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# Influence of Water Turbidity Upon the Solar Radiation and Photovoltaic Response of Amorphous Silicon Based Underwater Solar Cells

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## ABSTRACT

To meet global energy demand, photovoltaic (PV) energy technologies should be rescaled and upgraded. A facile way is to head towards underwater PVs to create stable and reliable renewable energy sources in the aquatic regime. Current work comprehends an experimental study on the behavior of solar radiation and the performance of amorphous silicon (a-Si) solar cell in diverse underwater conditions. The main focus of the study is to investigate the impact of water turbidity on insolation power and device performance at various depths. Both the irradiance power and the cell performance showed an inverse correlation with the water turbidity. The turbidity values for the lowest turbid double distilled water (DDW), low turbid lake water (LTLW), and high turbid lake water (HTLW) were measured to be 0.1 NTU, 2.5 NTU, and 6.6 NTU respectively. Also, a percentage drop in solar irradiance at a depth of 20 cm for different water types was captured.

**Keywords:** underwater solar cell, amorphous silicon solar cell, turbidity

## 1. INTRODUCTION

The energy crisis has always been a major concern worldwide. To solve this, people have come up with many ideas like leveraging renewable energy sources such as solar energy [1]. Still, energy crisis persists due to insufficient harvesting of solar energy in different ways like solar water heaters, photovoltaic (PV) solar panels, thermal energy harvesting, concentrating solar power, and many more. However, these PV cells only harvest the solar energy that falls on land, and unfortunately, all the solar radiation that falls on the water surface (nearly 70% coverage of the earth's surface) gets wasted. These facts push to approach towards using underwater PVs also for harvesting solar energy. Also, in terrestrial conditions, solar panels get heated up fast which causes the panel to be less efficient, and its surface often gets covered with dust, leaves, birds, etc., which causes shading loss which contributes to nearly 60% of the losses [2]. Placing solar panels underwater can help in improving the efficiency as it will reduce the thermal drift [3]. Clearly, placing solar cells underwater will provide self-cooling and self-cleansing of the surface. Apart from this, marine systems like underwater vehicles, autonomous systems, and sensors are limited by the lack of power sources for long-term operation and typically rely on on-shore power or power from solar cells situated on land or above the water surface [4,5].

Shockley and Queisser estimated that the maximum efficiency that can be obtained from a land-based single junction solar cell is 34% [6]; however, when the solar spectrum gets narrow, the maximum efficiency limit increases [7]. Studies have been carried out on theoretical calculation of efficiency which yields that when indoor solar cells are illuminated with light sources with narrow emission spectra like LEDs and sodium discharge lamps the cell can operate at efficiencies nearly 60% and 67% respectively [8]. When light is transmitted through the water, a similar narrowing of the irradiance spectrum is observed which gives a thoughtful idea about an increase in the efficiency limits of underwater solar cells [5]. While there are many benefits of placing solar cell underwater but it comes with many challenges. The main challenge comes in the form of insolation. Not all the wavelengths have the ability to penetrate deep inside water. When solar radiation falls on water, nearly 2% of it get reflected back at the surface, and the rest gets transmitted. Out of this transmitted radiation, 27% gets absorbed up to 1 cm and 70% is absorbed up to 3 m depth [9]. It was found that single-crystalline solar cells show higher efficiency at shallow depths [10]. On testing amorphous silicon (a-Si) solar cell in variable water environment, it was observed that artificial sea water (3.5% salinity) does not show significant changes on the output power up to the depth of 20 cm [11].

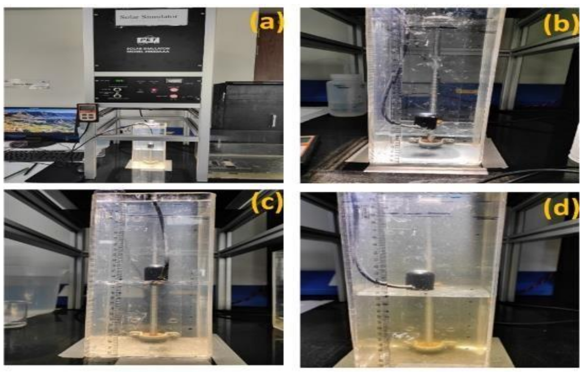


Fig. 1. Experimental setup (a)Solar simulator and submerged pyranometer; submerged pyranometer in (b)DDW, (c) LTLW and (d) HTLW

Other challenges include temperature gradient, wave, salinity gradient, turbidity, algae formation, durability of cell, encapsulation of cell etc. Many works have been done in order to understand the performance of cell in underwater environment. Wang et al. reported that the turbidity of water affects the solar irradiation more than salinity of the water [12]. In this work various water characterizations are done on turbid water. a-Si solar cell is used for this study as it performs better than monocrystalline and polycrystalline solar cells in underwater conditions [13]. For all the underwater applications of solar cell, water turbidity plays an important role as it will affect the insolation and the cell performance. However, no work has so far been reported to investigate the impact of water turbidity on the actual device performance of the a-Si solar cells. Therefore, herein, the role of water turbidity on the cell performance at varying depths is investigated.

## 2. EXPERIMENTAL PROCEDURE

The experimental work was carried out in the laboratory by designing and executing an underwater setup for solar PV. An acrylic tank of dimension 10×10×30 $cm^3$ was used to study solar cell behavior in underwater conditions. The a-Si solar cell (5 V, 9.9 mA) was purchased from Panasonic-BSG, Japan (Sanyo Semiconductor co.,2007). Solar Simulator SS50AAA (Class AAA) with Air mass (AM 1.5 G) and Xenon short-arc lamp of 150 W was used for providing solar insolation. The solar simulator was calibrated at 100 $mW/cm^2$ (equivalent to 1 Sun) using a submersible pyranometer (PYR) sensor from Apogee Instruments Inc., USA. The a-Si solar cell was encapsulated using polydimethylsiloxane (PDMS) with a 3D printed enclosure as per our earlier reported work [14].

The behavior of solar radiation in underwater conditions was studied for double distilled water (DDW) and lake water environment with two different turbidities i.e., High turbidity lake water (HTLW) and Low turbidity lake water (LTLW). The J-V and P-V characteristics of the a-Si cell were obtained using B2912A precision source/measure unit (Keysight Technologies). The whole experimental setup including the pyranometer in different water conditions is shown in Figure 1. Throughout the experiments, the water bath was kept turbulence free while measuring the irradiance and cell parameters.

## 3. WATER CHARACTERIZATION

Three different types of water were taken which were DDW (obtained from MEMS Lab, BITS Pilani, Hyderabad Campus), HTLW (Shamirpet lake, Hyderabad, India), and LTLW (Prepared by adding DDW in HTLW) characterized based on their turbidity, total dissolved solids (TDS) and electrical conductivity, whose values are provided in Table 1. Turbidity measurement was done using turbidity meter (Eutech Instruments, Singapore) and the TDS value and electrical conductivity were measured using Conductivity/TDS/OC/OF meter (Eutech Instruments, Singapore).

Table 1 shows the turbidity values, electrical conductivity, and TDS of DDW, LTLW and HTLW

| Water type | Turbidity (NTU) | Conductivity (µS/cm) | TDS (ppm) |
|---|---|---|---|
| **DDW** | 0.1 | 4.7 | 2.40 |
| **LTLW** | 2.5 | 478 | 238 |
| **HTLW** | 6.6 | 513 | 257 |

## 4. RESULTS AND DISCUSSIONS

### *4.1* Solar irradiance and water studies

In order to understand the behavior of the a-Si solar cells (in underwater environment) with the water turbidity, three different water-types with different turbidity values were taken into consideration. DDW was taken as the standard water-type with the lowest turbidity value of 0.1 NTU. Water from a nearby lake (Shamirpet lake, Hyderabad, India), with the turbidity value of 6.6 NTU, in natural conditions was taken as the highest turbid water source. Instead of taking intermediate turbid water from some other source, it was prepared by diluting the HTLW with the DDW, to make sure that the constituents are similar in shape and size, which play a decisive role in determining the optical characteristics of the water. The turbidity value for this water was measured to be 2.5 NTU. In addition to this,

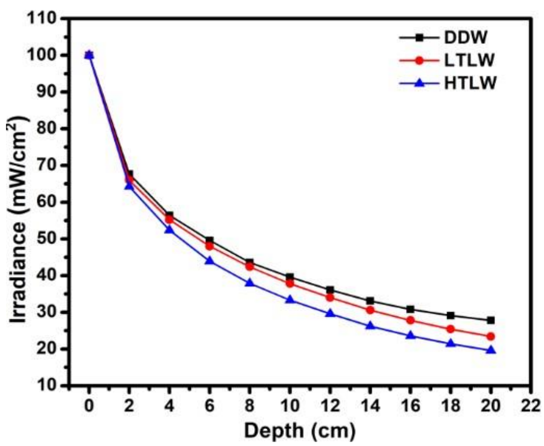


Fig. 2. Variation of irradiance power with the increasing depth in DDW, LTLW and HTLW

the other water parameters such as, TDS values, and electrical conductivity were also measured.

These values are tabulated in Table 1. Figure 2 shows the variation of solar radiation with the increasing depth in these three different water environments. The figure clearly indicates that the irradiance power decreases with increasing depth for all the waters. More interestingly, it also reveals that the irradiance power reduces significantly with increasing turbidity and hence shows an inverse correlation. The percentage drop in irradiation power at 20 cm in DDW, LTLW and HTLW were measured to be 72%, 77% and 80% respectively. These studies are in linewith the reported literature [15].

### *4.2 J-V response with varied water turbidity*

The J-V curves of the a-Si solar cell with varying depth (0–20 cm) in all three water environments were measured at room temperature conditions. The irradiance power at the surface was set for 1 sun condition (100 mW/cm$^2$) and the J-V response with the depth was measured accordingly for all the conditions. Figure 3 shows the J-V curves for a-Si solar cell with

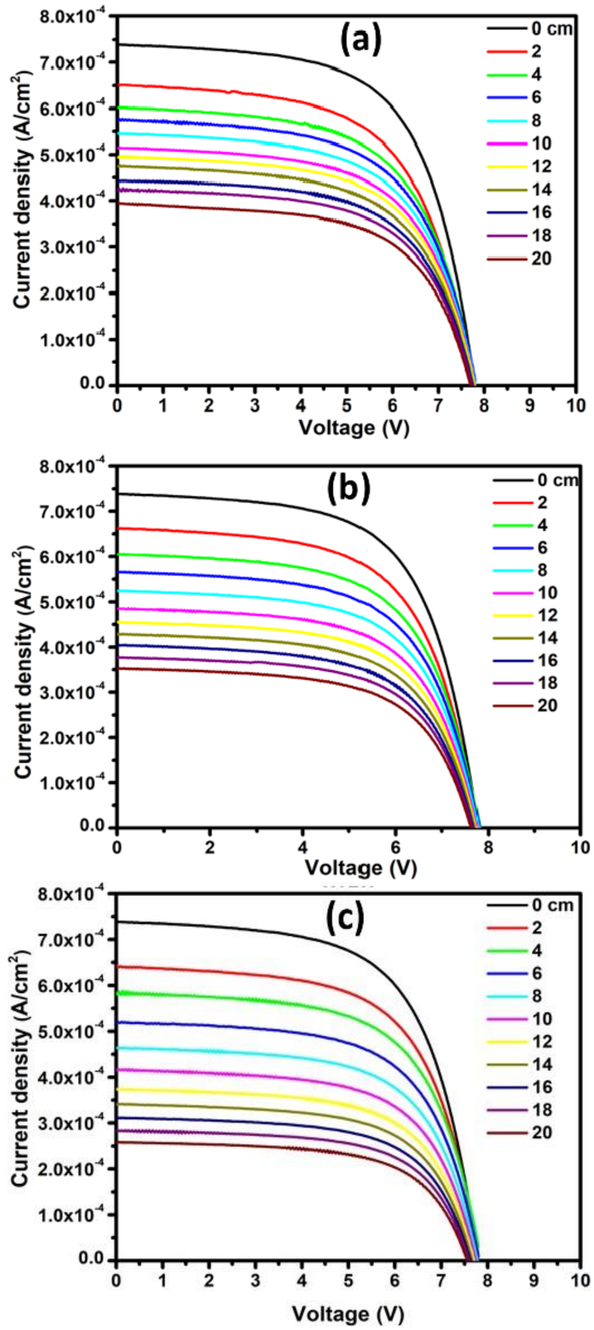


Fig. 3. J-V characteristics for a-Si solar cell with respectto depth for (a) DDW, (b) LTLW and (c) HTLW

respect to depth in all the three environments. The open circuit voltage ($V_{OC}$) value of the device under investigation was found to be almost constant (nearly 7.7) for all the depths. However, comparatively a remarkable reduction in $J_{SC}$ values with depth was noticed for all the waters as clearly depicted in Figures 3(a-c). The inverse variation of $J_{SC}$ values with depth can be attributed to the variation of insolation with depth as discussed in Section 4.1. Interestingly, the $J_{SC}$ values showed a significant variation with the turbidity values.

The variation of P with V, in different water environments, measured at a depth of 20 cm is plotted in Figure 4 (a). This figure clearly indicates that the output power of a-Si solar cell has the maximum values in the lowest turbidity water (DDW) at all the depths and vice versa. Despite the huge reduction in PV power with the

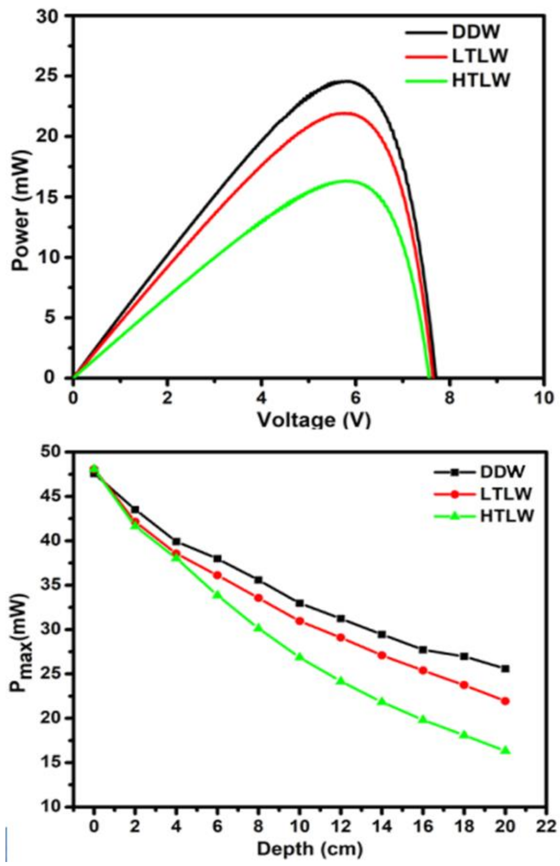


Fig. 4. (a) Variation of power with voltage in different water environments at 20 cm and (b) Variation of Pmax values at different depths for all the water environments

increasing turbidity, the a-Si cell, still shows a significant PV response deep inside (20 cm) the highly turbid water.

Furthermore, for quantitative comparison of the photovoltaic response with the water turbidity, we have also evaluated the variation $P_{max}$ values at different depths for all the water environments. The variation given in Figure 4 (b). Interestingly, this plot lends support to above analysis. However, another fascinating observation is noticed in this graph. At the lower depths, the variation of the $P_{max}$ values for the different water environments is very low. However, as the depth increases, the variation in P values is found to be significantly higher. The prime reason for this might be the concentration of the particulate matter in the HTLW with depth owing to the gravitational potential. Therefore, the comparative reduction rate will be higher at the deep depths than at the shallow depths. The percentage drop in the $P_{max}$ values in comparison to the surface $P_{max}$ values, evaluated at 10 cm depth and 20 cm depth are given in Table 2.

Table 2 shows the percentage drop in Pmax values of a-Si solar cell at depth of 10 cm and 20 cm and Pmax value at 20 cm

| Parameters | DD Water | HTLW | LTLW |
|---|---|---|---|
| **Drop in $P_{max}$ up to 20 cm** | 45% | 66% | 54% |
| **Drop in $P_{max}$ up to 10 cm** | 31.8% | 44% | 36 |
| **$P_{max}$ at 20 cm (mW)** | 24.5 | 16.3 | 21.9 |

## Conclusion

In this work, the behavior of solar radiation underwater with varying turbidity and depth have been examined. Three water environments with turbidity 0.1 NTU (double distilled water), 2.5 NTU (low turbid lake water) and 6.6 NTU (high turbid lake water) were used for this study. The irradiance power shows an inverse association with increasing depth and increasing turbidity. To understand the correlation between insolation and cell performance in underwater conditions, amorphous silicon (a-Si) solar cell was tested in all the three water environments. In all the cases, drop in $J_{SC}$ and $P_{max}$ was observed with varying depth. Moreover, $P_{max}$ value reduced with increasing turbidity from 24.5 mW (0.1 NTU) followed by 21.9 mW (2.5 NTU) to 16.3 mW (6.6 NTU) which shows an in-line variation as according to irradiation power drop. Here, a-Si solar cell showed a good performance despite having many challenges in underwater conditions, which suggests that there is a huge potential for underwater photovoltaics for solar energy harvesting and defense applications.

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