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Technical Note

Submerged photovoltaic solar panel: SP2

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ABSTRACT

The behavior of a photovoltaic (PV) panel submerged in water is studied. A sizeable increase of electric power output is found for shallow water. Experiments have been carried out for single crystalline silicon panels. Results are discussed and the increase in efficiency is investigated and understood. Operating problems are analyzed and the advantages of using underwater solar panels are pointed out.

1. Introduction

Over the last 20 years there has been a great effort in research and development in the photovoltaic (PV) field, focusing on three main directions:

- to increase the efficiency of both PV cells and panels
- to reduce cost for kW peak
- to develop easy to handle and durable new materials for PV systems

Considerable results have been attained, see for example reference [1]. The practical management of an operative solar panel is, however, as yet far from being optimized and in particular two problems are critical:

- the cleaning of the panel: dust, leaves or birds can strongly reduce the efficiency of a PV panel and the maintenance can be very expensive.
- the temperature drift: most PV materials have a negative temperature drift and this entails a lower efficiency when weather conditions are optimal for energy production. The reduction can reach 30% in summer radiation conditions [2,3].

This paper is devoted to studying the effects obtained by a PV panel submerged in water and to evaluating the problems and the advantages of this new use of a consolidated technology, both theoretically and experimentally.

To the authors' knowledge, the literature provides only one analysis of the efficiency of submerged panels, with particular attention given to the possibility of using PV panel in deep water; see references [4] and [5]. On the contrary, the present analysis will concentrate on the effects in shallow water.

This system will be called *Submerged Photovoltaic Solar Panel*, henceforth indicated by the acronym SP2.

2. Submerged panel: light reflection and thermal effects

Two main effects increase the efficiency of a commercial panel placed in water:

- reduction of light reflection
- absence of thermal drift

The light reflection on a commercial PV panel is related to the material used to shield the PV active material. In most panels this is glass with a refraction index of $n \approx 1.53$. An intermediate layer of water with $n = 1.33$ changes the reflected fraction of an incoming perpendicular ray from 4.4% to 2.0% because water reduces the income impedence radiation. This effect is enhanced if the light is not perpendicular and becomes more important for wide incidence angles.

To evaluate the percentage of reflected radiation, an optical model of behavior of solar rays through two layers has been

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developed. The reflectance has been calculated by means of Fresnel Formula, where the refraction indexes of water and glass are used. The angles that the incident, reflected and refracted rays make to the normal are given by the law of reflection and Snell's law. By using this model, it is possible to estimate that the average gain in July and in January, at a latitude of 45°, is of 2.5% and 4.5% respectively. In the absence of direct solar radiation, if only diffused light is present, the average increase is of about 4.1%.

This percentage has been calculated averaging the value of total reflected intensity over the radiation contribution and taking into account the reflection on the air-water and on the water-glass interfaces. The diffusion part of the radiation has also been taken into account. Thermal effects are much more important and are characterized by a set of temperature coefficients. Usually five basic parameters are given:

(1) short-circuit current (I_{sc})
(2) maximum power current (I_{mp})
(3) open-circuit voltage (V_{oc})
(4) maximum power voltage (V_{mp})
(5) maximum power $P_{mp} = I_{mp} \cdot V_{mp}$,
as well as the global panel efficiency (η).

In the literature there are many articles on the measurement of the temperature coefficients. Table 1 is taken from reference [2] with minor modifications (the last column has been added using equation (3) of reference [2]). This table summarizes outdoor measurements of effective temperature coefficients (I_{sc}, I_{mp}, V_{oc}, and V_{mp}) for a variety of commercially available photovoltaic modules. In the table, the units for the temperature coefficients have been normalized to 1/°C by dividing the coefficient by the value of the parameter at ASTM Standard Reporting Conditions (1000 W/m^2, AM = 1.5, 25 °C).

If the PV panel is submerged in a pool, the temperature can range between 20 and 30 °C, whereas in the case of lakes and the sea the typical temperature range is between 10 and 20 °C. These numbers must be compared with the temperature of a standard panel (without forced cooling) in good weather condition, which in the summer may even reach 70 °C. In this experiment the water temperature was of 30 °C.

In this case the temperature difference between a submerged panel and a standard panel exposed in air is of 40 °C, with an average gain of 25% for single crystalline panels, 20% for poly-crystalline silicon panels and 15% for amorphous silicon panels.

3. Solar spectrum in shallow water

The strong improvement in efficiency discussed in the above section is decreased by the changes in solar spectrum at different water depths. Clean water is a strong light absorber but fortunately this absorption occurs mainly in the red-infrared region. Fig. 1 shows what happens to the solar spectrum at different depths. The crystalline silicon spectral response has been superimposed so as to highlight that the hindrance of solar radiation takes place in the region where PV conversion is less effective.

Table 1
Typical effective derivatives temperature coefficients for commercial modules at 1000 W/m^2 and AM = 1.5 measured outdoors (see [2]).

Module	dI_{sc}/dT (1/°C)	dI_{mp}/dT (1/°C)	dV_{oc}/dT (1/°C)	dV_{mp}/dT (1/°C)	dP_{mp}/dT (1/°C)
M55, c-Si	0.00032	−0.00031	−0.0041	−0.0053	−0.0056
SP75, c-Si	0.00022	−0.00057	−0.0039	−0.0049	−0.0055
SQ-90, c-Si	0.00016	−0.00052	−0.0038	−0.0048	−0.0053
ASE300, mc-Si	0.00091	0.00037	−0.0036	−0.0047	−0.0043
MSX64, mc-Si	0.00063	0.00013	−0.0042	−0.0052	−0.0051
MST56, a-Si	0.00099	0.0023	−0.0041	−0.0039	−0.0016
UPM880, a-Si	0.00082	0.0018	−0.0038	−0.0037	−0.0019
US32, a-Si	0.00076	0.0010	−0.0043	−0.0040	−0.0030

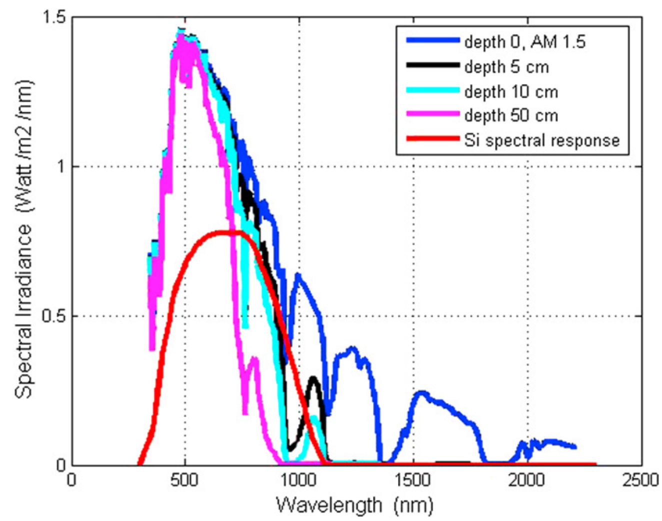

Fig. 1. Variation of solar radiation with water depth with superimposed crystalline silicon spectral response.

It is possible to estimate the gain or loss in efficiency, with respect to a PV panel in a standard position, outside the pool, by studying the combined effect of the solar spectrum dumping at a given water depth and the efficiency spectrum of the PV material, corrected by the temperature drift. As an example, amorphous silicon will be discussed in detail. In this case the increment due to absence of thermal drift is smaller than in single crystalline silicon so the gain in efficiency due to this effect and to the minor light reflection is limited to 14%, which occurs when water depth is 1 cm. However, the efficiency spectrum is shifted through the visible frequencies so that the loss due to the water absorption is limited and an interesting efficiency is obtained even at a depth of 50 cm. So, in order to evaluate the relative efficiency, at a given temperature and water depth, the spectral efficiency has to be folded with the residual radiation spectrum at different depths. In Fig. 2 the water temperature has been assumed to be Tw = 25 °C, the dry panel temperature is Td = 65 °C, and the temperature drift coefficient has been assumed to be 0.55%/°C, 0.45%/°C and 0.25%/°C respectively for single, poly and amorphous silicon cells. Furthermore, the spectral efficiency of the three panels has been calculated integrating the solar spectrum multiplied by the water absorption coefficients at the different wavelength. The reduced photon number impinging on the panel is compensated, for depth less than 10 cm, by the absence of thermal drift.

It is evident that the efficiency is increased or reduced, depending on the choice of the PV material and on the operating depths.

4. Experimental test

A four-month long test has been performed on a single crystalline silicon panel using a pool where it was possible to position the panel at several depths. Some results are shown in Figs. 3 and 4, where three identical panels are studied and compared.

(1) panel-1 is placed in air exposed to solar radiation
(2) panel-2, SP2, is submerged under 4 cm of water
(3) panel-3, SP2, is submerged under 40 cm of water