

Submerged Photovoltaic Solar Panel: SP2

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Abstract

The Efficiency of a photovoltaic panel submerged in water is studied. A considerable increase of efficiency is found for shallow water. Experiment is done for single crystalline silicon panels. Results are discussed and the increase in efficiency is analyzed and understood. Operating problem are analyzed and advantages of using undersea solar panels are prompt out.

1 Submerged Panel

Over the last 20 years there has been a great effort in research and development in the photovoltaic (PV) sector, which has mainly focused in three directions

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

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

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

In this paper we study the effects obtained by a PV panel submerged in water and we evaluate theoretically and experimentally the problems and the advantages of this new use of a consolidated technology. The literature furnishes, to our knowledge, only one analysis of the efficiency of submerged panels with particular attention to the possibility of using PV panel in deep water; see references [3] and [4]. On the contrary, we will concentrate our analysis on the effects in shallow water.

2 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 $n \approx 1.55$. An intermediate layer of water with $n = 1.33$ changes the reflected

T_c ($^{\circ}\text{C}$)	V_{mp} (V)	I_{mp} (A)	P_{mp} (W)	η_{PV} (%)
25	34.0	2.34	79.6	13.1
60	26.1	2.35	61.3	10.1

Table 1: Average parameters of 72 single crystalline silicon solar cells ASE-100-DGL-SM module, measured at cell temperature T_c and irradiance at 840 W/m^2

fraction of an incoming perpendicular ray from 4.5% to 2.6%. This effect of course is enhanced if light is not perpendicular and becomes more important for wide incidence angles.

We have estimated, through Fresnel formula, that the average gain in July and in January at a latitude of 45° is of 2.% and 4.5% respectively. In absence of direct solar radiation, if we have only diffused light, the average increase is of about 4.1%.

Thermal effect are much more important and are characterized by a set of temperature coefficients. In general 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 $P_{mp} = I_{mp} \bullet V_{mp}$.

as well as the global panel efficiency (η).

Literature gives many articles on the measurement of the temperature coefficients and some parameters for silicon panels are shown in table 1 taken from reference [2] where the direct measurement for single crystalline silicon cells at 25°C and 60°C are given.

The efficiency loss $\Delta\eta_{PV}/\Delta T$ is given by $-0.06(\%/K)$ so that the power drop from 79.6 to 61.3 W with an increase of temperature $\Delta T=35^{\circ}\text{C}$. Loss in efficiency is of about 30%

Table 2 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 $1/^\circ\text{C}$ by dividing the coefficient by the value for the parameter at ASTM Standard Reporting Conditions ($1000\text{ W}/\text{m}^2$, $\text{AM}=1.5$, $25\text{ }^\circ\text{C}$).

Module	dI_{sc}/dT ($1/^\circ\text{C}$)	dI_{mp}/dT ($1/^\circ\text{C}$)	dV_{oc}/dT ($1/^\circ\text{C}$)	dV_{mp}/dT ($1/^\circ\text{C}$)	$d(P_{mp})/dT$ ($1/^\circ\text{C}$)
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

Table 2: Typical effective derivatives temperature coefficients for commercial modules at $1000\text{ W}/\text{m}^2$ and $\text{AM}=1.5$ measured outdoors.

If the PV panel is submerged in a pool the temperature can range between 20 and $30\text{ }^\circ\text{C}$, whereas for lakes and sea the typical range of temperature is between 10 and $20\text{ }^\circ\text{C}$. These numbers have to be compared with the temperature of a standard panel (without forced cooling) with good weather condition in the summer which may even reach $80\text{ }^\circ\text{C}$. For the sake of comparison we will assume that the average temperature with a good level of solar radiation of $800\text{ W}/\text{m}^2$, should be $60\text{ }^\circ\text{C}$. In this case it is easy to see that the temperature difference between a submerged panel and a standard panel exposed in air is of about $40\text{ }^\circ\text{C}$ with a gain in average of 20% for single crystalline panels, 15% for polycrystalline silicon panels and 10% for amorphous silicon panels.

3 Solar spectrum in shallow water

The strong improvement in efficiency discussed in the above section is contrasted by the change in solar spectrum at different water depth. As a matter of fact, clean water is a strong light absorber but fortunately this absorption occurs mainly in the red-infrared region. In figure 1 we show what happens to the solar spectrum at different depth. We have superimposed the silicon efficiency spectrum in order to evidence that the hindrance of solar radiation take place in the region where PV

conversion is less effective. It is possible to estimate the gain or loss in efficiency,

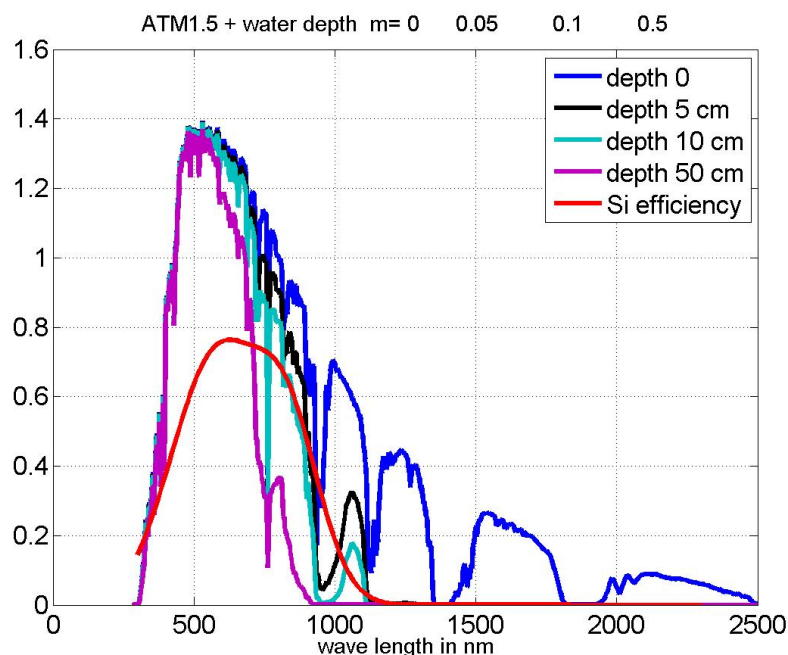


Figure 1: Variation of solar radiation with water depth with superposed silicon efficiency spectrum in arbitrary units

with respect to a PV panel in a standard position by studying the solar spectrum dumping at a given water depth folded with the efficiency spectrum of PV material, corrected by the temperature drift. As an example we discuss the amorphous silicon. In this case the increment due to absence of thermal drift is smaller than in single crystalline silicon so the gain in efficiency is limited to 10%. However the efficiency spectrum is shifted through the visible frequencies so that the loss due to the water absorption is limited and we get interesting efficiency even at a depth of 50 cm. In figure 2 the behavior for single poly and amorphous silicon are given as a function of water depth.

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

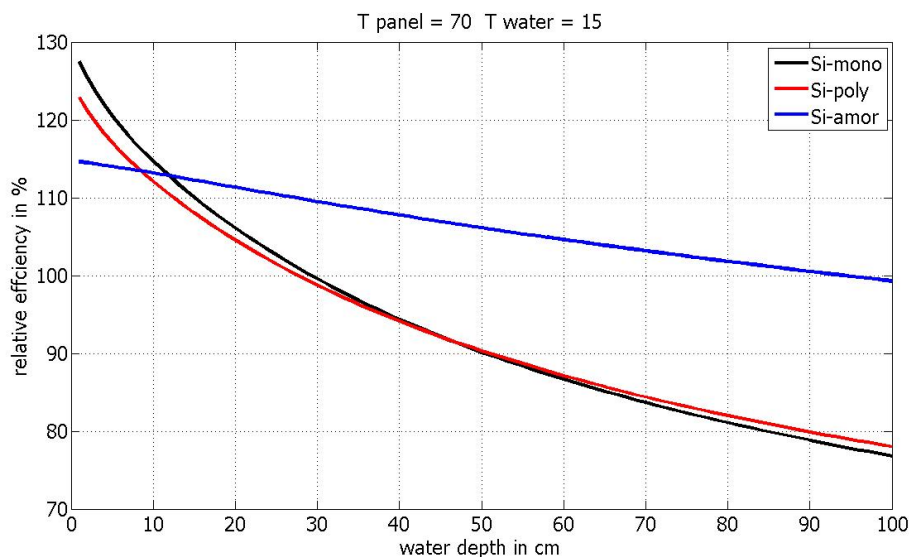


Figure 2: Efficiency increase with the water depth

4 Experimental test

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

1. panel-1 is placed in air exposed to solar radiation
2. panel-2 is submerged under 5 cm of water
3. panel-3 is submerged under 40 cm of water

These measurements were carried out in Pisa at the latitude of $43^{\circ} 43'$ on April 28 2008. They show a record of 150 minutes and the plots represent the output power of panels (optimized with a tunable electric resistance), and the power of solar radiation for square meter registered with a pyranometer (reduced by a factor 100 in order to represent it on the same figure).

After 100 minutes of record panel-1 and panel-2 are swapped. This is necessary to ensure that the measured effect is not due to an *ab initio* difference in the performance of the two panels compared.

The experiment analysis is quite clear. The power output of the three panels is essentially proportional to the solar radiation but with some relevant difference. In detail:

- panel-1 and panel-2 have almost the same output at the very beginning but, panel-1 exposed to solar radiation, warms up to 40 degrees. As water temperature is 15 °C, we estimate a gain of about 10% which matches the 10% value found experimentally.
- when panel-1 and panel-2 are swapped the temperature of the two panels at the beginning is essentially the same. So the starting point also is the same but the warming of panel-2 gives rise to a better performance of panel-1.
- panel-3 submerged of 40 cm has an efficiency reduce of about 15%. This should be compared with the value estimated in simulation of about 14%.

We note that when the two panels (1 and 2) have the same temperature, the efficiency of the submerged panel is slightly lower by about 2%. This should be the result of two antagonist effects: the absorption of solar radiation for the submerged panel (which reduces the panel efficiency of 5%) and the increase in the incoming radiation (of about 2%).

This effect is small and will be further analyzed under different radiation conditions in order to check the advantages of the graded refraction index which lower the input impedance of the incoming radiation. Surface conditions are also important and have to be carefully analyzed.

5 Practical problems and conclusion

Measurements have been done for four months without encountering any problem in the electric management of the panels. The panels used are the commercial ones and have been used submerged without any modification except a careful insulation of the electric cables.

The panels, submerged and not, have been placed in flat position. This slightly reduces the average efficiency but gives better results in the summer and allows to simply solve problems related to the support frame of the floating structure and to cleaning.

Cleaning problems are more easily solvable than for panels exposed in air to normal weather conditions. We did a periodic cleaning on the submerged panels, every month, without any measured loss of efficiency, on the contrary the non submerged one suffers an efficiency loss of more than 10%.

The managing of the apparatus is simple and practical. Further tests with different types of panels (poly-crystalline, and amorphous silicon, thin film panels

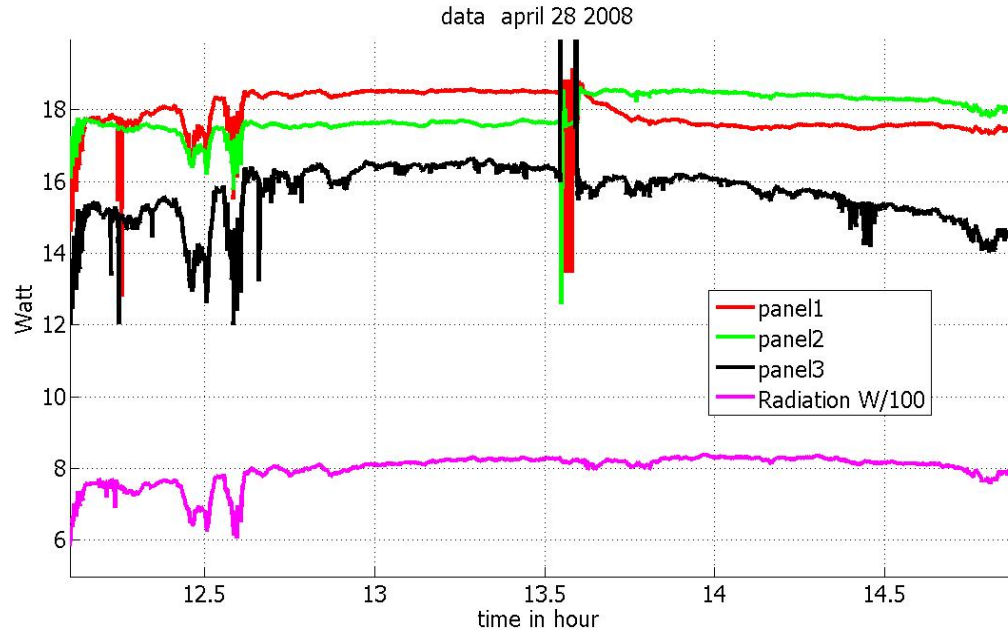


Figure 3: Measurements of PV conversion at different depths

etc) are in progress.

6 Acknowledgments

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References

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