured irradiance distribution on a flat lambertian receiver.

The analysis of the irradiance distribution confirms that over 95% of the direct solar radiation collected by prototype SAC is confined within the boundaries corresponding to a 1cm-wide receiver as it was anticipated from raytracing.

As it can be seen from Fig. 11, the irradiance level of central zones of the receiver does not exceed 60 suns which means that the hot spot in the receiver center has been practically eliminated. Despite the actual energy profile is not shaped exactly the same as the calculated profile (1), notable flattening of the central part of measured distribution can clearly be seen.

The size of the focal spot determining the geometrical concentration has revealed a good stability with respect to the receiver misalignment or small displacements, as well as concentrator tracking errors of up to 0.3°. As it was expected from raytracing, large longitudinal misalignments of up to 45° simulating one-axis tracking showed only the effects of cosine dependence of surface illumination on the incident angle.

However, unlike the concentration ratio, the flux uniformity exhibited a considerable sensitivity to the proper receiver positioning and alignment. The replacement of individual slats and the effects of slats being slightly loose in the side wall slots also affected the shape of flux distribution without degrading the overall concentration.

Fig. 12 shows the change in the flux map for a receiver which is moved away by 2-3 millimeters from the designated target plane. It can be noted that, despite the flux distribution became sharper exhibiting even higher concentration in the receiver center, the "flat" area degraded significantly. Nevertheless, the peak concentration in the center increased by only 10 to 15 per cent being still well below the levels which could be expected in a traditional system designed for 40-suns geometrical concentration with no provisions for uniformity.

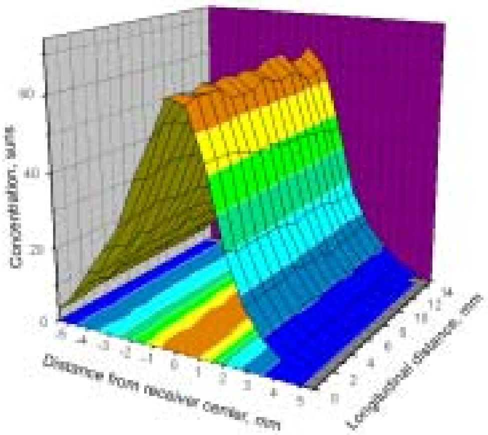

Fig. 12: Flux map for a displaced receiver.

CCD cameras are fundamentally linear offering a high signal to noise ratio in bright field conditions. Therefore, the gray level values in the captured images are linearly proportional to the target surface illumination. This allowed us to estimate the optical efficiency of the concentrator by comparing the signal counts corresponding to different illumination levels for the lambertian target exposed to a concentrated beam and to the direct sunlight.

Depending on different methods for measuring and subtracting the background and direct illumination, the calculated optical efficiencies were in the range of 86% to 89%. These values are higher than those obtained from electrical tests with photovoltaic receivers. On the other hand, the value of 89% is close to the "ideal" efficiency based on the specular reflectivity of the aluminum coil employed in the prototype. Therefore, there results can be regarded as a rather upper estimate requiring further verification.

5. FURTHER DEVELOPMENT

A larger demonstration concentrator prototype with the active aperture of about 30 ft^2 is being built. In this prototype, we are continuing the development of the described concentrator PV system and adaptation of SAC for photovoltaics.

The improved concentrator will provide a better flux uniformity and further simplify concentrator fabrication. It will have a symmetric configuration with relatively low profile which should simplify incorporating the module into arrays. Another goal of this effort is to adapt the concentrator to it possible use with PV receivers based on conventional silicon PV cells and adapted for about 20-suns uniform concentrations.

6. CONCLUSIONS

A pilot-prototype CPV system based on the slat-array concentrator has been developed and tested by two independent methods and using different photovoltaic receivers.

The study of concentrated flux profiles with CCD imaging confirmed the validity of our estimates of geometrical concentration ratio (38 suns) based on raytracing. This concentration is among the highest ever tried for linear focus CPVs utilizing no secondary optics.

The obtained good agreement between the calculated and measured optical parameters demonstrated that the developed concentrator design method and raytracing software can be used for designing the slat-array mirrors in a wide range of concentration ratios and illumination regimes for photovoltaic receivers. It also confirms that the selected concentrator fabrication technique and sun tracking were adequate in terms of required tolerances for providing the desired performance.

The measured solar to electric efficiency of the experimental CPV system based on a triple-junction PV cell was nearly 80%, while the optical efficiency of the concentrator alone was estimated to be about 85%. Note that the predicted efficiency being about the same was based on mirror reflectivity of 95%, whereas the reflectivity of the actually used aluminum coil could be as low as 89%. Thus, we can deduce that the solar to electric efficiency of the prototype CPV can be further increased by about 5% or more if a higher-reflectivity material is used for concentrator slats.

The improved flux uniformity demonstrated by the developed prototype can help eliminate the hot spots in the concentrator's focus and thus preserve the performance of photovoltaic cells and prolong their service life.

Due to skew positioning of slats, SAC can utilize about 40% more reflective laminate material than a parabolic trough having the same active aperture. However, the sufficient structural rigidity and wind resistance are achieved in SAC with much less material thickness. Therefore, the costs associated with the increase in laminate consumption are offset well in excess by the reduction in material weight. For example, the weight of the reflector in prototype SAC is about 0.47 kilograms which makes the weight to active aperture ratio of less than 3 kg/m^2 and which is considerably less than the weight of a similar-size trough reflector. Moreover, the reflective slats of SAC mirror can be produced inexpensively and in large quantities. Therefore, the costs associated with manufacturing solar mirrors can be significantly reduced.

The savings in concentrator support frame are perhaps even more important since the structures can be responsible for 40 to 65 per cent of the total cost in all kinds of concentrating systems. In the developed CPV prototype, the support frame for the concentrator and PV receivers is completely integrated into the design and weights about 6 kilograms per m^2 of aperture area.

Thus, the test results generally validate the slat-array concentrator concept and suggest that the proposed approach can be regarded as a low cost alternative to the parabolic trough concentrators.

7. ACKNOWLEDGEMENTS

This research was supported through the California Energy Commission's Public Interest Energy Research (PIER) Program and administered by the Sacramento Municipal Utility District (SMUD).

8. REFERENCES

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