Performance and Characterization Results from Concentrator Photovoltaic Demonstration Field-test

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The purpose of this study is to investigate conventional photovoltaic (PV) and concentrator photovoltaic (CPV) system performance. The CPV system is operational in Okayama, Japan. The impact of different climates conditions on the system is studied. The system has been collecting data since 2011. The relationship between CPV performance and the environment is more complex than that of the conventional flat-plate PV. It is important to define the primary factors leading to these differences and accelerate installation as a clean energy generation. One of the factors is spectral distribution. Furthermore, the relationship between the I-V characteristics of the system and the environment parameter is discussed.

Key Words
CPV, concentrator, Performance, Multi-junction solar cell

1. Introduction
The multi-junction III-V concentrator solar cell achieved a record-breaking cell conversion efficiency of 46.0% in 2014 with four-junction solar cells. The new highest module efficiency of 36.7% was reported from Fraunhofer Institute for Solar Energy System (FhG-ISE) with four-junction cells in 2014. The concentrator photovoltaic (CPV) system is a new technology that uses the multi-junction III-V concentrator solar cell. The idea is to reduce solar cell material by using optics and increasing the conversion efficiency by using a high irradiance concentrate ratio (100 to 1000 times the nominal condition). This third-generation photovoltaic technology breaks records every year; the world record of multi-junction III-V concentrator solar cell has improved by more than 10% by absolute value in the past decade. However, a reasonable CPV system efficiency is around 30%. There is a large difference between the system conversion efficiency and the cell conversion efficiency.

A project was set up to investigate the characteristics of the CPV system. There have been several studies on the CPV system and it is known that the primal factors affecting the CPV performance are incident irradiance, module and lens temperature, and solar spectral distribution. However, the CPV performance is also affected by other factors such as alignment, tracker error, and soiling. In this paper, the seasonal CPV performance and effects of these factors were investigated using the I-V curve and various performance parameters.

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2. Experimental and Measurement System

The current investigation involved analyzing a CPV and a fixed PV system. The field-test data were taken from systems installed in Okayama, Japan. A 27-kWp grid-connected CPV system, manufactured by Daido Steel Co., started operation in 2011 (Fig. 1). A 1-kWp conventional fixed c-Si flat-plate PV (FPV) system was operated as a reference system (Fig. 2). The fixed PV system was installed on a surface at a 30° angle.

The design of the CPV system is based on point focus PMMA Dome Fresnel lenses 9), a secondary optic, and III-V multi-junction solar cells, as described in Table 1 and Fig. 3. This high concentration design (>100x) can significantly reduce the size and cost of the III-V cell. However, the CPV module requires an accurate two-axis tracker and only a direct normal irradiance (DNI) is used to generate energy. There are two-pedestal trackers for the CPV system. Each array of the CPV system consists of two sub-arrays and is connected to the 10-kW inverter. Each sub-array is designed with five parallel strings of six series-connected modules and three different types of modules are connected in the arrays. The measuring system consists of an I-V curve tracer for each array, meteorological data including direct normal solar spectrum and extensive instrumentation for measuring the CPV performance.

An automatic data acquisition system (DAS) and extensive instrumentation were set up for measuring the PV system performance 4). An I-V curve was taken every 10 minutes from January to December 2012. The FPV and CPV array are connected to the inverter and dis-connected from inverter when connected to the I-V curve measuring system for measuring I-V curves. The scanning time of the I-V curve is 500 msec. Each array was disconnected from the inverter while measuring the I-V curves. Therefore, the AC power generation was not significantly affected.

At the same time, all relevant meteorological data such as DNI, tilted surface global irradiance (TGI) and module temperature were recorded. A platinum resistance thermometer (PT100) was mounted close to the cell for measuring the temperature of the CPV module. There are three PT100 sensors on each selected module (Fig. 4). A total of 6 modules and 18 locations were measured by the PT100 sensors for each pedestal (Fig. 5). The average value of the two module temperatures was used for calculation of the array temperature effects. A type T thermocouple was mounted at the back side of the module for measuring the temperature of the PV modules (Fig. 6). The average value of the two module temperatures is used for analyzing the PV array.

Table 1 CPV module Description.

| Name                      | Description                        |
|---------------------------|------------------------------------|
| Cell                      | InGaP/GaAs/Ge                      |
| Number of cell            | 25 cells                           |
| Geometric concentrating ratio | 555 X                               |
| Nominal dimension         | 830 x 830 x 229 mm                 |
3. Results and Discussion

Performance results from the concentrator photovoltaic demonstration field-test were investigated. The field-test data were taken from the CPV system and the FPV system since 2011. These results were analyzed using the I-V curve data.

The energy generated from the CPV system was higher than that from FPV system on a clear sky day (Fig. 7). On the other hand, hardly any energy was generated from the CPV system on cloudy day. A characteristic of CPV that differed from the FPV is shown in Fig. 8 and Fig. 9. It is well known that the fill factor (F.F.) of CPV is much higher than that of the FPV. Moreover, the fill factor is affected by other environmental conditions such as alignment and incident angle.

All data discussed in this paper was sorted according
to a standard deviation of less than 2% of incident irradiance for 1 hour and DNI > 700 W/m², in order to avoid misleading from a synchronism of measurement.

3.1 Temperature Coefficients

The irradiance at the cell surface for CPV is more than 400X. Therefore, heat dissipation performance is one of the key factors for the CPV module and array. This CPV module is designed to cool cell temperature without any forced cooling system, a process known as passive cooling. Fig. 10 presents a histogram of array temperature and ambient temperature for the same time period. The median ambient temperature is 17.9 °C. The temperature of the arrays are 45.0 °C, 50.6 °C, 50.1 °C and 53.5 °C in order of FPV array and three CPV array from no.1 to 3. The temperature of CPV is only ~8.5 °C higher than that of FPV. This result shows an acceptable cooling performance of the CPV module. The absolute effect of temperature to the Voc was ~0.137%/K for CPV array and -0.266%/K for FPV array (Fig. 11).

3.2 Effect of Incident Irradiance

The performances of the CPV and the FPV reflect differences in incident solar insolation. The CPV system has a much higher efficiency than the FPV system. However, CPV can only generate power from the DNI. Thus, the difference between incident solar DNI and TGI is important in evaluating performance 11). Fig. 12 shows the effect of incident irradiance. The short-circuit current (Isc) of both FPV and CPV have a strong relationship with the incident irradiance which is one of the basic characteristics of PV. This relationship is more scattered in the case of CPV than that of the FPV. This dispersion is due to other effects like spectral effect, alignment effect, etc. Moreover; the degree of variation for each array depends on the module alignment.
3.3 Effect of Air Mass and Fill Factor

The spectral effect is one of the important issues for CPV performance. In this section, for the ease of analysis, we try to investigate the spectral effect as air mass (AM) dependence. Given that the AM represent a spectral effect, the relationship between the F.F. and AM can be determined. Fig. 13 shows F.F. as a function of AM. It is difficult to define dependence between AM and F.F. Fig. 14 shows time dependence of F.F. with different seasons. The reason why F.F. is not clearly related to the AM is that the F.F. of CPV arrays is affected by a tracker error, arising due to tracker alignment and accuracy. Therefore, module alignment and tracker distortion can be key factors affecting CPV performance.

4. Conclusion

The CPV arrays consisting of III-V multi-junction solar cells were measured with a conventional fixed c-Si flat-plate PV (FPV) array by placing them side by side in an outdoor environment. This analysis was carried out to determine the effects of module temperature, incident irradiance (DNI for CPV and in-plane irradiance for FPV), air mass, and alignments. The results indicate that the effect of the module temperature is less than half on the CPV array as compared to that on the FPV array. The effect of incident irradiance on the Isc was clearly shown for both the CPV and FPV arrays. However, the CPV array's result was scattered due to other effects such as spectrum.
and alignment. A clear dependence of F.F. characteristics on air mass was not found. A reason for this could be that the F.F. depends on the tracker error, which fluctuates with time and season. The results indicate that the module alignment and tracker distortion are key issues affecting the CPV system performance, while the alignment issue must be reconsidered.

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