A NOVEL 500W PHOTOVOLTAIC CONCENTRATOR

Sergey Vasylyev
SVV Technology Innovations, Inc.
P.O. Box 375
W Sacramento, CA 95691
vasilyev@svvti.com

ABSTRACT

This paper describes the design of a new linear concentrating PV (CPV) module based on the Slat-Array Concentrator (SAC). The device was conceived as a demonstrational prototype for future photovoltaic power generating modules having a significantly reduced area of PV cells. A new R&D project, supported by the California Energy Commission and Sacramento Municipal Utility District in 2001-2004, views SAC as an efficient and lower cost alternative to the commonly used concentrators which can make better use of the direct solar radiation particularly through the electricity generation.

The new CPV module has a total active collector area of 30 ft^2 (about 2.8 m^2) and weights about 10 kg/m^2 which includes a support frame. The wind drag is greatly reduced in this concentrator due to its open-latticework configuration. It is designed to operate at the geometrical concentration ratio of 20 suns and power capacity of about 500 Watts when high-efficiency cells are employed. It can also be used with conventional PV cells adapted to higher-density fluxes, e.g., quality monocrystalline silicon cells manufactured with narrower grid line spacing. Due to an optimized design, the concentrated flux is distributed about evenly across the PV receiver.

The module was mounted on a biaxial tracker to maximize the energy output during the day and tested using a PV receiver with known characteristics. Flux maps were also obtained using digital imaging of the concentrator's focal spot and compared to the irradiance profiles predicted from raytracing.

1. INTRODUCTION

Numerous studies have demonstrated that the concentrator PV technology is a lower cost alternative to the flat-plate photovoltaic arrays. While the high-concentration approach can more fully exploit the benefits of high-end multi-junction cells and produce maximum power per unit area, CPV modules working at low and moderate concentrations may help utilize a more abundant category of conventional cells made of silicon. Besides reducing the area of PV cells, the concentrator technology takes the advantage of higher cell efficiencies at more intense illumination levels.

SVVTI has been involved in the design and development of a novel-type solar concentrator called the Slat-Array Concentrator (SAC). SAC is a simple linear version of forward-focusing concentrators more broadly referred to as reflective lenses [1]. One of the applications of these concentrators being actively pursued in recent years is a concentrator PV module which could be used in future distributed power generation plants.

Several prototype modules based on SAC have been built and evaluated under R&D contract with the California Energy Commission (CEC) and Sacramento Municipal Utility District (SMUD). The most recent device was a proof-of-concept implementation of a 30ft^2 CPV module designed for up to 500 Watts of power output. The overall goal of this project was to explore new technical solutions to the problem of more efficient collection of sunlight and its use for power generation and reducing the dependence on conventional (non-renewable) sources of energy in California and elsewhere.

2. SYSTEM DESIGN

The concentrator optical configuration is similar to that of a smaller prototype described in our earlier paper [2]. It is based on an array of concave reflective slats positioned in a stepped arrangement and focusing the incident sunlight by reflecting it downward onto a narrow strip of PV cells.

The CPV structural design, however, has been modified to employ two arrays of reflective slats facing toward one another in a symmetric arrangement. This was done to better utilize the concentrator aperture and make the module more compact by reducing its relative vertical dimensions.

Fig. 1 shows schematically the mutual disposition of reflective slats and two linear PV receivers. As it can be seen from the figure, the device forms two concentrated beams crossing each other approximately midway between respective concentrator arms and receivers.

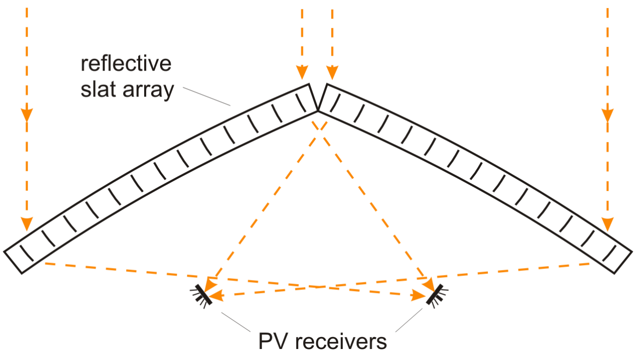


Fig. 1: A conceptual design of slat-array CPV.

The optimized SAC is based on 28 reflective slats and has an active aperture of about 30 ft^2. Its geometrical concentration ratio was reduced from about 40 suns tried previously to 20 suns to ease the requirements for PV cells and possibly even employ conventional one-sun cells. The system was adapted for the uniform illumination of a 4 cm-wide strip of PV cells.

Each slat being about 6 ft. long and 4.6″-wide was made of commercially available aluminized sheet with approximately 89% weighted hemispherical reflectance for the solar spectrum. The slats were designed to be of the same size and shape (see Fig. 2) which helped unify the manufacturing process. In the course of design optimization, they were also made almost flat in appearance to reduce the effect of shape imperfections on the concentrator performance.

In order to give the slat reflectors a desired concave shape with a large radius of curvature, they were bent to a radius on a specially fabricated template. The required structural rigidity for the mirror was secured using lightweight longitudinal stiffeners made of aluminum coil and attached to the back of each slat.

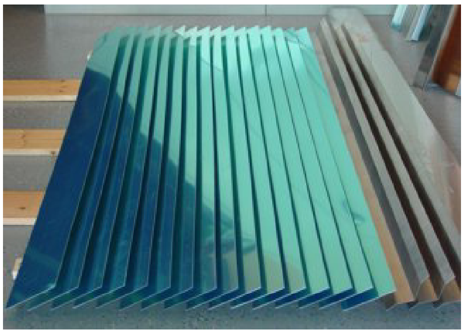


Fig. 2: A sample batch of slat reflectors.

A lightweight aluminum frame was constructed to support the slat reflectors and a pair of T-shaped aluminum receiver support beams. The final assembly weighting less than 30 kg (which corresponds to the distributed weight ratio of about 10 kg/m^2) was installed on a two-axis tracker for continuous operation. Fig. 3 shows the experimental CPV system based on SAC.

Fig. 3: Experimental slat-array CPV.

3. CALCULATED PERFORMANCE

The positions and mutual alignment of slat reflectors were individually selected using raytracing to obtain a uniform flux and still maintain 20x geometrical concentration.

The optimization of concentrator optics revealed the advantages of arranging the slat reflectors in a non-imaging array. It became possible to eliminate any hot spots by spreading the focal line about evenly across the receiver with only a single stage of reflection. Fig. 4 shows a calculated irradiance profile in the target plane of the slat array.

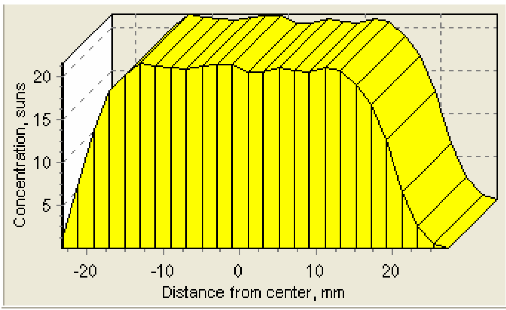


Fig. 4: Predicted flux distribution with no secondary optics employed.

As some flux irregularities still remained at the peripheral zones of the focal area (see Fig. 4), a focus improving secondary was considered to fix that. Fig. 5 shows the respective flux distribution improved using a secondary reflector.

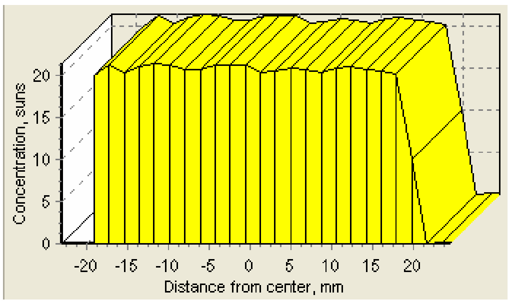


Fig. 5: The positive effect of a secondary reflector on flux distribution.

The secondary reflector is optional in this system. However, as raytracing has shown, it can be useful for reducing the energy spillage and further homogenizing the concentrated flux. It was designed merely as a pair of narrow reflective flaps attached to both sides of the strip of PV cells. Since these flaps only intercept 5 to 10 per cent of the concentrated flux, the respective losses on secondary reflection are negligibly small, unlike most other systems employing secondary optics.

4. FIELD TEST APPROACH

Outdoor tests were performed in Sacramento, CA area in August-September 2004. The measurements aimed at verifying the predicted system performance included short-circuit current measurement using a test PV receiver with known characteristics and flux mapping using a high-resolution digital CCD camera.

The test PV receiver was based on four 1cm×1cm high-efficiency triple junction cells connected in series and densely packed across the concentrator's focal line. During measurements, it was actively cooled by water circulating through its heat spreading plate so that the temperature of cells could be constantly kept in the range between 25°C and 30°C. Fig. 6 shows the experimental receiver with a detachable secondary reflector.

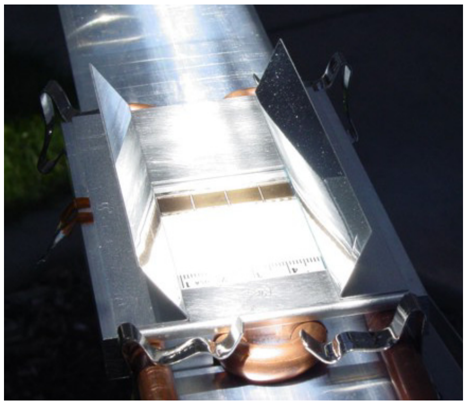


Fig. 6: Experimental PV receiver.

A 5cm×4cm light scattering target was attached to the receiver for capturing the focal spot images. It employs a quality glass plate having an optically dense layer of compacted barium sulphate powder deposited on one side of the plate. Fig. 7 shows a typical grey-scale image of the focal spot visualized with the scattering target.

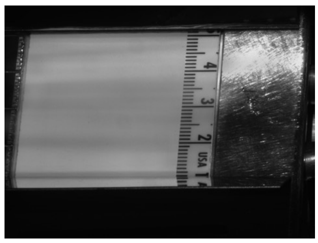


Fig. 7: An image of the concentrator's focal area.

The direct normal irradiance was measured with a pyrheliometer installed on the same tracking platform as the concentrator (Fig. 8). As the tests involved the comparison of electric current measurements for the PV receiver exposed to the ambient and concentrated sunlight, we also used a pyranometer to subtract the diffuse component of solar radiation when calculating the short-circuit current ratio.

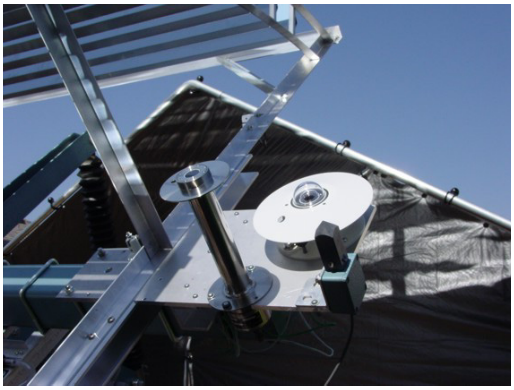


Fig. 8: Solar radiation measurement and tracking sensors.

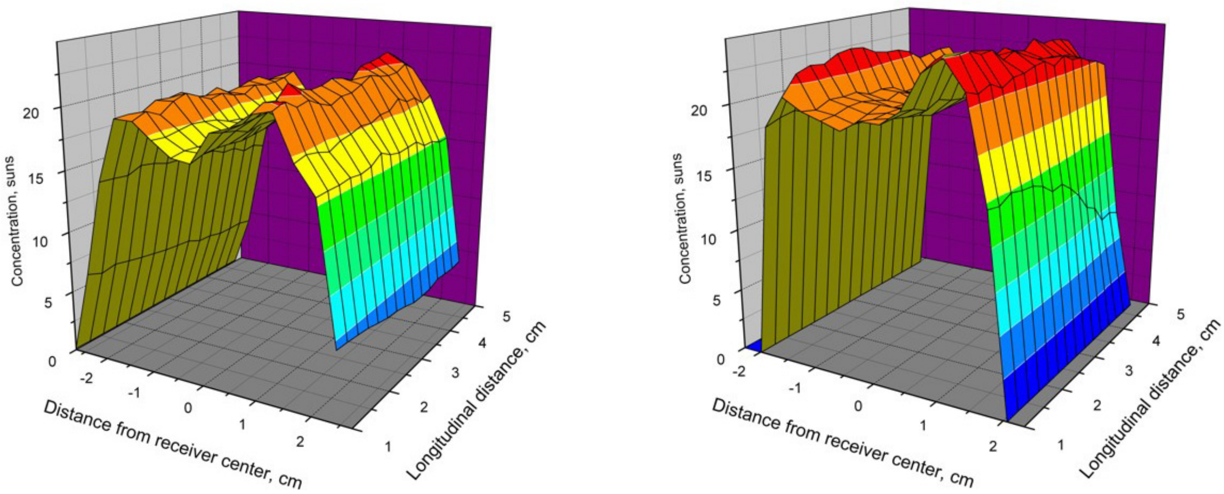
The obtained data sets including the electrical current, voltage, temperature of PV cells, as well as the levels of direct and total insolation were measured simultaneously using a multi-channel datalogging unit and then downloaded to a PC for further analysis. The multi-channel data feed helped to normalize the corresponding values of short circuit current and peak power output for the standard 1 kW/m^2 flux more accurately. Relative humidity, ambient air temperature and wind speed were also measured for most datasets.

5. RESULTS AND DISCUSSION

Fig. 9 shows the concentrated beam projected to a T-shaped receiver support beam underneath the slat array concentrator.

Fig. 9: A 6 ft. long focal line created by the array of slats.

The results of flux mapping (Fig. 10) show that the concentrator performed fairly well with and without the secondary reflector. As it was expected, the reflective strips added to the system for improving the focus actually helped reduce the energy spillage. This can be seen from more distinct boundaries of the flux map and from slightly higher flux intensities observed across the focal line in Fig. 10 (b).



a) b)

Fig. 10: Measured flux map for a 5-cm fragment of the focal line without (a) and with (b) a secondary reflector.

Despite the fabrication tolerances used for the reflective slats and concentrator frame of this device were significantly relaxed in comparison to our previous prototypes, we obtained a notably better flux uniformity on PV cells. This is mainly due to a lower concentration ratio used for this CPV and also due the use of focus improving secondary.

The measurements of PV receiver electrical output were mostly conducted with the secondary reflector attached. The average value of short-circuit current measured under the concentrated flux constituted 0.21 A. This is only 0.03 A short of the expected value which was calculated by the interpolation of electrical current vs. concentration dependencies provided by the cell manufacturer. The open circuit voltage was 10.4 V which is exactly four times the rated voltage of a single cell used in the receiver.

The specific peak power output measured for the experimental CPV was 1.9 Watts per centimeter length of the linear PV receiver. This corresponds to about 86% of the 2.2 W peak power expected for the receiver based on the factory-provided cells parameters calculated for 20x concentration and assuming no optical losses. Thus, the obtained percentage can be used as an estimate of concentrator optical efficiency. This estimate is close to the reflectivity of the slat material which validates the optical design and fabrication method for SAC collector.

As the test PV receiver covers only about 0.35% of the total focal area of the prototype CPV, we estimate that this system could generate up to 530 Watts of peak power provided the receiver is extended to the full length of the concentrator's focal area with a high packing factor.

During outdoor tests, SAC demonstrated another advantage of composing the concentrator by an array of spaced apart reflectors. We found this design to be effectively deflecting even relatively strong winds which could be problematic for a concentrator formed by a single, large-area surface and supported by such a lightweight frame. However, a further study of wind load resistance of SAC is needed for quantitative assessment of savings on the weight and costs related to the support structure compared to conventional concentrators such as parabolic troughs.

6. CONCLUSIONS

A single-stage PV concentrator consisting of a reflective latticework was demonstrated to be scalable up to at least 500W modules. The assessment of the proof-of-concept prototype has shown that obtaining a substantially uniform illumination of PV cells is achievable in rear-focus concentrating systems at concentration ratios as high as 20 suns and at the maximum intercept factor.

No complex shapes such as parabolic profiles, etc., were used in the design. All structural and reflector components were fabricated using only straight or circular profiles. The experience obtained in the fabrication of reflective slats indicates that they can be easy to fabricate in large quantities from sheet metal using a continuous process such as roll-forming.

A very small curvature of slat reflectors compared to other concentrating mirror designs suggests that they are compatible with many kinds of lamination techniques and materials. Perhaps, a thin glass mirror laminate can also be used without the concerns about its fracturing when attaching the mirror to the slat substrate and bending it to the required shape.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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2. S. Vasylyev, "Performance Measurements of a Slat-Array Photovoltaic Concentrator", American Solar Energy Society, *Solar 2004 Conf., July 11-14, 2004*, Portland, OR.