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Research Article

Low-concentration Optical Enhancement in Solar Panels

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Abstract: A simple, inexpensive approach aimed at cost reduction is through sunlight concentration enhancement with geometrical optics. Solar panels (~10-70 W_p range) were investigated with up to two mirror reflectors in order to determine gains in output in both dry and humid environments. Flat glass mirrors with 70% reflectance were used to direct sunlight to the solar panel surface create maximum of ~2.4 x sunlight enhancement. Averaged over different panels sizes operating in dry climate, gains in short-circuit current and peak power were 49.2 and 35.8% respectively; for the humid climate, respective gains were 29.7 and 23%. Continuous measurements as a function of time between 10:30 AM to 3 PM revealed respective current and power gains of 22.7 and 14.2%. Simple air cooling was determined to increase power output by 10%.

Keywords: CPV, low-concentration PV, optical concentration system, Si solar panel

INTRODUCTION

Power output of a solar panel can be significantly enhanced by based on geometrical optics by simply adding reflectors to direct sunlight to its surface. In its simplest manifestation, four mirrors can enhance the sunlight concentration to 5 x in comparison with no mirrors (1 x). Commercially available glass mirrors exhibit ~70% reflection efficiency (Stone *et al*., 2004). Therefore, 4 mirrors will achieve sunlight concentration enhancement of 3.8 x. Assuming linear solar panel performance as a function of sunlight, a maximum gain of 3.8 can be realized. This approach is also attractive due to its in-expensive construction and lack of cooling requirement. Historically, Concentrated PV (CPV) systems fall in two categories: low (<10x) concentration systems based on simple Fresnel mirror type configurations (Rabl, 1977) and high (>10-1000x) concentration (Klotz, 2000; Hermenean *et al*., 2010) systems based on focusing sunlight into small spots. In general, the CPV systems are based on either imaging or non-imaging geometrical optics operating either in reflection or refraction mode. Several types of non-imaging, reflective low-concentration CPV systems including parabolic (Sylvester *et al*., 2008), Fresnel mirrors (Rabl, 1977) and heliostat types (www.sinovoltaics.com/topics/hcpv/) have been investigated. Fresnel lens with high concentration is an example of high concentration CPV system (Hermenean *et al*., 2011).

The work reported here is based on static two-mirror Fresnel configuration. With larger number or mirrors or reflecting facets, accurate sunlight tracking is needed. For low (<10 x) optical concentration systems, the total sunlight incident on the panel surface is the sum of direct sunlight plus n* times the direct sunlight, where n is the number of mirrors. Based on mirror angle and its dimension relative to the solar panel, sunlight tracking requirements is relaxed for a limited range of sun movements in the sky (Rizk *et al*., 2011). Hence, in this experiment our objectives are to investigate PV panels performances; under low-concentration optical enhancement and humid versus dry climate effectiveness.

METHODOLOGY

Experimental configuration:

Outdoor experiments (dry climate, Albuquerque, New-Mexico, USA): Figure 1 describes the experimental configuration employed here for evaluation of solar panel power enhancement in Fresnel mirror setup. Mirror to panel size ratios and reflection angles were chosen such that each mirror effectively illuminated entire panel area during 11 AM to 1 PM daylight hours (Florin and Contin, 2011), Fig. 2 exhibits a picture of typical two-mirror Fresnel mirror configuration with solar panel at the center. These low (<10 W_p) power custom-designed solar panels were fabricated at SERI/UKM laboratory with 16% efficient mono-crystalline Si solar cells. Higher power panels were purchased from commercial vendors.

Electronic data acquisition program was based on measuring voltage and current as a function of

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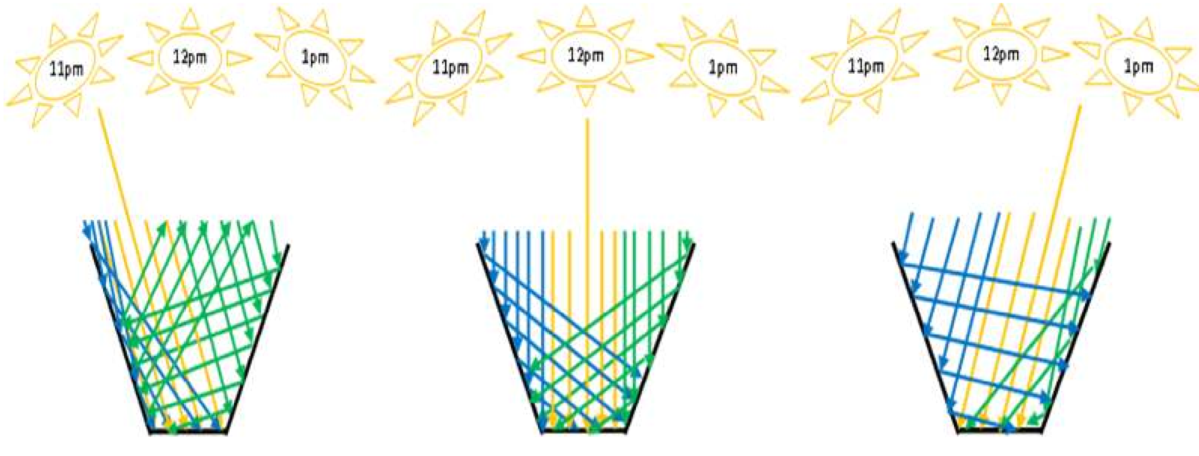
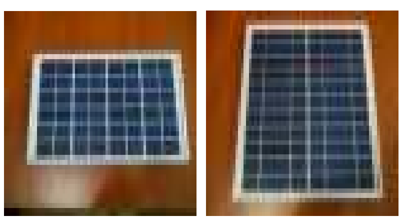


(a) (b) (c)

Fig. 1: Two-mirror Fresnel configuration for non-tracking system designed for operation during daylight hours from 11 AM to 1 PM (a-c)

Fig. 2: Two-mirror Fresnel optical enhancement system



(a) (b)

Fig. 3: Polycrystalline silicon solar panels with one-sun peak output power of; (a): ~7 W_p; (b): ~5 W_p

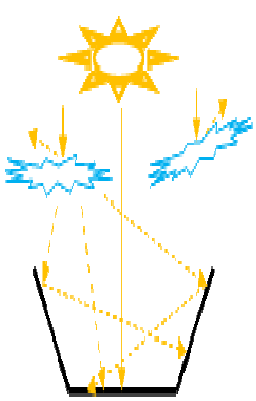


Fig. 4: Direct and diffused sunlight incident on a Fresnel mirror solar panel configuration

resistance across the panel output. A commercially available electronics load power supply capable of providing resistance variation across a broad range was chosen and controlled with a personal computer using "LABVIEW" software. Solar panel current and voltage were simultaneously measured as a function of resistance. Response of current as a function of voltage was plotted to determine relevant panel Parameters including output (P_{max}), maximum Voltage (V_m), current (I_m), open-circuit Voltage (V_{oc}), short-circuit current (I_{sc}), series Resistance (R_{series}), shunt Resistance (R_{shunt}) and Fill Factor (FF).

Outdoor experiment (tropical climate, Bangi, Selangor, Malaysia): Same experimental configuration and data acquisition routines were followed cat Solar Energy research Institute Selangor, Malaysia. Two solar panels were fabricated with polycrystalline Si solar cells diced into smaller pieces. Figure 3 exhibits pictures of the 5 and 7 W_p solar panels used for output enhancement work reported here.

Review of experimental parameters:

Effect of light intensity: Solar cell performance is related to the incident light and spectral responses (Ivan *et al*., 2013). As reflectors are installed to enhance sunlight concentration, panel output power increases proportionately. In general, the short-circuit current is a linear function of light intensity, while open-circuit voltage is a slowly increasing function of light intensity.

Sunlight may be considered as the combination of direct and diffused parts. Figure 4 illustrates difference between the direct and diffused components of incident sunlight on a solar panel. In a dry climate, negligible cloud cover leads to minimal scattering such that the sunlight is almost 100% direct. In contrast, a tropical climate, typical of Malaysia, cloud coverage omnipresent with an unpredictable 0-100% variation,

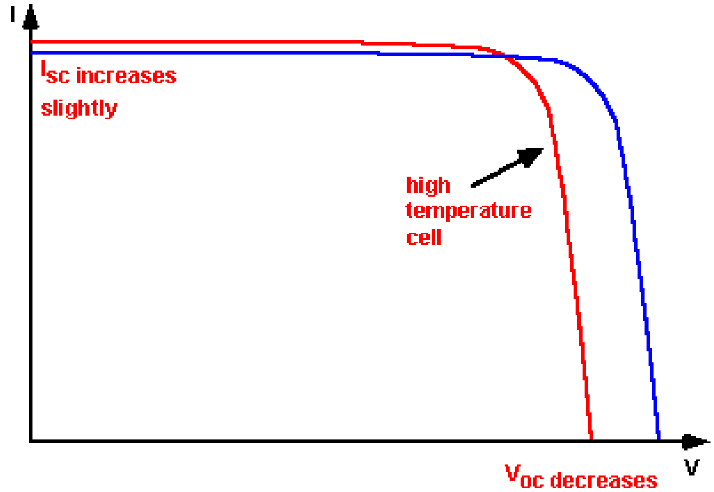


Fig. 5: Crystalline Si solar cell current-voltage response as a function of temperature

therefore, a significant fraction of sunlight is in the form of scattered, diffused radiation. Scattered diffused radiation is not as strong as direct due to scattering losses in multiple directions. Hence, for reflecting optics a significant fraction of the incident radiation will not be directed to the panel surface.

Effect of temperature: With increasing sunlight concentration, solar cell temperature also rises, which reduces its efficiency. Efficiency of silicon solar cell is a function of temperature being higher at lower temperature (Mosalam Shaltout *et al*., 2000). As a function of temperature, the solar cell open-circuit voltage, V_{oc}, decreases inversely with temperature. Solar cell current-voltage variation as a function of temperature is plotted in Fig. 5. It should be noted that I_{sc} is not a sensitive function of temperature. The heat-induced I_{sc} and V_{oc} losses will be reflected in R_{series}, R_{shunt} and fill factor.

Impact of partial shading: Partial shading of solar cell either through cloud cover or physical obstruction will also significantly reduce output power. This is due to series inter-connection of solar cells in the panels (Dezco and Yahia, 2008). Since the solar cells in a panel are connected in series, the panel output will be limited by the lowest light-generated current. Studies on shadow effect have determined that even with 6% of the panel surface under shadow, the power reduction will reach 50%.

EXPERIMENTAL RESULTS

Outdoor experiment (dry climate, Albuquerque, New Mexico, USA): Figure 6 and 7 exhibit representative Light current-Voltage (LIV) measurements from 50 W_p solar panel with and without reflectors. Figure 8 summarizes the output enhancement data from two mirrors reflector configurations for 10, 50 and 70 W_p solar panels, respectively. Averaged solar panel power and short-circuit current enhancements of ~35.8 and 49.2%, respectively were demonstrated.

Table 1: Summary of LIV measurements for solar panels in ~10 to ~70 W_p range

Panel type (W_p)	No. of mirrors	I_{SC} (A)	V_{OC} (V)	R series (Ω)	R shunt (Ω)	FF (%)	Power (W_p)
10	0	5.39	1.99	0.12	1.89	64.2	6.88
	2	7.19	2.09	0.10	1.02	60.6	9.12
50	0	3.98	18.30	1.22	29.10	67.4	48.90
	2	5.79	18.10	0.98	20.10	64.2	67.20
70	0	5.45	21.00	0.98	28.30	69.3	79.30
	2	8.43	20.50	0.79	14.80	63.2	109.20

Table 1 summarizes principal solar panel LIV parameters without and with two mirror reflectors. R_{SERIES} on average has been reduced by ~16%, R_{Shunt} by ~40% and FF by ~7%. The large reduction in shunt resistance may be attributed to temperature-dependent leakage current enhancement.

The LIV measurements summarized in Fig. 8 and Table 1 were carried out during peak sun hours. Solar panels were kept in sunlight only during LIV measurements lasting ~5 min. In order to evaluate enhancement typical of actual deployment environment, LIV measurements were carried out on solar panels left in the sunlight from 10:30 AM to 3 PM. Figure 9 plots of short-circuit current (Fig. 9a) and peak power (Fig. 9b) as a function time for nominal 10 W_p solar panel; relative I_{SC} and W_p gains have been plotted in Fig. 9c. The data in Fig. 9 illustrates that as expected environment, gains in performance are between 11 noon to 1 PM. By averaging data over the 10:30 AM to 3 PM time frame, it is possible to approximate performance gains in non-tracking environment. Figure 9 reveals ~22.7 and ~14.2% gains in I_{SC} and W_p respectively. These gains, as expected, are substantially lower than observed in Fig. 8.

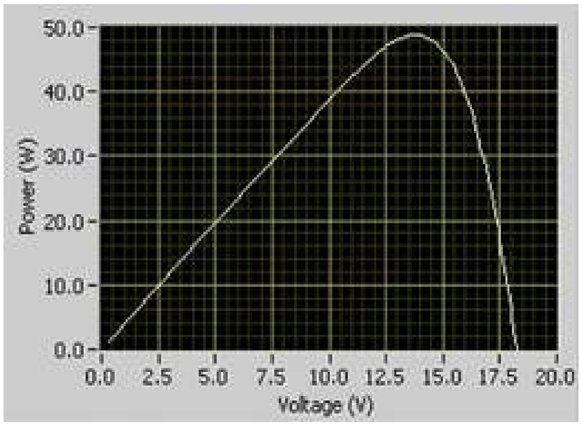


Fig. 6: Light current-voltage measurements from a 50 W_p solar panel without mirror enhancement

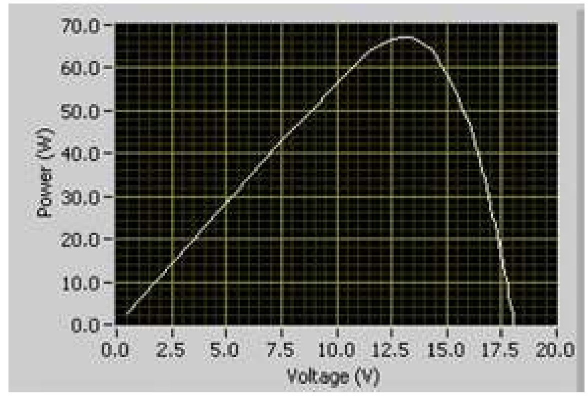
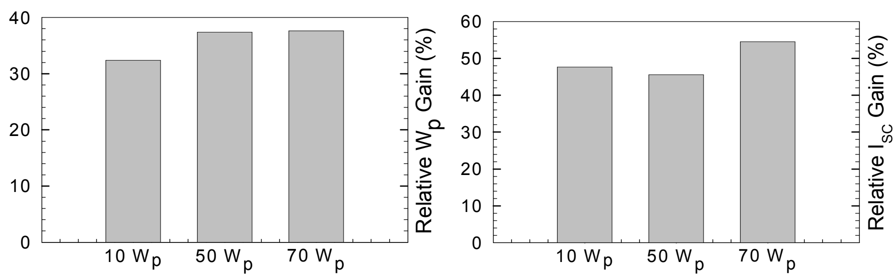
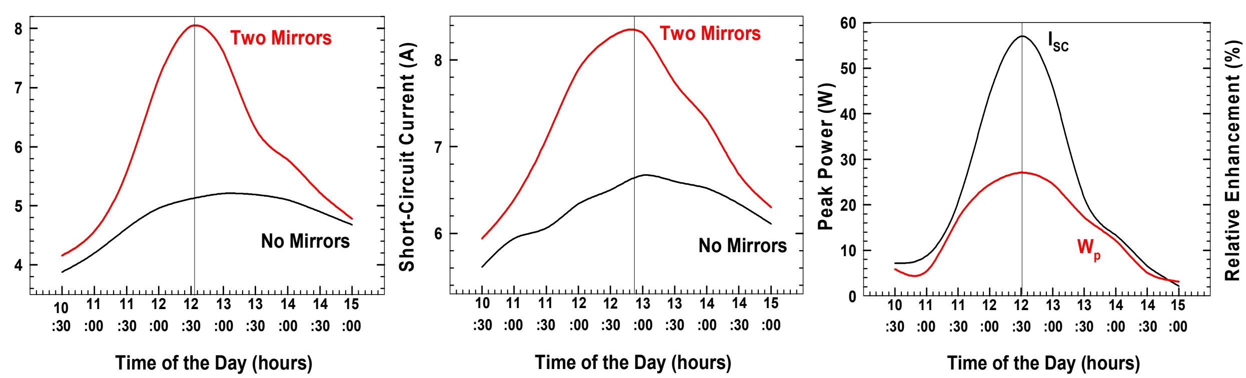


Fig. 7: Light current-voltage measurements from ~50 W_p panel with two-mirror enhancement of peak power to ~70 W_p



(a) (b)

Fig. 8: Vertical bar-chart plot of percentage enhancement from three solar panels with output in 10-70 W_p range; (a): Peak power; (b): Short-circuit current



(a) (b) (c)

Fig. 9: (a): Variation of I_{SC}; (b): Peak power as a function of day time; (c): Relative percentage gains have been plotted in

In the dry climate, simple air-cooling was investigated in order to determine its impact on output. Table 2 summarizes the results with and without the air cooling. It appears that cooling is more effective at higher sunlight concentrations.

Outdoor experiment (tropical climate, Bangi, Selangor, Malaysia): Using similar experimental configurations, LIV measurements from the two solar panels identified in Fig. 3 have been summarized in Fig. 10. The response of two panels is opposite to each other. Peak power and I_{SC} gains averaged for the two panels were respectively 29.7 and 23%. In general, it is quite difficult to acquire consistently repeatable measurements due to large variations in cloud cover, humidity and temperature, which are known to cause significant variations in performance (Ivan *et al*., 2013).

Table 3 summarizes principal LIV data from 5 W_p and W_p solar panels. R_{SERIES} for two panels is reduced in 17-24% range, R_{Shunt} is either reduced by 15% or

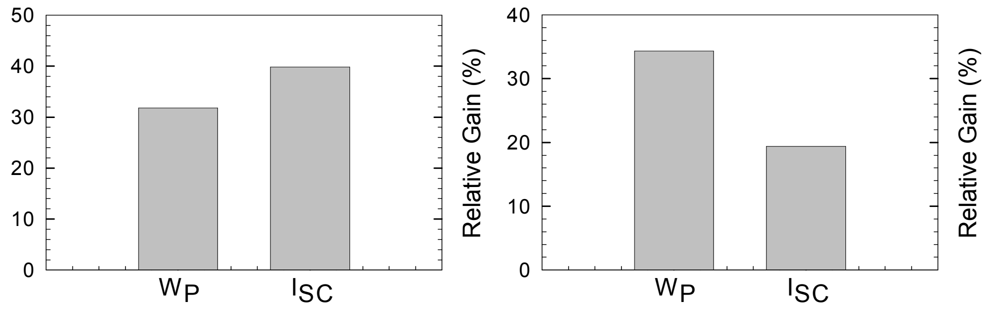


Fig. 10: Vertical bar plot for relative gains in; (a): 7 W_p; (b): 5 W_p solar panels in tropical climate

Table 2: Air-cooling of 2-mirror reflector systems

No. of mirrors	W_p (W) without cooling	W_p (W) with air cooling	Relative gain (%)
0	6.88	7.40	7.6
2	8.32	9.12	9.6

Table 3: Summary of LIV measurements for 5 and 7 W_p solar panels

Panel type (W_p)	No. of mirrors	I_{SC} (A)	V_{OC} (V)	R series (Ω)	R shunt (Ω)	FF (%)	Power (W_p)
5	0	0.67	12.7	6.60	66.2	57.4	4.9
	2	0.80	12.5	4.90	68.8	61.4	6.6
7	0	1.03	11.3	3.64	42.1	59.3	6.9
	2	1.44	11.3	3.00	35.6	60.0	7.7

increased by 4% and the FF variation is between 1-6%. In comparison with LIV data for larger panels operating in dry climate conditions, major difference is in the shunt resistance which was reduced by 40% relative to either increase or ~15% reduction observed for these panels. It is likely that for larger areas, thermally-induced leakage current is significantly higher.

CONCLUSION

Relative comparison of solar panel output enhancement with low-concentration optics reveals its effectiveness in both dry and tropical climate conditions. In dry climate, dominance of direct sunlight leads to higher and repeatable performance gains. In tropical climate, a combination of direct and diffused sunlight makes this method less effective. Discrete data acquisition approach employed here also leads to large fluctuations in data due to rapid fluctuations in temperature, solar insolation and humidity.

In a diffuse climate, the incident light is scattered randomly, therefore, mirrors are not able direct it uniformly onto the panel surface. Since, solar cells in a panel are connected in series; therefore, even if one solar cell has less intensity, the output of the entire panel will be reduced substantially. Therefore, low concentration optical enhancement methods based on reflective optics will not be effective. This conclusion is supported by a recent comparative study of reflective and refractive optical concentration systems (El-Ladan *et al*., 2014) in which refractive approach was determined to be superior in tropical environment.

Averaged over different panels sizes operating in dry climate, gains in short-circuit current and peak power were 49.2 and 35.8%, respectively; for the humid climate, respective gains were 29.7 and 23%. Continuous measurements as a function of time between 10:30 AM to 3 PM revealed respective current and power gains of 22.7 and 14.2%.

Another consideration is heat-related output reduction as solar concentration is increased. Simple air-cooling was determined to be effective. Simple air cooling was determined to increase power output by 10%. A more advanced cooling system such as water flow system, air flow system or either the combination of both systems would be more effective. In order reduce uncertainty in data, measurement methodology must include simultaneous acquisition of the following parameters:

- Panel temperature measurement
- Wind measurement
- Humidity measurement
- Solar insolation measurements over entire panel surface

With such detailed measurements acquired simultaneously to be reported later, linear relationship between sunlight concentration and output power enhancement can be established. Finally, integrating two-axis tracking will be needed to fully realize the potential of such output enhancement systems.

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