A 550X CONCENTRATOR SYSTEM WITH DOME-SHAPED FRESNEL LENSES
- RELIABILITY AND COST-

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ABSTRACT: The new concentrator system was developed by NEDO project from 2001 to 2003. The evaluation research was done in 2004. The conversion efficiency of a concentrator solar cell (InGaP/InGaAs/Ge) was more than 37 % as high as 500 X optical concentration ratio. The peak efficiency of the concentrator module in the best sunshine condition with error was 31.5 ±2 % and the most frequent efficiency was 28.6±2 %. The main problem in reliability of concentrator module with environmental-sensitive III-V solar cells, degradation by concentrated UV beam, is extensively studied. The estimated lifetime of the 550X module is more than 20 years. It is anticipated by the acceleration test but the degradation of the acceleration test meets the result of outdoor exposure test well.
Keywords: Concentrators, High-Efficiency, Reliability

1 INTRODUCTION

The high-performance PV modules had been made by mono-crystalline silicon cells, including HIT cells developed by SANYO[3]. The highest efficiency module confirmed by independent testing lab was a 778 cm^2 (designed illumination area) and 22.7 ±0.6 % efficient flat-plate module made by PERL monocrystalline silicon solar cells [1][2]. The III-V multi-junction cells have been holding higher cell efficiency [4][5][6], but the modules, flat-plate or concentrator, have not broken the record established by the silicon cells.

The concentrator modules using III-V multi-junction solar cells suitable to the practical terrestrial application have been developed in various countries. Concentrator modules using high efficiency III-V multi-junction solar cells are expected to reduce the cost of PV significantly [7]. 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) sub-module efficiency under 500 X concentration despite of the use of 2-junction solar cells [8][9]. 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 sub-module [10]. Spectrolab showed a prototype of a 400 X module with reflector concentrator optics, and demonstrated 1000X concentration operation of the cell and outdoor operation by Entech's SunLine line-focus module with good durability of 5 months, although the module efficiency was not announced [11].

In spite of these pioneering efforts, there have been no challengers to the well-established mono-crystalline silicon technologies. There may be several reasons. One is the module size. It was easy to demonstrate high performance of the concentrator cell on a simple testing bed, typically on a flash tester. Possibly, it was not easy but not very difficult to fabricate a sub-module. But new technologies were required to expand a module size to practical use with keeping its high performance.

This paper overviews the new technologies contributed to establishing a substantially high jump of the world record in any types of PV modules. The discussion is done especially on performance, reliability and applications.

2 TECHNOLOGY OVERVIEW

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

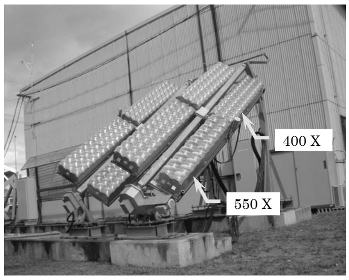

Figure 1: 550 X and 400 X modules on two-axis trackers using open-loop control. The bottom right module with two lines of lenses is a 550 X 150 W module. The remainder are 400 X 200 W modules. The overall system rating is 1550 W.

- Use of 7 mm square InGaP/InGaAs/Ge lattice-matched concentrator solar cells with optimum design of grid electrodes for 500 X optical concentration ratio. Conversion efficiency measured by the independent testing laboratory using Low-AOD AM1.5D spectrum was 37.2 %.
- Super-high pressure and vacuum-free lamination of the solar cell that suppresses the temperature rise to 20 degrees under 550 X geometrical concentration illumination of sun beam [12][13].
- 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 with negligible voltage loss. [14]
- A new encapsulating polymer that survives exposure to high concentration UV and heat cycles. [15][16]

- Beam-shaping technologies that illuminate the square aperture of the solar cell, from a round concentration spot. [17][18]
- Homogenizer technologies that give a uniform flux and prevent the conversion losses that stem from chromatic aberration and flux intensity distribution. [17][18]
- 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.

3 UNCORRECTED AND CORRECTED EFFICIENCY

The conversion efficiency of the solar cell under standard spectrum (Low-AOD AM1.5D) tested by independent testing laboratory was more than 37 % at 500 X of optical concentration ratio.

Both 400X and 550X modules were evaluated by 4 test sites. 3 sites were operated by independent organization (see Table 1). 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

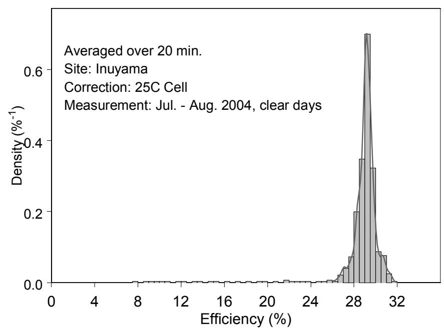

Figure 2: Histogram of the corrected module efficiency for a clear summer day

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. The output power was calculated from I-V curves taken at one minute intervals, the module temperature, and the direct normal irradiance and 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. Without the smoothing, the module efficiency will be overestimated by the relatively large time constant of the pyrheliometers, when the direct beam abruptly increases due to the clearing of small clouds. A histogram of the corrected efficiency is shown in Figure 2. Considering possible an error in measurements, including variation among pyrheliometers and temperature coefficient, 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 %.

4 PERFORMANCE IN THE FIELD

Almost one-year observation showed a seasonal fluctuation inherent to MJ cells and stable energy output. The total energy was 264 kWh/m^2 by 1980 hours of sunshine duration. The annual efficiency (annual energy generation divided by annual insolation) was 20.5 %. This is almost two times more energy than typical flat-plate system despite the well-known preconceived idea that CPV is not suitable to wet area like Japan (see Figure 3).

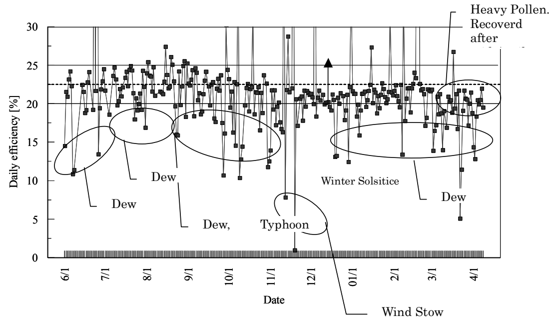

Figure 3: (Daily power generation) / (Daily insolation)

It was observed that the efficiency was high in the summer and low in the winter. The valley was found around the winter solstice. This is because of the spectrum matching effect. It has been studied by Fraunhofer ISE both by indoor experiment and outdoor measurement [19][20]. The III-V 3J concentrator cell we used was InGaP/InGaAs/Ge cell and the output current is constrained by the top junction. When the sunheight is low, the direct beam spectrum contains less blue component by scattering in the air and thus loses the efficiency. Efficiency dropped sharply when air mass exceeded 2.5. The duration with more than 2.5 of air mass is high in winter solstice so that the daily-integrated efficiency was low.

One of the myths is why efficiency does not have a peak at around the summer solstice. Right now, we have not reached to a good explanation.

Another important factor that influences power generation is water condensation on the lens. When this appears, valleys of Fresnel prisms are filled by water and lost concentration function. The conversion efficiency drops according to the area of water condensation.

5 RELIABILITY AND FAIL-SAFE

5.1 Fail-safe

One of the concerns for the reliability of concentrator modules is safety against some accidents. For example, the concentrated solar beam may burn the interior of the module components including internal cables, if the solar tracker has some problems and off-axis beam hits outside the solar cell. It was true in the early history of the concentrators [21][22]. The current non-imaging concentrator Fresnel lens maintains beam intensity within plus or minus 0.9 degree of tracking error, but the beam intensity substantially drops out of that acceptance angle [23][24]. These characteristics help to reduce the thermal flux from off-axis beam to unwanted components. The homogenizer glass rod shifts the focal surface from the cell area and thus reduces intensity of the off-axis beam. The temperature rise by off-axis beam from 850 W/m^2 direct normal irradiance was typically 15 K [25].

5.2 Robustness

The hail impact test was conducted onto Fresnel lens. It was shown that the lens thickness was important to survive against 90 km/hr hail impact. Some thin film surface coatings partly helped to raise robustness against impact in thin lens design.

Static load test was conducted to see robustness against wind. We have experienced heavy snow (20 cm thick in Inuyama site) in this year. We found that snow did not stay on the module (or lenses), possibly because of tracking. Therefore, it is safe to say that the test load can be decided exclusively by wind.

5.3 Lifetime of sealing polymer

Since III-V solar cells are more reactive against environment than silicon solar cells, they need complete sealing from environment. However, the transparent sealing polymer on the solar cell is exposed by concentrated sunlight and may be damaged by UV [26]. Even though the sealing polymer keeps transparency, the mechanical strength would be usually degraded and have a chance of breakage of sealing. The typical environmental chamber test, including hot-wet test, thermal cycle test and freezing cycle test were not sufficient to unveil the potential damage, because the degradation mechanism was different.

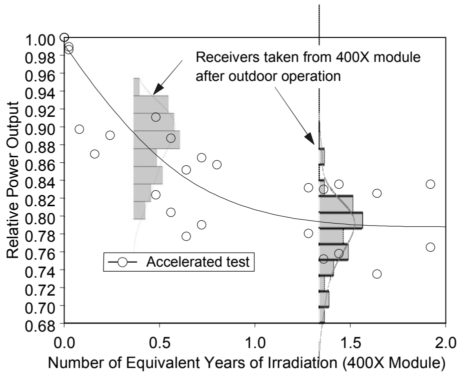

Figure 4: Comparison between the acceleration test and outside exposure test

A good method is to expose concentrated UV in wet environment while the receiver is cooled and collects water condensation by water-cooled Fe-Metalhalide lamp [26]. The acceleration ratio was examined by the comparison with outdoor exposure test of 400 X module (see Figure 4).

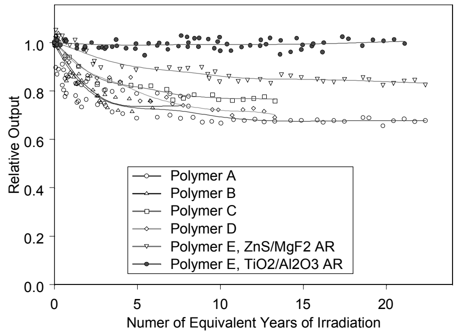

Figure 5: Acceleration test by simultaneous concentrated UV irradiation and water condensation.

Various kinds of polymers were examined. Most of the polymers did not survive in 20 year's of accumulated concentrated UV, but we found one polymer that exhibited more than 20 year's of lifetime (see Figure 5).

6 COST

Various aspects including capital cost, labour and material cost determine the cost of the PV module. With the effort of PV industries as well as the expansion of the scale of the management, the ratio of capital cost and labour cost are decreasing. The final effort is to be devoted to reducing the material cost. The material cost will be an indication of the potential for lowering the module cost with manufacturing growth.

The concentrator modules of the past were believed to be massive metal structures. It was true that they used big heat sinks or water-cooling system. Many present concentrator modules successfully spread concentrated heat to the back body and do not rely on heat sinks. Our module succeeded to reduce the weight to a level comparable to a typical thin-film solar module. The concentrator module is expected to overwhelm the typical multi-crystalline silicon module after some technical innovations.

7 APPLICATIONS

One of the possible applications in Japan is a rooftop on the apartment houses. A new lightweight open-loop tracker (see Figure 6) and lightweight module is being developed. This is a two axis tracker moving as an astronomical globe. The hour angle axis points the polar star and seasonal change is performed by another slope axis. The weight is 0.3 kg/w including modules. The weight does not include the base structure. It is also important to develop low weight module. We are now developing 0.08 kg/W lightweight module for this rooftop application. The challenge is to realize robust structure against 60 m/s wind load by standard metal works.

Another interesting application is what we call the tree planting PV (Figure 7). The CPV only utilizes direct beam in the sunlight, which is often harmful for tree planting. The CPV system without the back cover is transparent to the diffused sunlight. The CPV module shades the strong direct beam and provides rich diffused sunlight to plants. With this transparent module, the area under the module is no longer the dead area. Different from "see-through" flat-plate module, the power generation is not compromised at all.

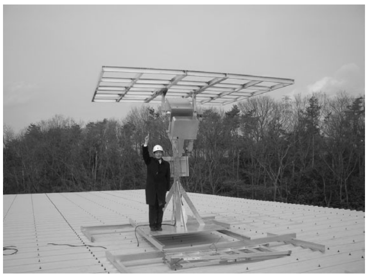

Figure 6: A new 3kW tracker for rooftop application

Figure 7: CPV for "Breeding Plants" that collects direct beam and provides diffused sunlight to the underneath plant.

8 CONCLUSIONS

The highest efficiency module with many new technologies was developed by a NEDO project. It is a work of a collaboration of III-V semiconductor technology, optics, mechanical engineering and etc. The project was carried out mainly three private companies, Sharp, Daido Steel and Daido Metal with 5 Universities, including Nara-AIST, Fukui University, Toyota Technological Institute, Tokyo University of Agriculture and Technology, Toyohashi University of Technology, and one organization PVTEC. The R&D was done from 2001 to 2003. The evaluation study was done in 2004.

Our achievement is summarized in Table 2.

Table 2: Achievement by NEDO CPV project (2001-2003 R&D, 2004 Evaluation; 3 companies and 5 Universities)

Cell	Performance: > 37 % at 500 X
	Grid optimization for high concentration
	New tunnel junction for higher current density
Lens	Performance: 86.2 % at 550 X
	Dome-shaped Fresnel lens by injection molding
	37 yrs material lifetime by acceleration test
Receiver & Module	Performance: 31.5±1.7 % (correction: 25 C cell), 28.9 % (Uncorrected)
	New technologies: Kaleidoscope homogenizer, passive cooling by epoxy lamination etc.,
	20 yrs. lifetime against concentrated sunlight
Tracker	Open-loop tracker, 20 yrs maintenance-free
System	One-year field test: 1.6 times more energy than mc-Si PV even in cloudy Japan.

Now, the NEDO project is over, but three companies continue development by themselves.

Finally, although we have succeeded to develop the highest efficient module, our Odyssey is not over. We are moving toward higher concentration application while keeping a position of the highest performance. We are doing research for higher efficiency, robust and lower cost III-V concentrator cells. We are doing research to unveil myths of strange behavior multi-junction and concentrator PV cells and systems under realistic operation conditions.

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