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Outdoor performance of large scale DSC modules

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Abstract

To elucidate possible challenges for outdoor practical use of dye-sensitized solar cells, outdoor performance of large scale DSC modules made of series-connected 64 DSC cells have been examined for a half year. This is almost the first long term outdoor test of full-fledged DSC modules. Although DSC modules still need the larger area than conventional Si solar cell modules to attain the same rated output because of lower rated energy conversion efficiency, the measured data teach that DSC modules yearly generated 10–20% more electricity than conventional crystalline-Si modules of the same rated output power. This result also teaches that the energy conversion efficiency obtained by the certified measurement under 1 Sun condition does not always coincide with the electricity generated outdoors yearly, and is not a crucial measure to evaluate the performance of solar cells. The outputs of four modules showed similar monotonous slow and steady decreases, showing potential outdoor use of DSC. Simultaneously, it indicates that there are still remaining challenges to overcome one by one in attaining higher performance keeping long term stability.
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1. Introduction

Since the closing years of the last century, we have confronted serious global environmental problems such as greenhouse effect caused by mass consumption of fossil fuels. To overcome these problems, development of renewable, clean energy sources is imperative common challenges for mankind to live in the 21st century. Among them, solar energy is an ideal one being completely renewable, safe and clean. Sunlight can be directly converted to electricity by solar cells. Although single- or poly-crystalline Si solar cells play the lead for practical use now, difficulties in their cost reduction still stand in the way of popularization. Thus, solar energy has still been left without vigorous utilization. Shortage of raw material Si resources to manufacture solar cells is also coming just around the corner. Therefore, new types of low cost solar cells are anticipated.

In 1991, O'Regan and Graetzel of Swiss Federal Institute of Technology at Lausanne developed dye sensitized solar cells (hereinafter referred to as DSCs) as a new class of low cost solar cells [1], whose solar energy conversion efficiency (hereinafter referred to as Eff) was reported to be as high as 7.1% in a simulated solar light, and 12% in diffuse daylight. According to this report, the performance of DSCs was almost as good as that of conventional Si-based solar cells despite of its simple fabrication process. The raw materials used there were of low costs, very abundant in natural resources, and harmless to human beings. Disuse of high temperature thermal treatments nor treatment in vacuum condition in the production line enable remarkable cost reduction in comparison with conventional solar cells. All these features were sufficient enough to attract attention because it will totally change the present sluggish situation and accelerate popularization of solar energy conversion if DSCs can

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be manufactured at a much lower cost than conventional solar cells.

Since then, not a few data have been reported on the performance of small sized DSCs, however, scarcely any outdoor data of electricity generation performance and durability test for practically designed full-fledged modules have been reported. To elucidate potentials and possible challenges of DSC for practical use, outdoor performance of large scale DSC modules was examined.

2. Experimental

Each solar cell used in a module was of 10 cm × 10 cm in size. A glass substrate with a transparent conductive oxide (TCO) layer was coated with a 10 μm thick layer of TiO_2 ultra fine powder with an average diameter of 15 nm to form a photoelectrode. As for sensitizer, ruthenium complex: [Ru(4,4′-dicarboxylate-2,2′-bipyridil)$_2$(NCS)$_2$] was employed. To cover 10 cm × 10 cm area, silver finger electrodes covered with anti-corrosion coating are also attached to collect electricity. Another glass plate with a TCO layer was chemically loaded with fine Pt particles to form a catalytically active counter electrode. After forming a cell structure combining the photoelectrode and the counter electrode using an ionomer sealant (Dupont, Surlyn1702), methoxypropionitrile electrolyte with 0.05 M LiI, 0.5 M *tert*-butylpyridine, 0.6 M dimethyl imidazolium iodide and 0.1 M I_2 in between the two electrodes to form a solar cell. The series connected 64 cells were attached to a tempered glass and waterproofed to form a module as shown in Fig. 1. Several modules, thus, fabricated were set on a rooftop of a building of AISIN SEIKI Co. Ltd. for outdoor performance test as shown in Fig. 2. The place of the outdoor test was located at southern part of Kariya City at lat. 35°10′N, in azimuthal angle: 0° facing due south, tilted at 30°. The amount of insolation and corresponding electricity generated had been monitored for a half year. A conventional commercially available single crystalline silicon module (the product number of the module: SM55 supplied by Siemens and Shell Solar GmbH, the rated output of which is 55 W under the 1 Sun insolation and the size of which is 0.329 m × 1.293 m, indicating the conversion efficiency of 12.9%) was also tested for comparison in the second row

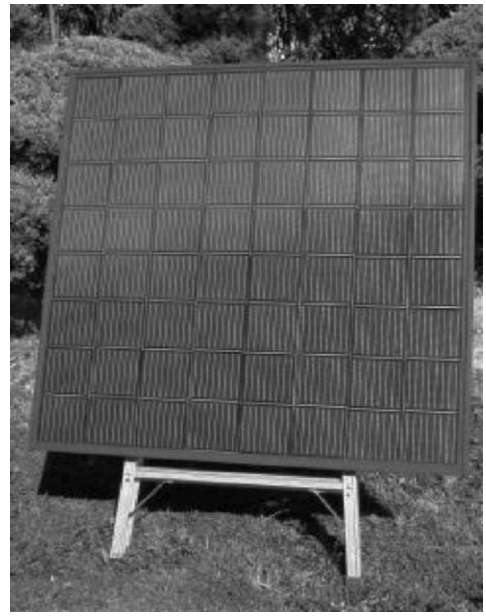

Fig. 1. DSC module composed of series connected 64 cells.

Fig. 2. Outdoor test of DSC modules.

of module stands behind the first row of the module stands in Fig. 2.

Here it should be mentioned that the electricity generated by these DSC modules was partly supplied for this building use via an inverter.

3. Results

Fig. 3 shows a typical example of a variation of insolation and generated electricity from sunup to nightfall. Since the rated output powers are different between the DSC module fabricated here and the commercially available single crystalline silicon module, the generated electricity was converted into the value for rated output power of 1 kW for ease of comparison. Fig. 3 shows DSC module generated more electricity than Si module throughout the day. Especially, DSC has advantages over Si module at mid-morning and at mid-afternoon.

Figs. 4 and 5 show the data of generated electricity on typical clear and sunny days, and typical cloudy days from December to July, respectively. On the clear and sunny days, DSC modules generate 10% more electricity than the single crystalline Si module. On cloudy days, to our surprise, DSC

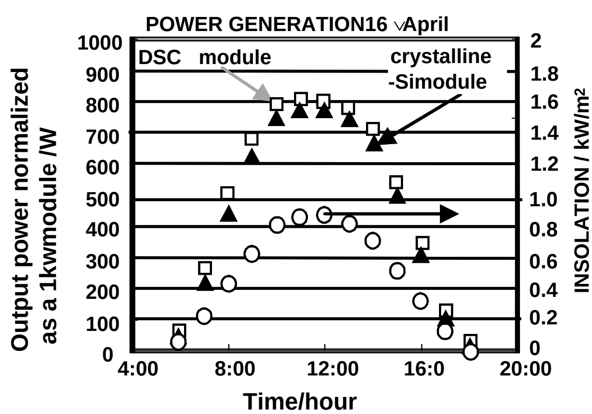

Fig. 3. Variation of insolation and generated electricity from sunup to nightfall on April 16 for the DSC modules and the Si module. Output power is converted as a 1 kW module.

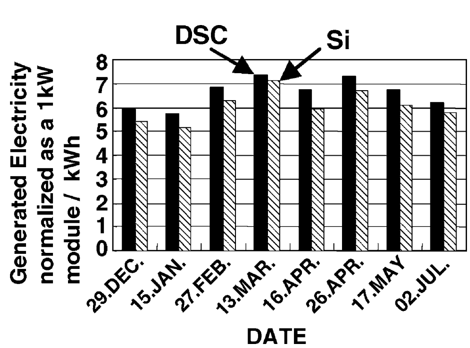

Fig. 4. Example of generated electricity for clear and sunny days between December and July for the DSC modules and the Si module. Output power is converted as a 1 kW module.

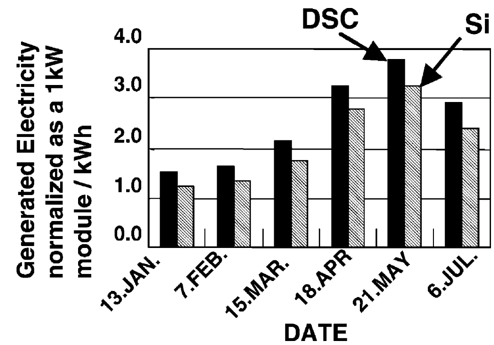

Fig. 5. Example of generated electricity for cloudy days between December and July for the DSC modules and the Si module. Output power is converted as a 1 kW module.

modules generate so high as 20% more electricity than the single crystalline Si module, although total electricity generated was obviously lower than that of clear and sunny days.

Variations of electricity generated by four DSC modules were monitored for a half year to examine the durability as shown in Fig. 6. The four modules showed similar monotonous decrease for 180 days without significant deviations between the modules. Detailed inspection after the outdoor durability test revealed trace of leakage of electrolyte in one of the four modules.

A similar result was also obtained in an outdoor exposure test of a 10 cm × 10 cm cell in a damp-proof box, indicating no significant effect of moisture on the results in Fig. 6. Analyses of degradation were performed including, for example, particle induced X-ray emission (PIXE) analysis of electrolyte extracted from this cell after the outdoor exposure test, searching for trace of ruthenium caused by possible desorption of dye molecules from the TiO_2 electrode. Details of the analyses of degradation will be reported elsewhere.

4. Discussion

In the DSC development, much effort has been focused on improving Eff [2,3]. Because of the limitation of electronic conductivity of the TCO layer on the glass electrode, most of studies have been done with very small cells with its active area around or less than 1 cm^2 (here in after, referred to as “mini-cell”). Recently, several works have been reported on long term stability in some accelerating conditions of degeneration, such as a high temperature (e.g. 85 °C) durability test in the dark, and light soaking test under a continuous simulated 1 Sun insolation, although they still based on mini-cells [4–7]. Correspondence of these artificial durability tests to outdoor tests like the present study must be examined sooner or later. Putting aside the difference between outdoor test and artificial indoor test, tests on modules and tests on mini-cells may also elucidate different aspect of phenomena.

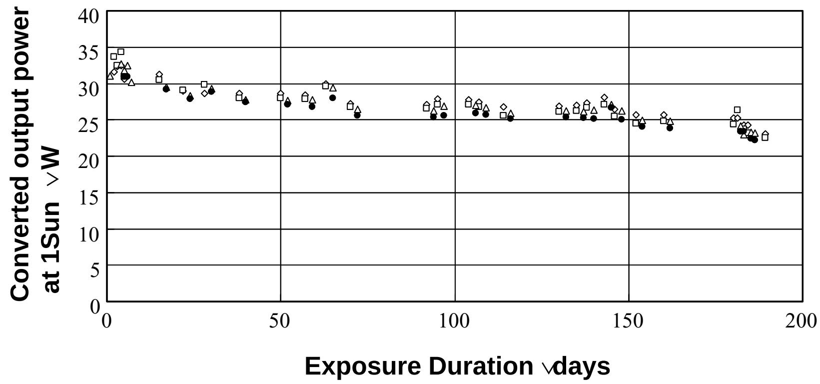

Fig. 6. Variation of electricity generated by four DSC modules for a half year.

Anyway, these fundamental research activities have revealed various properties of DSC.

It is often experienced that the generated electricity does not increase linearly with increase in light intensity [8,9]. Consequently, Eff decreases with increase in light intensity. This phenomenon seems to be attributed to rate limitation of ionic transport or catalytically activated redox reaction on the electrode in DSC, which is effective only in the case of relatively high electric current caused by exposure to an intense light. Since this phenomena has not been experienced in the case of Si cells in which no ionic transport process or catalytically activated redox reaction are involved, difference of Eff s between DSCs and Si cells depends on the light intensity. Under the certified condition of solar cells evaluation: 1 Sun, DSCs give relatively low Eff compared with Si cells. Since the insolation of 1 Sun takes place in only limited few hours around midnoon on limited clear and sunny days in summer, it is easily conjectured that DSCs are not usually exposed to so disadvantageous conditions from sunup to nightfall throughout the year compared with Si cells.

There are also several evidences that an increase in temperature causes increase in Eff, although detailed dependence of Eff on temperature differs from cell to cell depending on the type of electrolyte employed [10,11]. Generally, Eff of DSCs increases with temperature from somewhere around the room temperature to a certain temperature and then begin to decrease beyond this temperature. This phenomenon may be caused by the decrease in viscosity of the electrolyte with increase in temperature, which promotes ionic transport and results in increase in Eff. Therefore, during the summer season, a DSC possibly generates more electricity than expected by its rated output power. On the contrary, it is well known that Si cells lose their output at the elevated temperature on the roof based on the nature of semiconductor. In this point, DSC can get advantage again over Si cells especially in the summer time.

The dependence of electricity generation of Si cells on the angle of light incidence, naturally follows pure geometrical cosine low except for the effect of surface reflection in the region of glancing incidence. In DSC, however, pronounced light scattering in the sintered TiO_2 layer in DSC might have given more light harvesting efficiency than that simply derived from the angle-of-incidence effect, giving more electricity generation at the intermediate oblique incidence of light than expected by geometrically estimated value [12].

Thus, the three factors (1) effect of light intensity, (2) effect of temperature, (3) effect of angle of incidence of light, possibly give advantage to DSC over Si cells for total generated electricity throughout a year.

According to Figs. 3–5, a DSC module generated more electricity than a single crystalline Si module of the same rated output irrespective of (a) the hour of a day, (b) weather, and (c) seasons. This is exactly an outdoor experimental proof of possible advantage of DSC over Si-cells (1)–(3) as mentioned above that DSC modules can generate more electricity than single crystalline Si solar cell modules of the same rated output based on the half year outdoor exposure of practically designed full-fledged modules.

To put it the other way around, so far as one cares total electricity generated, one can choose a DSC of lower Eff than a single crystalline Si solar cell if there is no critical limitation of area. In other words, Eff obtained by the certified measurement under 1 Sun condition does not always coincide with the electricity generated outdoors, and is not a crucial measure to evaluate the performance of solar cells. Here, it should be noted again that DSC modules still need more area than conventional Si modules of the same rated output power because of lower Eff of DSC than that of Si cells, although Eff of DSC was reported to have gone beyond 10% reproducibly very recently [13].

Fig. 6 tells there is still intrinsic degradation of performance, and it is still important to go back to fundamental researches to overcome this degradation, and come back to the outdoor test with full-fledged modules.

5. Conclusions

(1) Outdoor performance of large scale DSC modules made of series-connected 64 DSC cells have been

examined for a half year, showing potential outdoor application of DSC.

(2) The measured data teach that DSC modules yearly generated 10–20% more electricity than conventional crystalline-Si modules of the same rated output power.

(3) For practical use, there are still remaining challenges to overcome one by one in attaining higher performance keeping long term stability.

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