COMPARISON OF EFFICIENCY MEASUREMENTS FOR A HCPV MODULE WITH 3J CELLS IN 3 SITES

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ABSTRACT

A new HCPV with 3J solar cells and new concentrator optics consisting in a dome-shaped Fresnel lens and a kaleidoscope homogenizer was presented in the last SCC2003. This paper summarizes the evaluation done by three independent organizations and a manufacturer.

The peak uncorrected efficiency for a 7,056 cm^2 400 X (Geometrical concentration ratio) module with 36 solar cells connected in series was 26.6 % was measured in house. The peak uncorrected efficiencies of the same type of the module with 6 solar cells connected in series and 1,176 cm2 area measured by Fraunhofer ISE, NREL and Toyohashi University of Technology were 27.4 %, 24.8 % and 25.9 % respectively. The peak uncorrected efficiency for a 550X and 5,445 cm^2 module with 20 solar cells connected in series was 28.9 % in house. The peak uncorrected efficiency of the 550X (Geometrical concentration ratio) module evaluated by Toyohashi University of Technology was 27.0 %. The temperature corrected efficiency under the best sunshine condition in Japan for the 550X module was 31.5 ±1.7 %.

INTRODUCTION

Concentrator modules using high efficiency multi-junction solar cells are expected to reduce the cost of PV significantly[1]. The cost of the module drops as the increase of the concentration ratio.

The use of III-V monolithic multi-junction solar cells under high concentration was extensively studied by the Fraunhofer ISE and Ioffe Institute, and achieved 24.9 % (197 cm^2) and 22.7 % (768 cm2) under 500 X concentration despite of the use of 2-junction solar cells [2][3]. It is anticipated that the efficiency will reach to 28 % with the use of 3-J solar cells. Other studies were carried out in US. O'Neill demonstrated the low concentration (8.5 X) and 30.0±1.5 % technology using 8.5 cm wide linear focus module [4]. Spectrolab showed a prototype of a 400 X module with reflector concentrator optics, and demonstrated 1000X concentration and outdoor operation by Entech's SunLine line-focus module with good durability of 5 months, although the module efficiency was not announced [5].

In spite of the advantage of III-V multi-junction solar cells, there are, however, only two companies, Amonix and Solar Systems, in the world successfully doing business with concentrator photovoltaics using silicon solar cells [6][7].

This paper discusses on the performance of the HCPV module with 3J cells and dome-shaped Fresnel lenses evaluated by three independent organizations.

TECHNOLOGY OVERVIEW

The module described in this paper (see Fig. 1) was developed using the following new technologies.

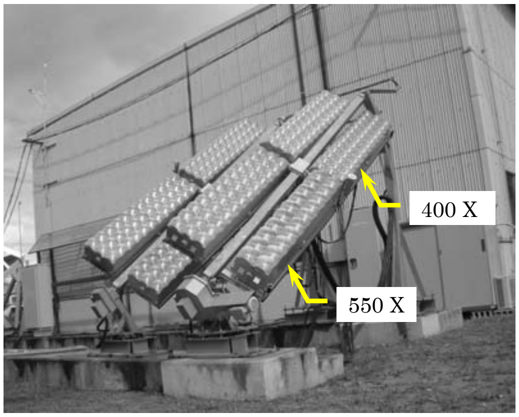

Fig. 1: 550 X and 400 X on an open-loop tracker. The right down module with two lines of lenses is 550 X 150 W module and the rest are 400 X 200 W module. The total rating is 1550 W.

- Super-high pressure and vacuum-free lamination of the solar cell that suppresses the temperature rise to only 15 degrees (including temperature rise in solder and tab metals) under 550 X geometrical concentration illumination of sun beam [7][8].
- Direct and voids-free soldering technologies of the fat metal ribbon to the solar cell, suppressing hot-spots and reducing the resistance, thereby allowing a current 400 times higher than normal non-concentration operation to be passed [8]

- A new encapsulating polymer that survives exposure to high concentration UV and heat cycles [9]
- Beam-shaping technologies that illuminates the square aperture of the solar cell, from a round concentration spot. [10][11]
- Homogenizer technologies that give a uniform flux and prevent the conversion losses that stem from chromatic aberration and surface voltage variation. [10][11]
- An assembly tolerance of up to 1.75 mm. There is no need for special optical alignment. Even local mechanical industries can assemble the main body

UNCORRECTED MODULE EFFICIENCY SUMMARY

A mini system and mini module were fabricated and sent to these organizations, including NREL in USA (mini module), Fraunhofer ISE in Germany (mini module) and Toyohashi Univ. Tech. in Japan (mini system). They were evaluated by their own ways (see Fig. 2- 4).

Fig. 2. Mini System operated by Toyohashi University of Technology

Fig. 3. HCPV module in production design (200 Wp)

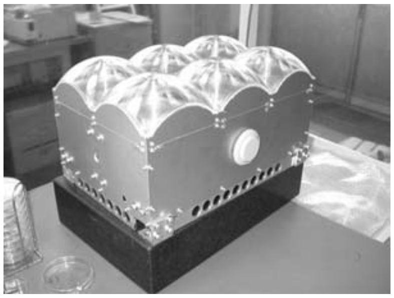

Fig. 4. Mini module for evaluation in NREL and Fraunhofer ISE

Table 1 lists an evaluated results. All the results were “UNCORRECTED”. Different from flat-plate modules, the corrected procedure is not agreed internationally.

Table. 1 Uncorrected peak efficiency measurement

Concentration	Area cm^2	Site	Ambient	Uncorrected Efficiency	DNI W/m^2
400 X	7,056	Inuyama, Japan Manufacturer	29 C	27.6 %	810
400 X	7,056	Toyohashi, Japan Independent	7 C	25.9 %	645
400 X	1,176	Fraunhofer ISE, Germany Independent	19 C	27.4 %	839
400 X	1,176	NREL, USA Independent	29 C	24.9 %	940
550 X	5,445	Inuyama, Japan Manufacturer	33 C	28.9 %	741
550 X	5,445	Toyohashi, Japan Independent	28 C	27 %	777

Table 1 summarizes measured efficiency in three different sites. The peak uncorrected efficiency for the 7,056 cm^2 400 X module with 36 solar cells connected in series was 26.6 %, measured in house. The peak uncorrected efficiencies for the same type of the module with 6 solar cells connected in series and 1,176 cm^2 area measured by Fraunhofer ISE and NREL were 27.4 % and 24.9 %, respectively. The peak uncorrected efficiency for the 550X and 5,445 cm2 module with 20 solar cells connected in series was 28.4 %. Table 1 summarizes the measured efficiency in three different sites. The Inuyama Site is located North of Aichi Prefecture, Japan N35.4° and E137.1°, 30 km from seashore and 3 km from a major river and operated by Daido Metal Co., Ltd. (One of the manufacturer of the concentrator system). The test system was constructed on the ground. The Toyohashi Site also located in Aichi Prefectrue, Japan in N34.7° and E137.4°, 3 km from seashore, and operated by Toyohashi University of Technology, an independent organization. The test system was constructed on the rooftop of the building. The reason for the relatively lower efficiency of NREL is not clear now. Although the output current of the solar cell is constraint by the top junction, the focal distance of the module was adjusted in Japanese spectrum which is more red-rich due to wet climate and more air turbidity. Actually, FF measured in Japan has a peak at around 850 W/m^2 DNI and gradually increases, which implies that the module has a best spectrum condition at a small turbidity of the air. This is a possible reason why the efficiency measured by NREL was less than the measurement in Japan. [12].

EVALUATIONS IN NREL and Fraunhofer ISE

Typical daily trend in a clear day in NREL site is shown in Fig. 5. The maximum direct normal irradiation reaches 1012 W/m^2 and the air turbidity is small. The spectrum at the sun height corresponding to air mass 1.5 is closed to the newly proposed Low AOD spectrum (see Fig. 6), which is more accurate than the AM1.5D spectrum in US and it is thought true in Japan [21,22]. The test in

NREL is closed to the standard testing condition (standard spectrum condition and 1 kW/m^2 irradiance).

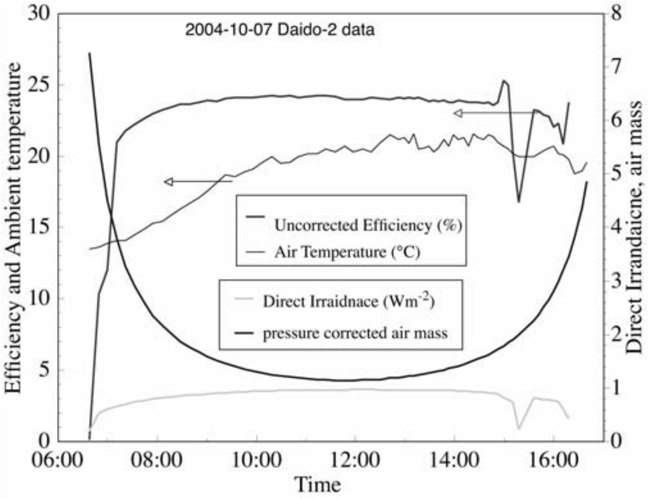

Fig. 5. Cell temperature relative to module temperature with given thermal flux –NREL-

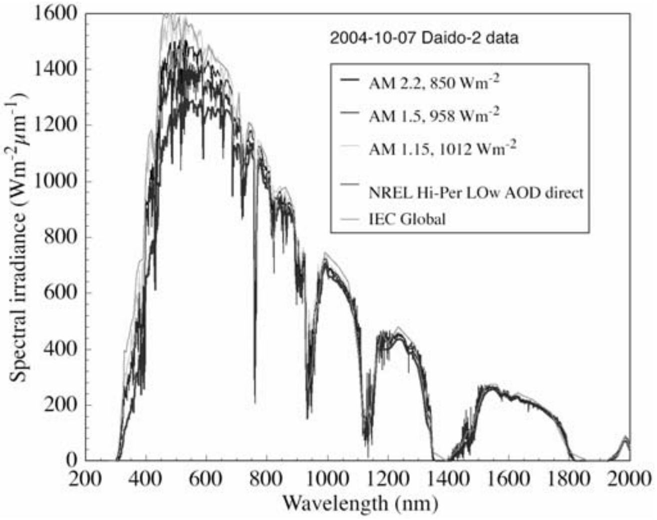

Fig. 6. Direct beam spectrum on the day of Fig. 5 –NREL-

The evaluation in Fraunhofer ISE is a performance evaluation. The mini module was mounted on the same tracker to other modules (Fig. 7).

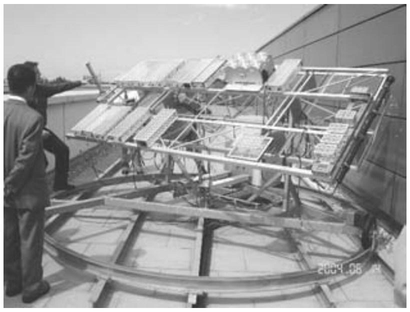

Fig. 7. Tracking system with the mini module in Fraunhofer ISE

The mini module was mounted in March. However, it was found that the receivers were seemed to be degraded by concentrated UV [25,26]. It was replaced recently. The improved receivers are the same to those of 550 X modules with 20 years of accelerated lifetime in concentrated UV exposure [26]. The uncorrected efficiency histograms of both mini modules (before and after replacement) were shown in Fig. 8 and Fig.9.

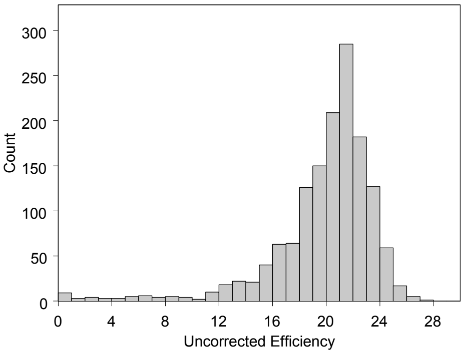

Fig. 8. Histogram of the uncorrected efficiency BEFORE replacement (degradation by UV) –Fraunhofer ISE-

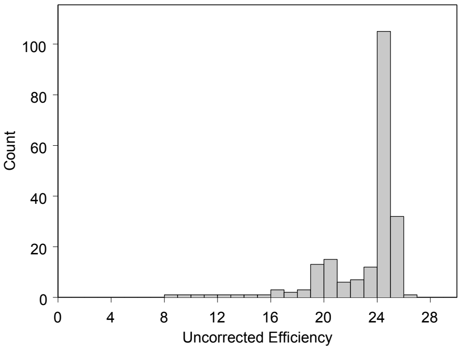

Fig. 8. Histogram of the uncorrected efficiency AFTER replacement (robust design against concentrated UV) –Fraunhofer ISE–

CORRECTED EFFICIENCY IN HOUSE

It is known that the HCPV with multi-junction solar cells are sensitive to spectrum change [13]. For the purpose of fair comparison to the flat-plate module, the efficiency at 25 C cell temperature in the spectrum closed to AM1.5G was tried.

First, the temperature coefficient was often evaluated by non-concentration measurements. However, with the increase of the concentration ratio and short-circuit current, the influence of the dark current is supposed to be logarithmically decreased and thus leads to less temperature coefficient [15,16]. The temperature correction was done with the coefficient delivered from a theoretical calculation from Syracuse computer model for multi-junction cells and modules [8][17-20]. The absolute value of the coefficient logarithmically drops with the increase of the current density per dark current density.

Next, the cell temperature of the concentrator cell is not always the module temperatures measured by a thermocouple mounted on the module body. In most cases, the concentrator solar cells are electrically isolated from the module body. In contrast to a flat-plate module, the concentrated heat flux flows through the heat conducting but electrically insulating layer to the module body. The cell temperature is raised by the product of heat flux and thermal resistance. The additional temperature correction result from the temperature gap between the module and the cell was done in proportion to the direct normal irradiance.

Table 2. Possible errors in efficiency measurement

Error Source	Measurement Error	Impact to Measured Value
Pyrheliometers	± 2.5 %	± 0.80 %
DNI Reading from Pyrheliometers	± 2 %	± 0.64 %
Power Measuement	± 2 %	± 0.64 %
Temperature Measuement	± 3 K	± 0.19 %
Cell Temperature Estimation	± 5 K	± 0.32 %
Temperature Coefficient Estimation	± 0.05 %/K	± 1.12 %
Root of Square Sum		± 1.7 %

Finally, the output power was calculated from I-V curves taken in one minute intervals, the module temperature, and the direct normal irradiance was smoothed using a moving average method over 20 minutes. This procedure was done to compensate for the difference between time constants of the solar cells and the pyrheliometers. Considering possible an error in measurements, the peak efficiency value in the best sunshine condition with error was 31.5 ±1.7 % and the most frequent efficiency was 28.6±1.7 % (See Table 2).

Again, this was for comparison to the flat-plate module.A realistic rating method may be a histogram in uncorrected efficiency [13].

CONCLUSIONS

A 400 X and a 550 X HCPV modules were evaluated in three independent organizations. It is expected to develop a accurate and easy-to-use rating procedures for environmentally sensitive HCPV module performance.

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