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Comparison of multi-crystalline silicon PV modules' performance under augmented solar irradiation

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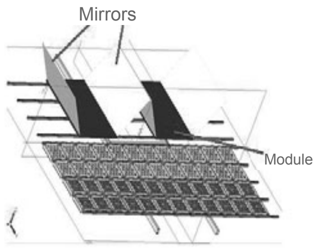
ABSTRACT

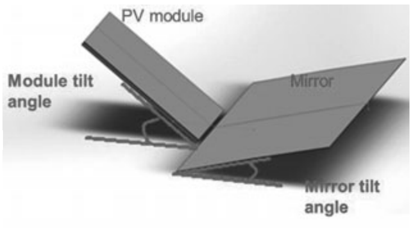
In developing photovoltaic (PV) systems with reliable lifetime performances, it is critical to have quantitative knowledge of not just initial properties and performances, but also their performance over the warrantied 25 year lifetime. In 2010, the Science for Energy Technology Workshop, convened by U.S Department of Energy (DOE) Basic Energy Science, prioritized photovoltaic module lifetime and degradation science (L&DS), which serve as the basis for quantitative and mechanistic understanding of lifetime performance. In order to better understand degradation rates and mechanisms of PV systems in the real-world environment, the SDLE SunFarm at Case Western Reserve University has been created, which is a highly instrumented outdoor test facility with 148 PV modules and > 8000 samples on sun for weathering and degradation studies of materials components and systems designed for long-lived energy systems. I-V and power performance of 10 multi-crystalline silicon PV modules from different manufacturers, using baseline and continuous power monitoring and comprehensive weather and solar resource monitoring, to enable time series analysis for insights into performance characteristics and initial degradation.

Five modules from each manufacturer were exposed using mirror augmentation in typical (Cleveland, OH) climatic conditions. The mirror augmentation used geometric concentration factors of 1X, 1.5X and 1.9X of the nominal 1 sun. The effect of mirror augmentation on the modules' performance is reported. A Daystar multi-tracer was used to measure I-V curves of individual modules every 15 minutes while power output under maximum power point tracking was monitored continuously. Monitoring environmental factors (wind speed, wind direction, rainfall, and humidity), solar resource, and module temperatures allow for determination of the effects of these conditions on module power production. Power data was corrected to standard test condition (STC) according to climatic and solar irradiance. Changes in fill factor, short circuit current, open circuit voltage and maximum power are reported for each module. With time series analysis, a better understanding of the module's performance over time and under environmental conditions can be developed.

INTRODUCTION

The basic design idea of Mirror Augmented Photovoltaics (MAPV) is using a low concentration system to harvest more solar irradiance on a single PV panel. Our approach is using reflectors combines with PV systems. Compares to a PV panel, the mirror has lower cost, lower weight and a lower light scattering rate. So if we are able to produce more power from a single panel instead of using more panels, we can lower the balance of system (BOS) cost. In this case, we are using flat back surface acrylic mirrors. The cost of mirror is 5-10% of PV panel with the same dimension. Fig.1 shows both tracked and fixed MAPV systems. In tracked MAPV design we placed two mirrors beside the module symmetrically, and mounted the whole system on to a tracker frame (Fig.1.a). The tracked MAPV design can provide higher concentration than fixed design and uniformed irradiance on the panel, but the cost of the tracking system is high. Fig.1(b) shows a fixed MAPV design with lower system cost. We combined one piece of flat mirror with fixed PV system. The mirror is mounted at an angle so that reflected irradiance can hit the panel surface. Both tracked and fixed MAPV designs were explored by other group members and collaborators [1]. This work focuses on the performance and power boost of MAPV systems under real-world solar irradiance and climate condition.





(a) (b)

Fig.1 (a) Geometric design of tracked MAPV. On the top half of the tracker's frame are two tracked MAPV systems in parallel. Each MAPV system has mirrors set beside the PV module. On the bottom half of the tracker's frames are four rows of sample trays. (b) Geometric design of fixed MAPV. The module was placed facing the south. The mirror is tilted at an angle to maximize the reflected irradiance on to the PV module's surface.

On the southern campus of Case Western Reserve University we implemented our outdoor test facility-- Solar Durability and Lifetime Extension (SDLE) Center SunFarm. Here we have 14 high precision dual axis trackers and 2 sites of adjustable tilt rack. A total number of 148 crystalline silicon PV modules from 24 different manufactures and over 8000 samples will be exposed on the SunFarm. The degradation rate of these silicon modules will be determined and compared to test results from different climatic zones in order to get better understanding of the lifetime and degradation mechanism of solar systems, components and materials [2]. The data acquisition system at the SDLE SunFarm includes power, irradiance, backsheet temperature monitoring, and climate data detectors. Power monitoring is accomplished in three ways: Daystar multi-tracer, Enphase

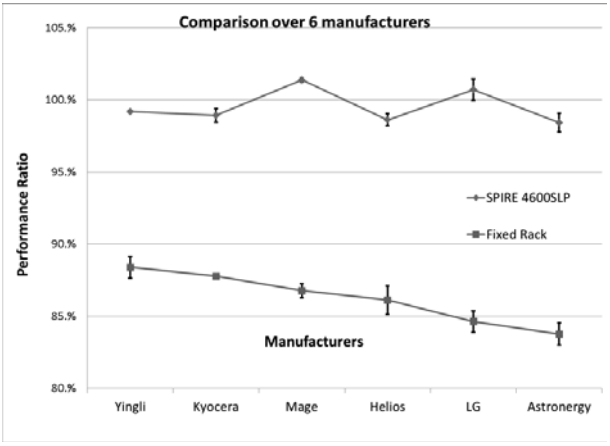


Fig.2 Performance ratio and standard deviation of indoor baseline and initial outdoor performance on a fixed rack tilt at 23° on a clear day in November of 18 crystalline-silicon panels from six different manufactures.

microinverter, and Solectria string inverter. Pyranometers were placed both on a tracker frame and horizontally for plane of array (POA) and horizontal irradiance monitoring respectively.

In Mount Vernon, Ohio, Replex Plastics LLC is collaborating with us on this MAPV project. They implemented a smaller scale outdoor test facility with one dual axis tracker, one single axis tracker and a fixed rack. Replex is focused on solar mirror and MAPV development. Most outdoor tests of MAPV were done at their SunFarm.

METHODS AND RESULTS

Initial performance comparison among 18 c-Si modules

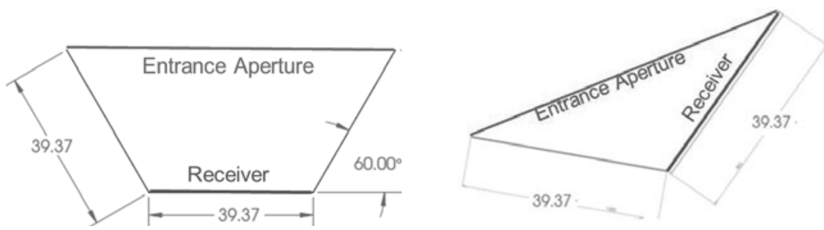
Eighteen virgin modules from six different manufactures (three fo each) were exposed to real-world solar irradiance on the fixed rack at the same time. All of these modules were baselined with an indoor SPIRE 6400 solar simulator before mounting on the rack. Both baseline results and outdoor performance data, using a clear day in November, were normalized to standard test condition (STC) of 1000W/m^2 and 25℃ [3]. Fig.2 shows the performance ratio with standard deviation, of both indoor solar simulator and outdoor expose result.

Geometrical and optical design of MAPV

Geometric concentration (C_g) of a CPV system is defined as ratio of entrance aperture (EA) divided by receiver area (RA) [4]. The optical efficiency (OE) of MAPV system is determined by the reflectance of the mirror. Previous research shows that the aluminum back surface mirror we use has an averaged 85% reflectance within the visible spectrum. The actual irradiance incident on the PV panel is given by the optical concentration (C_o). The relationship between C_g and C_o is given by equation 1.

$$\boldsymbol{C_o = 1 + (C_g - 1) \times OE} \quad (1)$$

In the tracked MAPV design, both of the mirrors are set at 60° to horizontal. The dimension of the mirror is same as the panel. Thus C_g =2.0 X and C_o = 1.85 X. The design of fixed MAPV is comparably complicated because the fact that the respective position of the sun and PV panel is always changing. We first built a CAD model in SolidWorks, then using TracePro, ray tracing-optimized the panel and mirror angle to get better concentration. The simulation result shows that with a panel tilt angle at 50^o mirror angle at 10^o the system has best averaged concentration rate. C_g =1.73 X for fixed MAPV and C_o =1.6 X.



(a) (b)

Fig. 3(a) shows the entrance aperture and receiver area of tracked MAPV design. The mirror was set at 60°. Fig. 3(b) shows the entrance aperture and receiver area of fixed MAPV design. The mirror tilt angle is 10° the module tilt angle is 50°

Outdoor test of tracked MAPV system

The test geometry of the tracked MAPV system is relatively simple because the sun light incidence angle is always perpendicular to the panel surface. The power boost measured from a single test is valid at any time of year. All of the power in Table 1 is normalized with the POA irradiance and air temperature [5].

About 300W power output from a nominal 220W panel was observed in the multi-crystalline silicon panel test (Table 1). A simultaneous non-augmented test with a panel of same model gives 205W power output. The power boost is 1.46. In the thin film test, power output from augmented panel is 117W, comparing with non-augmented panel, which produces 93W, the power boost is 1.26.

***Table 1**. Outdoor test result of four MAPV systems*

	Tracked		Fixed	
	m-Si	**tf-Si**	**m-Si**	**tf-Si**
Geometric concentration	2	2	1.73	1.73
Optical efficiency	85%	85%	85%	85%
Optical concentration	1.85	1.85	1.59	1.59
Non-augmented	205	93	195.4	91.8
Augmented	299	117	214.5	104.9
power boost	**1.46**	**1.26**	**1.10**	**1.14**

<u>Outdoor test of fixed MAPV system</u>

The difficulty of fixed MAPV testing is "how to evaluate the performance over a year?" To solve this problem we invented the "time machine". The basic function of the time machine is tilting the entire fixed MAPV system to various angles. Instead of waiting for the sun move to the position we need to test, we can tilt the MAPV system to simulate the relative position of the sun and the panel. Using the time machine we are able to survey the performance at noon time on fifteenth of each month in one day.

A multi-crystalline silicon module was tested with the time machine first. The power boost through a year shows a gullwing curve shape (Fig.5). The averaged power boost is only 10%. And averaged power output is 214.5W throughout a year (Table 1). Clipping was observed from the I-V curve (Fig.6). A thin film silicon module was also tested. No I-V curve clipping was observed (Fig.7) and the power boost rose up to 1.14. The averaged power output from an augmented system was 104.9W (Table1).

Fig.4 The "time machine" with fixed MAPV system

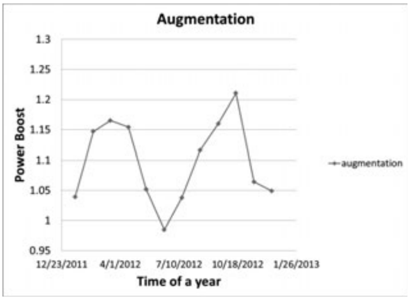


Fig.5 Power boost in different months of fixed MAPV system using multi-crystalline silicon panel through a year.

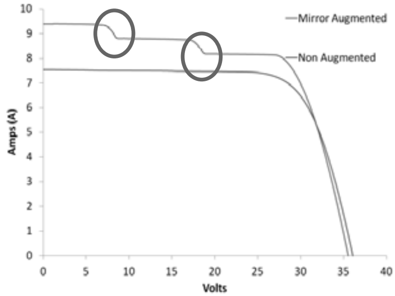


Fig.6 I-V curve of mirror augmented and non-augmented fixed multi-crystalline silicon panels traced with Daystar multi-tracer. Clipping was observed and marked on the augmented panel's I-V curve.

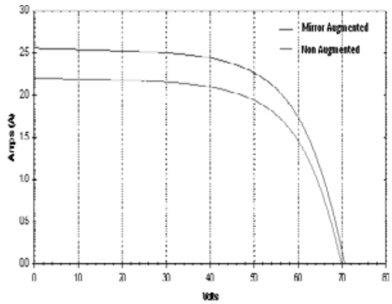


Fig.7 I-V curve of mirror augmented and non-augmented fixed thin film silicon panel. No clipping was observed.

DISCUSSION

<u>Initial performance comparison among 18 c-Si modules</u>

The baseline result of all six brands falls in the 100%±5% range as claimed by the manufacturers. Among these six brands, Mage and LG's average performance was even higher than the nominal power list on the data sheet. The outdoor test was taken simultaneously and these six manufacturers were sorted with their outdoor test result. Fig.2 shows that all the panels' performance falls to around 85% , while Yingli and Kyocera panels performs a little bit higher than 87%. The comparison of these two curves tells that indoor test with solar simulator do not necessarily indicate the real world performance.

<u>Outdoor test of tracked MAPV system</u>

The power boost of the tracked MAPV system with a single multi-crystalline silicon panel was 46%, and we noticed that the irradiance augmentation was 85% on the panel. From the I-V curve data, clipping was observed on augmented panel's I-V curve, which explained the fill factor drop with augmentation. We also observed the open circuit voltage decreased with the augmentation due to the fact that cell temperature is higher.

In the thin film silicon module test, only 26% power boost was observed, which was probably due to weather condition of the test. The test was taken on a partially cloudy day, and for a MAPV system, a reflector can only harvest the direct irradiance to contribute to the irradiance augmentation.

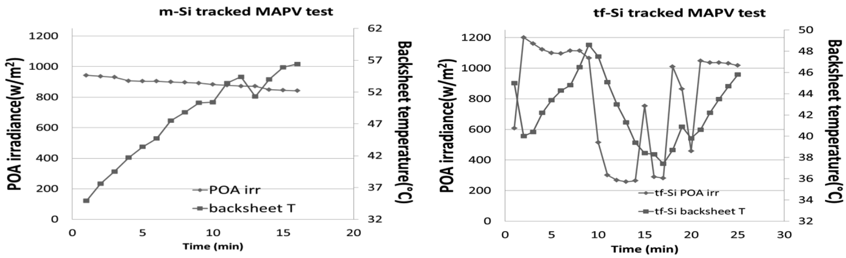
<u>Outdoor test of fixed MAPV system</u>

The gullwing curve shape (Fig.5) of power boost indicates that we optimized the irradiance augmentation in spring and autumn, but lose the reflected light in summer and winter. A further study of the cause of I-V curve clipping was accomplished by simulating the irradiance map of the module surface with TracePro ray tracing. The irradiance map shows that the reflectance from the mirror only covered several strings on the panel, the non-uniform irradiance causes a current mismatch between strings. The clipping on I-V curve directly causes the fill factor drop. To fix this problem, we considered using thin-film modules, which do not reacts adversely non-uniform illumination.

The result from thin-film panel shows that we do solve the strings mismatch issue. From the thin-film panel we got a averaged annual power boost of 14%, four percent higher than m-Si module. At the same time we notice that the averaged total power output of thin-film module is only 104.9W, comparing with 215.4W from the m-Si module test.

<u>Module backsheet temperatures and heating/cooling rates</u>

During the tracked MAPV test, we observed that panels' backsheet temperature was higher than non-augmented panel, and the panel was also experiencing a large temperature change rate. We monitored the backsheet temperature in both m-Si and tf-Si tracked MAPV test. During the m-Si test the backsheet temperature got as high as 57°C. The air temperature was 13°C during the test. And the heating rate was about 100.9°C/hr. The thin-film test was taken in a partially cloudy day, so the highest backsheet temperature observed was 50°C. Heating rate was 60°C/hr. But a backsheet cooling rate of 103°C/hr was observed when the irradiance dropped (Fig.8). In IEC standards [6,7]thermal cycling test, the maximum cooling and heating rates were defined as 100 °C/hr, which raises the question; "Does the MAPV design meet the IEC protocol?"



(a) (b)

Fig.8(a) and (b) show the backsheet temperature during the tracked mirror augmented test.

CONCLUSIONS

In tracked MAPV design we were able to produce producing 46% more power on a multi-crystalline silicon module, using flat acrylic mirror. The tracking system cost is a barrier to make tracked MAPV cost-efficient. Fixed MAPV has a lower system cost, but only got 10% annual power boosts. Using thin-film silicon modules we solved current mismatch issue in panel strings and achieved a power boost of 14%. By harvesting more solar irradiance we observed that the cells work at higher current and higher thermal stresses (including high temperature and large temperature change rate). Further work is needed to study their effects on PV panels' lifetime and degradation rate.

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