Advantages of Concentrator Photovoltaic System in High Solar Radiation Region

Rui MIKAMI*, Makoto INAGAKI, Masao MORIGUCHI, Ken-ichi KITAYAMA, Hiroyuki KONAKA and Takashi IWASAKI

Concentrator photovoltaic (CPV) systems are promising power generation systems for their high outputs per module active area and rated power compared with crystalline silicon photovoltaic (Si-PV) systems. In a field test conducted in Morocco, where solar radiation is high, our CPV system demonstrated approximately 2.5 times higher output power per module active area and 1.3 times higher output power per rated power than a Si-PV system under the condition of direct normal irradiation of 7.9 kWh/m^2/day. We have developed a tracker that faces the ground during the night, thus preventing soil or sand from accumulating on the glass surface of the CPV module and contributing to high power generation.

Keywords: concentrator photovoltaic system, power generation system, direct normal irradiance

1. Introduction

The authors are working on the development of a concentrator photovoltaic (CPV) system for high-efficiency power generation, to meet the growing demand for renewable energy-based power generation systems.(1)

In July 2012, a 100 kW CPV system started demonstration at Sumitomo Electric Industries, Ltd.'s Yokohama Works for use in large-scale megawatt-class power generation systems.(2) This was followed in March 2014 by the company's first commercialization of a CPV system. Subsequently, Sumitomo Electric shipped two CPV systems totaling over 15 kW to the University of Miyazaki. Moreover, in July 2014, CPV modules developed by Sumitomo Electric passed a test conducted by a third-party certification organization, the first time a Japanese manufacturer has met the Internatinal Electrotechnical Commision (IEC) standards.(3)

Concurrently with these operations, to prove the competitiveness of CPV systems, we have conducted field tests in the Kingdom of Morocco, a country in a high solar radiation region eager to introduce renewable energy. This paper reports on CPV's competitiveness based on power generation data obtained from the field tests conducted in Morocco.

2. Features and Challenges of CPV

CPV systems use lenses and other devices to focus direct sunlight onto small-area photovoltaic cells that convert optical energy to electrical energy. A CPV system consists principally of CPV modules and a solar tracker that keeps the modules constantly facing the sun.

CPV modules use high-efficiency multi-junction compound solar cells, which are made of stacked semiconductor materials of different levels of band gap energy so as to reduce loss in the light-sensitive band. Multi-junction compound solar cells have been reported by Soitec, a France-based company, to achieve the world's highest efficiency(4) of 46% at x508 light concentration (508 Suns, where 1 Sun = 1 kW/m^2). Germany-based AZUR SPACE Solar Power GmbH is mass-producing cells with 44% conversion efficiency.(5) Multi-junction compound solar cells in recent years have achieved improved conversion efficiency. They are expected to achieve exceptionally high efficiency of 50% or more in the near future through further technology development.(6)

Current megawatt-class solar power stations use Si-PV modules, the conversion efficiency of which is mostly 15% to 17%. Concentrator photovoltaics generate electric power using lenses that focus only direct sunlight onto solar cells. In contrast, without incorporating any lenses, Si-PV also generates power from light scattered by clouds on cloudy or rainy days when no direct sunlight is available.

As such, the competitiveness of CPV increases in regions where direct normal irradiation (DNI) is more prominent than scattered sunlight. Meanwhile, in such regions, concerns rise about CPV modules affected by dust. Therefore, the authors installed a CPV system in Morocco to ascertain CPV's competitiveness, quantify the effect of dust, and test relevant countermeasures.

3. Installed CPV System in Morocco

In March 2013, a CPV system was set up at the plant location of SEWS-CABIND MAROC S.A.S. (SEWS-CM), an overseas subsidiary of Sumitomo Wiring Systems, Ltd., in Casablanca, the Kingdom of Morocco.

Photo 1 shows the installed CPV system. To compare with Si-PV in power generation performance, this system has CPV modules at the center of the tracker and Si-PV modules (hereinafter, the "2-axis Si-PV") on the top and bottom of the tracker, which tracks the sun. The effective power generation area of the CPV modules was approximately 15.4 m^2, while that of the Si-PV modules was approximately 14.6 m^2.

Moreover, in September 2015, we installed another CPV system in Ouarzazate, which is in a higher solar radiation area than Casablanca. Photo 2 shows this additionally installed system. In Ouarzazate, the annual average cumulative DNI per day is approximately 7 kWh/m^2/day. Incidentally, the Moroccan Agency for Solar Energy (MASEN) also has a plan to deploy solar power generation in Ouarzazate. In the research area at a location under control by MASEN, 20 kW-class CPV system and a 10 kW Si-PV system fixed forward to south at a slope angle of 20 degrees (fixed Si-PV) were installed.

The CPV modules in Ouarzazate were higher in power generation performance per module active area by 6% than those in Casablanca due to changes to the cells and the optical design.

Conversion efficiencies of the photovoltaic modules used in the test in Ouarzazate were approximately 33% for CPV under the CSTC*1 (1000 W/m^2 DNI, AM 1.5D spectrum, 25°C cell temperature, and 0 m wind speed,) contrasting to approximately 17% for Si-PV under the STC*2 (1000 W/m^2 global normal irradiance (GNI), AM 1.5G spectrum, and 25°C cell temperature).

The tracker size used in the field test in Ouarzazate was 70 m^2, about twice as large as that (32 m^2) of the trackers installed at Yokohama Works and in Casablanca.

A power conditioner was connected to both the installed CPV and fixed Si-PV modules. Electric power generated by these systems was monitored at the AC end of each power conditioner.

Photo 1. CPV installed in SEWS-CM

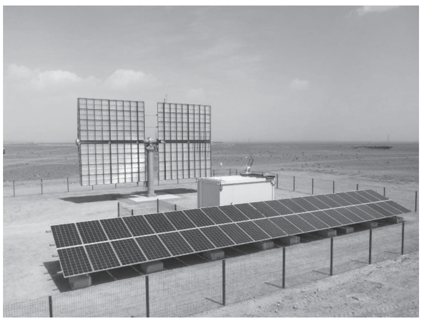

Photo 2. System installed in Ouarzazate
(Back: 20 kW-class CPV; Front: fixed 10 kW Si-PV)

4. Power Generation Demonstration by CPV in Morocco

Figure 1 shows power generation data obtained on November 4, 2015 in Ouarzazate. One important property of a power generation system is the cumulative amount of generated electric energy versus cumulative irradiation per day. Calculation of irradiation and power generation data obtained on that day showed that the CPV generated 2.6 kWh/m^2/day from the cumulative DNI of 9.1 kWh/m^2/day. In contrast, the fixed Si-PV generated 0.99 kWh/m^2 from global tilted irradiation (GTI) of 7.0 kWh/m^2/day.

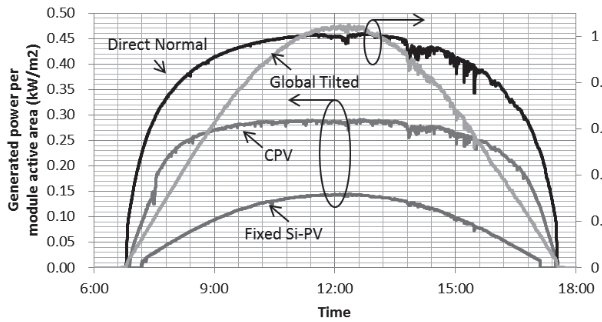

Fig. 1. Power generation data for Nov 4, 2015

Figure 2 shows data collected from the 18-month field testing of power generation in Casablanca along with power generation data obtained during the period from November 4 to November 20, 2015 in Ouarzazate. The figure plots the amount of generated energy versus cumulative DNI. As shown in the figure, the amount of energy per module active area generated by the CPV monotonically increased with cumulative DNI.

In comparison with the CPV's energy generation data collected in Casablanca, the amount of generated energy per module active area by the CPV system in Ouarzazate improved by 6%. It is quite probable that this improvement was, as discussed earlier, a result of

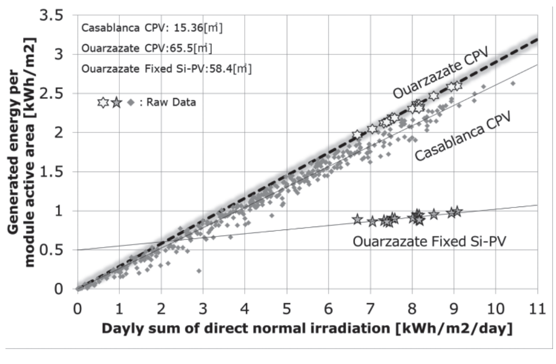

Fig. 2. Comparison of generated energy per module active area in Morocco

the 6% increase in power output per module active area of the installed CPV modules. The cumulative DNI averaged 7.9 kWh/m^2/day during the period from November 4 to November 20. In this period, the cumulative amount of generated energy per module active area averaged 0.91 kWh/m^2 for Si-PV and 2.27 kWh/m^2 for CPV. Consequently, the CPV generated an approximately 2.5 times higher amount of energy per module active area than the fixed Si-PV.

Figure 3 compares the CPV and the fixed Si-PV in generated electricity per rated power. The rated power figures were 21.9 kW for the CPV under the aforementioned CSTC conditions and 10 kW for the fixed Si-PV under the STC conditions. During the above-mentioned period, the generated energy per rated power averaged 6.81 kWh/kW for the CPV and 5.33 kWh/kW for the fixed Si-PV. Consequently, the CPV generated approximately 1.3 times higher energy per rated power than the fixed Si-PV.

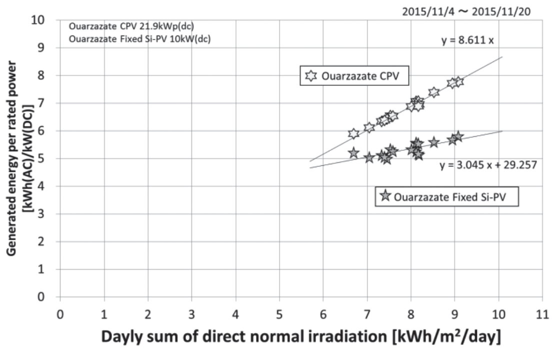

Fig. 3. Comparison of generated energy per rated power in Ouarzazate

5. Effects of Soiled Glass Surfaces in Field Testing of CPV Power Generation in Morocco

The field test conducted in Casablanca revealed that soiled glass surfaces of photovoltaic modules significantly affect power generation.

Soiling indexes were derived in the following manner. First, conversion efficiency (Eff) was determined by dividing the generated energy measurement taken at each prescribed time by the irradiance and effective area of that time. This was intended to remove the effects of changing spectra and irradiance on varying electric power generated by CPV and Si-PV. Moreover, the effects of temperature changes were excluded, as follows: The temperature of the back of each module was measured with a resistance thermometer (Pt 100); and temperature-corrected conversion efficiencies (Eff') at 25°C were determined using the temperature coefficient (−0.10%/°C) of compound semiconductor cells at the maximum power production (Pmp) for the CPV and, similarly, using the temperature coefficient (−0.41%/°C) at Pmp for the fixed Si-PV. The following temperature correction Eq. (1) was used.

$$Eff' = Eff \times (1 + \alpha (25 - T_{mod})) \quad (1)$$

α : temperature coefficient [%/°C]
T_{mod} : temperature of backside module

In the field test in Casablanca, the power generation performance of the CPV decreased by more than 10% within one week due to soiling, although depending on weather conditions. Moreover, as described earlier, CPV is more susceptible to soiling than Si-PV due to differences in the optical system. For this reason, to take power generation data in Casablanca, the PV modules were cleaned once every week.

To devise measures to counter the problem of soiling, how glass surfaces were soiled was investigated (Fig. 4). A model was conceived to describe deposits of airborne fine sand on glass surfaces, reaction of the sand with rain and dew condensation, and adhesion of a clay-like material on the surface. To verify the accuracy of this model, a test was conducted at the same location, exposing dummy samples to the environment. Two identical dummy modules were provided. The glass surface of one dummy module faced upward all the time, while that of the other dummy module faced downward constantly. In these installation conditions, the two modules were exposed to the environment for three days. Observations of the glass surfaces after exposure revealed that the extent of soiling varied radically depending on the orientation of the glass surfaces (Fig. 5). These test results revealed that: it is possible to reduce the amount of sand deposits by orienting the glass surfaces downward during night hours when electric power is not generated; and at the same time by doing so, the potential of rain and dew condensation to wet the glass surfaces decreases, thereby making it reasonable to expect reduced decreases in generated electric power resulting from soiling.

On the basis of the results of the field test conducted in Casablanca, the authors used a tracker

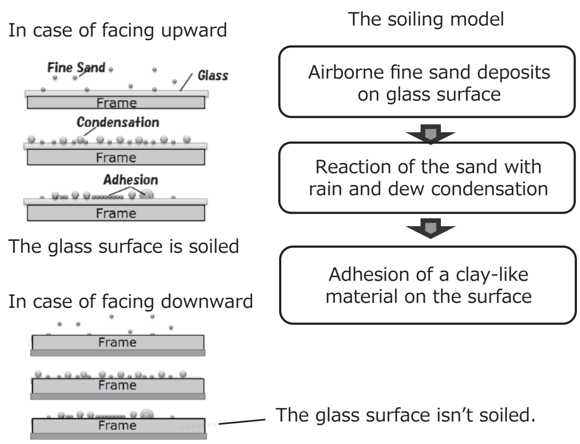

Fig. 4. Glass surface soiling process

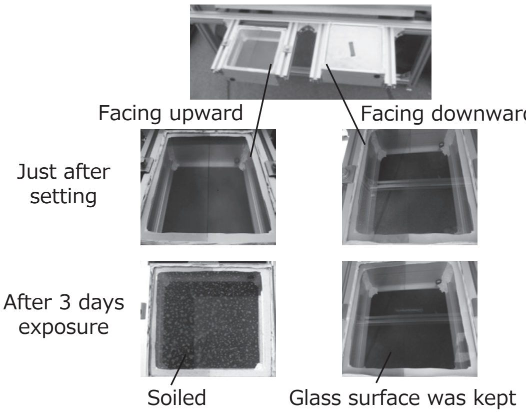

Fig. 5. Results of exposure test in Casablanca

designed to reduce loss resulting from soiling in the field test conducted in Ouarzazate in the Kingdom of Morocco (Photo 3).

The most prominent feature of this tracker was its capability to orient the glass surfaces of the installed photovoltaic modules downward (toward the ground) during night standby hours.

Tracking hours
(Glass surfaces track the sun.)

Night standby hours
(Glass surfaces face downward.)

Photo 3. Tracker installed in Ouarzazate

In the field test period from November 4, 2015 to November 20, the CPV system operated with its glass surfaces facing downward during night hours in standby mode. Figure 6 plots a graph representing decreases in generated electricity resulting from soiling during the above-mentioned period.

On November 4, the glass surface of each module was cleaned to begin exposure. The rates of decrease in temperature-corrected conversion efficiency, as compared with the first day, derived by Eq. (1) were plotted in Fig. 6. The slopes plotted on the graph in Fig. 6 represent the rates of decrease resulting from soiling. Decreases were 3% over 16 days both for the CPV and the fixed Si-PV.

Meanwhile, using power generation data obtained in Casablanca in October and November 2014, the rates of decrease in conversion efficiency were also determined. The decrease for the CPV reached 15% over five days, while the decrease for the dual-axis Si-PV was 3% over five days. Effects of the seasons and weather in areas where the PV modules were installed make simple comparisons inappropriate. However, in comparison with the rates of decrease in electric power generated by Si-PV in both areas, the decrease in generated electric power resulting from soiling is substantially lower with the CPV installed in Ouarzazate than with the CPV in Casablanca.

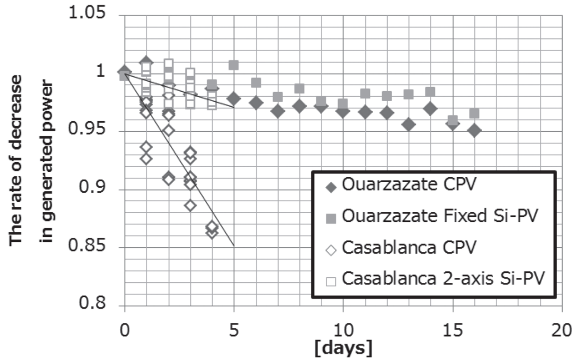

Fig. 6. Rates of decrease in generated electricity resulting from soiling in Morocco

6. Conclusion

CPV systems are expected to generate a large amount of energy per module active area and rated power. The authors conducted field tests of CPV systems in the Kingdom of Morocco, in which high irradiation is expected. The test results revealed that CPV system generate approximately 2.5 times higher energy per module active area and approximately 1.3 times higher energy per rated power respectively than fixed Si-PV system. Moreover, we installed a tracker capable of orienting the glass surfaces of CPV modules downward during night hours in standby mode and proved that the tracker exerts high anti-soiling performance.

Future tasks include collecting field test data over a long period of time in Ouarzazate to further prove the competitiveness of CPV systems in high-irradiation regions.

7. Acknowledgements

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Technical Terms

*1 CSTC: Concentrator Standard Test Conditions.
Standard conditions for testing CPV module output performance specified in the international standard IEC 62670-1
Direct normal irradiance (DNI) = 1000 W/m^2,
Spectrum distribution = AM 1.5D (ASTM G173),
Cell temp. = 25°C, wind speed = 0 m/s

*2 STC: Standard Test Conditions.
Standard conditions for testing crystalline silicon photovoltaic module output performance specified in the international standards IEC 60891 and IEC 60904
Global normal irradiance (GNI) = 1000 W/m^2,
Spectrum distribution = AM 1.5G (ASTM G173), and
Cell temp. = 25°C

*3 Irradiance/Irradiation: Irradiance: density of solar radiation incident on a given surface, expressed in W/m^2
Irradiation: the sum of irradiance over a time period, expressed in J/m^2 or Wh/m^2

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Contributors The lead author is indicated by an asterisk (*).

R. MIKAMI*


• Assistant Manager, Power System R&D Center

M. INAGAKI


• Power System R&D Center

M. MORIGUCHI


• Assistant General Manager, Infrastructure Business Promotion Div.

K. KITAYAMA


• Assistant General Manager, Power System R&D Center

H. KONAKA


• Assistant General Manager, Power System R&D Center

T. IWASAKI


• Group Leader, Power System R&D Center