Performance of solar panels at various depths in stationary water

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ABSTRACT

Photovoltaic Solar systems have become attractive for powering autonomous systems and various devices. So far, the installation and usage of solar photovoltaic systems has been limited to either land or space. Lately, underwater solar photovoltaic power generation has attracted interest due to some of its unique application in powering underwater devices. The thermal control and cooling that result makes it more dependable for underwater devices. Around the equator, and some other parts of the world, some regions can be quite hot compromising a panel performance. A systematic study on the performance of stationary under water panel using normal tap water would provide information on the applicability of underwater panels in such places. In this work, a detailed study was carried out to determine the performance of 20W monocrystalline photovoltaic solar panels locally acquired and placed at various water depths. A locally purchased plastic translucent water tank was filled with normal tap water and the panels placed in the water at various depths. Solar irradiance, ambient and panel temperature were obtained using a solar 02 device and an irradiance power meter which were connected to a solar current-voltage (I-V) analyzer. Data was collected at 30-minute intervals between 11:00 a.m. and 3:00 p.m. East African Time (EAT) for panels at different depths up to 0.6m. The results revealed that as the water depth increased form 0 m to 0.6m, the panel temperature reduced by 15.48% (at a rate of 0.062 °C/cm), ambient temperature decreased by 5.13%, solar irradiance decreased by 63.79% while power output decreased by 75.00 %. It was noted that the submerged photovoltaic panels reduced the cleaning problem and power loss caused by high temperature. However, positioning the panels deep reduces the power production due to decreased irradiance which has a strong effect on the photocurrent and hence the power production of the panel. It is therefore advisable to keep the panels just below the water surface to maximize power production. The set up can be applied in very hot places for better power production.

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INTRODUCTION

Due to land disputes between photovoltaic installations and development from other sectors such as agriculture, it has become difficult for PV power generation projects to find suitable terrestrial sites (Kumar and JayannaKanchikere, 2018; Ajitha *et al.*, 2019). As one way of resolving this problem, scholars have explored water-based photovoltaic (WPVS) such as floating solar PV panels that can be mounted on top of unexploited water surface or bodies and submerged solar panels which can be lowered in water but still generate power (Kumar *et al.*, 2020).

In WPVS, the panels act as water cover to mitigate water loss through evaporation process (Hayibo *et al.*, 2020). Water also favors the performance of the PV panel by reducing the cell temperature (Tina *et al.*, 2012; Clot *et al.* 2017; Sukarso and Kim, 2020). This reduction in panel temperature is attributed to thermal energy transfer from the module to the water body (water has a high specific heat capacity) creating a cooling effect. Apart from the above mentioned two benefits, WPVS offers many other benefits like reducing the growth of algae due to shading effect which deny them an opportunity of direct sunlight (Desai *et al.*, 2017). The exploitation of underwater solar power generation provides a remarkable advantage since many underwater gadgets and devices exist that require long-term endurance power sources (Segovia Ramírez *et al.*, 2021).

The study done on floating system design for Debre Mariam Island indicated that the power output was about 4.9 kW more than the conversional based solar power output. This was due to cooling effect created by the water bodies. The study found that high temperature and wind speed were the main factors that affected the output power of the conversional solar PV installation. The studies highlighted floating solar PV system how it enhanced energy efficiencies over the conversional solar PV installation (Taye *et al.*, 2020).

The study carried out in Metema and on Lake Tana, indicated that wind speed and temperature were the key factors affecting the performance of solar PV. To show the efficiency of solar PV panel on the land surface, the system was modeled and simulated using MATLAB/SIMULINK and it was observed that there was a drop in the efficiency but when solar PV was on water surface, the efficiency was observed to improve by 2.88% (Workineh and Taye, 2022).

Recent studies have revealed that submerged solar panels generate power (Ajitha *et al.*, 2019; Hahn *et al.*, 2019). For example, a study by Ajitha *et al.* (2019) shows that two key parameters that are responsible for reducing the efficiency of PV are; the water absorption of solar irradiance and lack of a tangible thermal balance. It was also discovered that it is possible to use small lakes, artificial basins or lagoons to install PV power plants of medium or large size and to choose the water depth of the solar PV panel to optimize energy production (Rosa-Clot *et al.*, 2010). Rosa-Clot *et al.* (2010) revealed that PV panels were able to operate efficiently while immersed in shallow or deep water. The simulated power between the depth of 0 and 50 cm was found to decrease at 10% for the thin films technology and at 20% for crystalline technology at the maximum depth of 50 cm. According to Rosa-Clot *et al.* (2010), an efficiency 10-20% was achieved in shallow water where the success of this experiment was site and time dependent. The results obtained in this study was through simulation of water depth up to 50cm but the work failed to compare between the simulated outcome and experimental one.

Tina *et al.* (2012) also did a study on the behavior of PV panel submerged in water and modeled the spectral response, reflection, refraction of the irradiance between the water-air interfaces and water absorption. The results for mathematical model developed were in conformity with the experimental results obtained though it was only limited to a PV sensor. On the other hand, this study only focused on the effect of cooling without looking at the possibilities of using underwater solar PV panels to generate power.

Mehrotra *et al.* (2014) and Gouvêa *et al.* (2017) assessed the electrical efficiency of solar Photovoltaic using the cooling technique of water immersion. The best performance of 17.8% of electrical efficiency was achieved when the water depth was 1cm under the proposed design and operating conditions. The study was done only on fixed temperature range of 31℃ and 39℃ with a water depth of 6cm only. Research done by JD Stachiw (1979) found out that solar panels performed effectively when submerged in water however, their output power reduced significantly on increasing submersion depth. A study by Jenkins *et al.* (2014), yielded experimental results showing the most useful underwater depth for harvesting solar power was 9.1m using high bandgap InGap. Elsewhere, Simfukwe *et al.* (2017), observed that high band gap cells like InGaP, performed better than traditional silicon panel in underwater (UW) environment. The researches above were primarily for military interest, with the goal of obtaining a significant amount of energy in deep water.

Another study by Li1 *et al.* (2017), examined the technical specifications of the poly-silicon photovoltaic panel in air; using Taiwan solar panel analyzer to examine the output properties of the solar panel at depths of 0 -15 cm under simulated light source. The findings of the experiment were evaluated and reviewed in depth with conclusions; the water depth influenced PV panels ' output power directly. The output power of the solar panel was found to decrease by half for a water depth of 5 cm when the incident light was direct, reducing by 2.57

W/cm. The solar PV panel's output power was affected by the short circuit current; with a rise of the solar PV panel’s water depth of 1 cm per time, yielding a decrease in the short circuit current and the output. Despite their findings, the researchers only used a simulative light source to test the performance of a polycrystalline silicon PV panel, ignoring the effect of real-time data, which normally presents a number of challenges to the researchers.

Ajitha *et al.* (2019) performed an experimental analysis of the photovoltaic panel in deep and shallow waters, offering a preliminary understanding of the performance behavior of underwater photovoltaic panels. They arrived at conclusions that the efficiency of the solar PV panel varied with respect to immersion depth. As the submersion depth of the solar PV panel increased, the output power decreased and that the solar power conversion efficiency decreased with decrease in output power. Despite all this, the study by Ajitha *et al.* (2019) only used two prototypes, one at 2cm depth and the other at 12 cm.

Although some bit of work on floating panels has been done, we have not come across a systematic study done within the equator (where the sun is almost overhead almost throughout the year) a study that would be beneficial to people living in hot regions where panel performance would be highly affected by extreme temperatures especially during the dry season. This study therefore focuses on the performance of a panel submerged in water at various depths and the following parameters, i.e., ambient and panel temperature, irradiance, efficiency, power, conversion efficiency and current were investigated.

MATERIALS AND METHODS

A design was made to establish an underwater environment for solar panel with an adjustable sledge chain. A commercially available plastic container made of polymethylmethacrylate (PMMA), commonly known as plexiglass or acrylic, was customized for the experiment. PMMA was chosen due to its good rigidity and near-glass-like optical features. A control sledge chain was built to adjust the depth of the solar panels. 20 W mono-crystalline solar panels (monocrystalline solar panels tend to be more sensitive to high temperature than polycrystalline or amorphous) were fixed on the sledge chain at a height difference of 0.1 m from one another. The solar panels were adjustable up to 0.6 m deep and were kept flat. Inclination of panels is meant to facilitate self-cleaning of the panel which is not an issue in this set up since the panel is already in a cleaning medium. Each panel was connected with two wires, two fixed PT300N probes and a standard HT304N solar cell sensor. Encapsulation of solar cell’s junction box and HT 304N standard cell was done using renin adhesive to make it water proof. The wires were routed out of the container and connected to a solar I-V analyzer. Figure 1 below shows the customized plastic container filled with normal tap water with rooted wires connected to the HT solar 02 and to the solar I-V analyzer while figure 2 shows an aerial view. The experiment was carried out at Department of Physics, University of Nairobi, in Chiromo campus latitude (1° South).

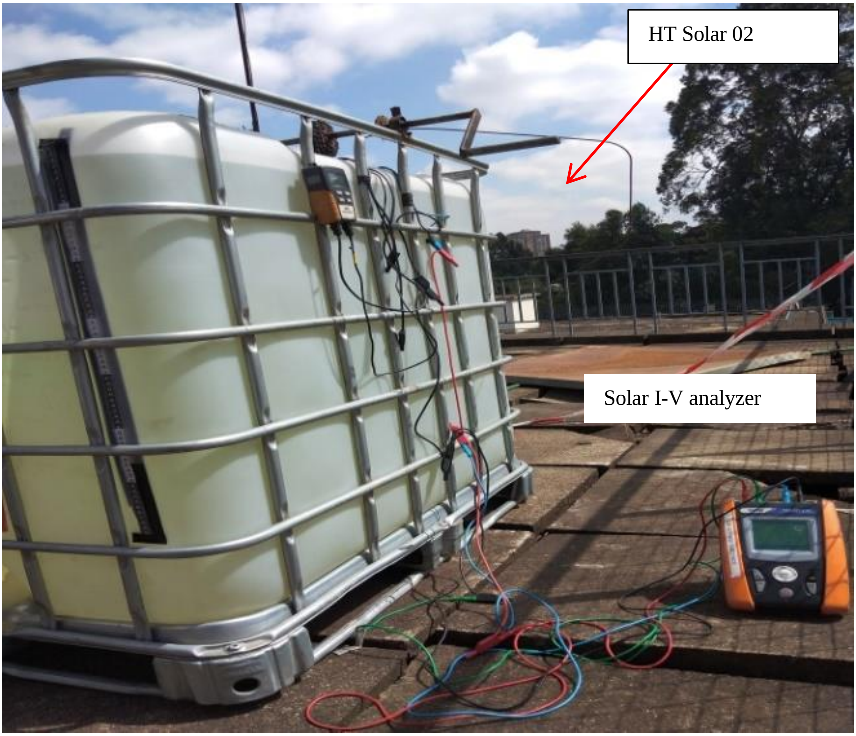

Figure 1. Experimental set up for the measurements: HT solar-02 and a Solar I-V analyzer

Different real time solar parameters were measured at an interval of 30 minutes starting from 11.00 am to 3.00 pm East African Time for 21 days. The data was extracted from the solar I-V analyzer and transferred to a computer. The data was pre-processed and some plots done to identify any outliers and remove them for further analysis. The data was then used to determine the maximum power generated, fill factor and efficiency of the solar panels immersed at different water-depth. The technical specifications of the module and physical dimensions of PV panel used in this study used are shown on the table 1 below.

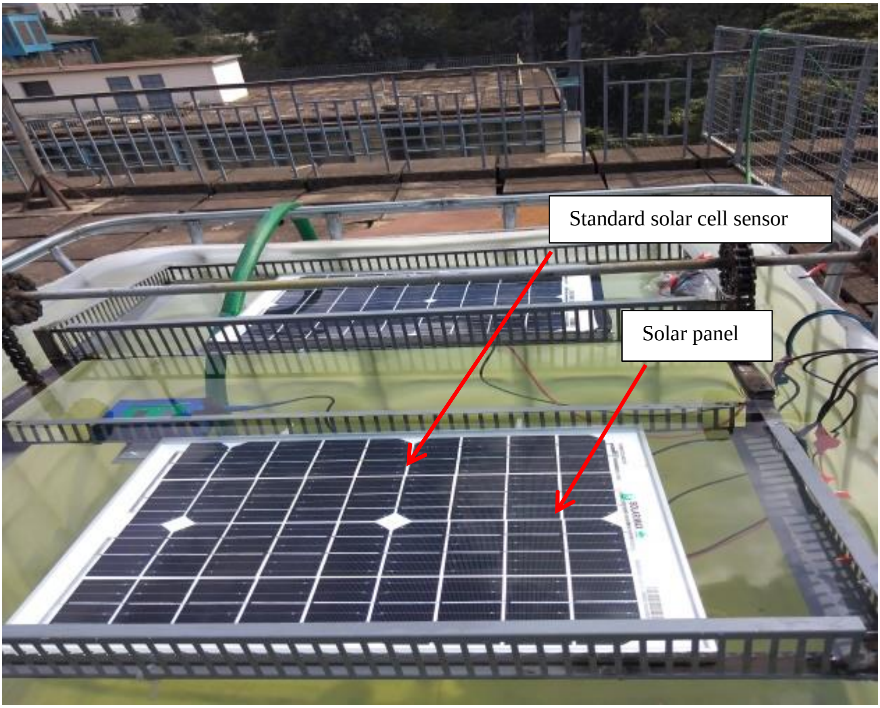

Figure 2. Aerial View of the photovoltaic panels supported by the sledge and support structure and floating on the water.

Table 1. Technical specifications of the mono-crystalline solar panel used.

Peak power (P_{max})	20 W
Size (length x breadth thickness)	450 mm by 360 mm by 20 mm
Short circuit current (I_{SC}) (Amps)	1.22 Amps
Voltage maximum power (V_m)	18 v
Open circuit voltage (V_{oc})	21.24 volts
Maximum power current (mp) (Amps)	1.12 Amps
Weight	1.93 kg
Test condition	1000 W/m^2, AM=1.5, T_c=25 ^oC
Power Tolerance	$\pm$3%

The I-V curve for the panels is generated from the diode equation

$$I = I_{PH} - I_O\left(e^{\left(\frac{V+R_S I}{nV_t}\right)} - 1\right) - \left(\frac{V+R_S I}{R_{Sh}}\right) \quad (1)$$

Where n is the ideality factor, V_t is the thermal voltage, I_{PH} is the photo-generated current, R_s is the series resistance, R_{SH} is the shunt resistance and I_O is reverse saturated current (Zieba Falama *et al.*, 2016).

The power conversion efficiency of the panel is given by:

$$\eta = \frac{P_m}{P_{in}} \times 100\% = \frac{V_{mp} l_{mp}}{AG_T} X 100\% \quad (2)$$

Where; η is efficiency, V_m is Maximum Voltage, l_m is Maximum Current, A is Area of the cell (m^2) and G_T is intensity of the radiation (w/m^2). The irradiance value $P_{in} = A_{pv} G_T$ of 1000W/m^2 for AM 1.5 spectrum (Waita *et al.*, 2006; Zoungrana *et al.*, 2017).

RESULTS AND DISCUSSION

Figure 3 below depicts the average variation of irradiance with water depth for weeks 3, 2, and 1, based on the days of the week with high irradiance. For the three weeks, all the graphs show an exponential decay curve with an average irradiance of around 870 W/m^2 on the surface declining to 351 W/m^2 at 0.6 m depth, a reduction of about 59.7 percent for week 3. The same trend is noted for week 2 and week 1, with a decrease rate of 57.8% and 59.8%, respectively. Solar irradiance was lowest in week 1 due to more cloud cover compared to the other weeks. The decrease in solar irradiance with depth was attributed to the water-air interface interfering with direct beams, resulting in uneven focusing and de-focusing of sunlight on the solar panel, as well as molecule absorption, scattering, and reflection from the water-air interface. We attribute the steeper drop of the irradiance for depths of less than 0.1 m to reflection and scattering of the incident radiation an effect which becomes less dominant beyond 0.1m and instead absorption and scattering becomes more dominant. However, we did not independently confirm the percentages of the contribution of each loss mechanism. These findings were consistent with the findings of Philip P. Jenkins' research (Jenkins *et al.*, 2014).

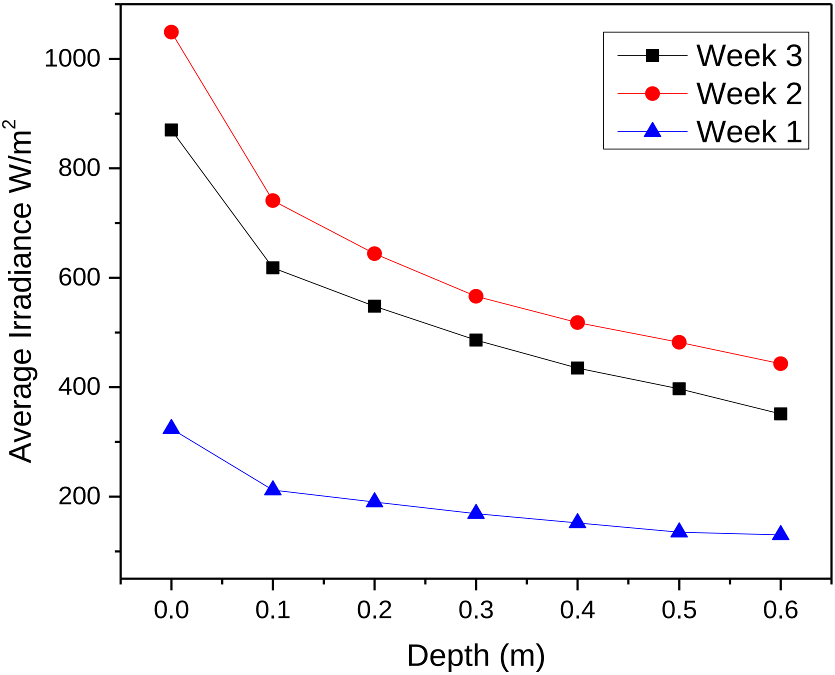

Figure 3. A graph of Irradiance against solar module depth in the water for week 3, week 2 and week 1

The solar panel temperature was a critical parameter to consider when assessing the performance of submerged solar panels. Figure 4 below shows the variation of module temperature with respect to water depth. The temperature of the solar panel decreases from an average of 23.9 ^{o}C at a depth of 0.0 m (floating panel) to 20.2 ^{o}C at a depth of 0.6 m at the rate of 0.062 ℃/cm. The curve has more or less the same shape as those for irradiance with depth. This trend suggests that there could be a correlation between irradiance and the panel. This can be explained by noting that with decrease in irradiance; the heating component of the radiation was similarly reduced leading to a similar trend in module temperature variation with depth. In Figure 4, second y axis on the right is an illustration of how ambient temperature (water temperature) changed with water depth. The shape of the graph is analogous to that of the panel temperature. The gradient, however, is less indicating that the ambient temperature decreased at a slower rate to that of the panel temperature. According to the graph, the water temperature fell from 23.4 ^{o}C for a floating panel to 22.2 ^{o}C when immersed at 0.6 m, a difference of 0.02 °C/cm. The observation is consistent with Mehrotra's *et al*. (2014) work.

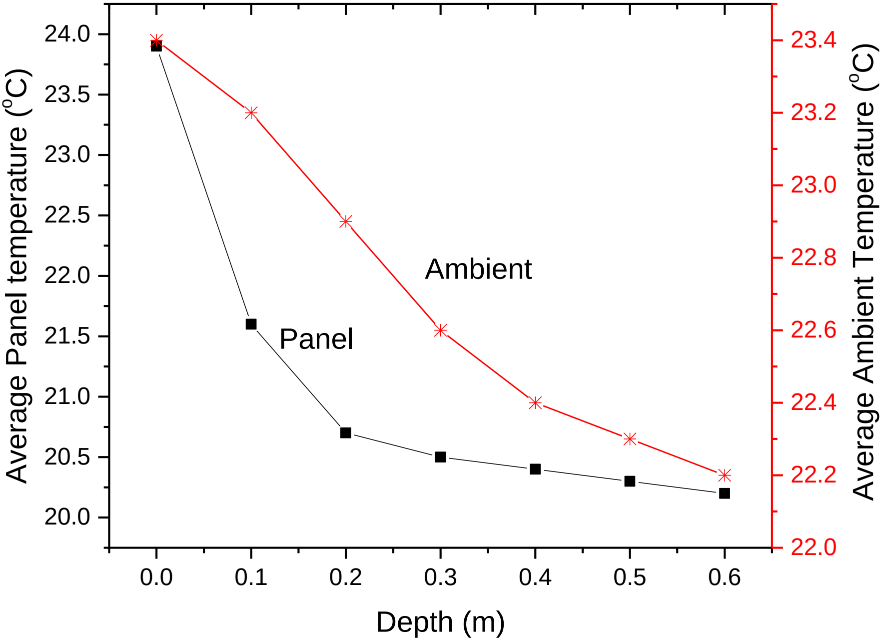

Figure 4. A graph of average Panel and Ambient temperatures against solar panel depth in the water.

Figure 5 (a) and (b) displays the Power-Voltage (P-V) and Photo Current-Voltage (I-V) characteristics of underwater mono-crystalline solar panel. A general decrease in photo current was observed and was largely attributed to the reduction in solar irradiance with depth in conformity with figure 3 above. The electrical metrics such as open-circuit voltage (V_{oc}), short-circuit current (I_{SC}) and maximum output power P_{max} were also observed to decrease with water depth. On average, the I_{sc} was found to vary from 0.82 A to 0.27 A (67.1% decrease), while V_{oc} was observed to have no change (22.5 V and 22.49 V) but P_{max} reduced from 12.73 W to 4.46 W (65.0%) as shown in figure 5 (b) below. The findings confirm the strong dependence of photocurrent on irradiance and hence power generation of the panel. Since the voltage is considered to be more temperature dependent, we don't see any change since the temperature variation was small. The observation was in agreement with the research done by L Li (Li *et al*., 2017).

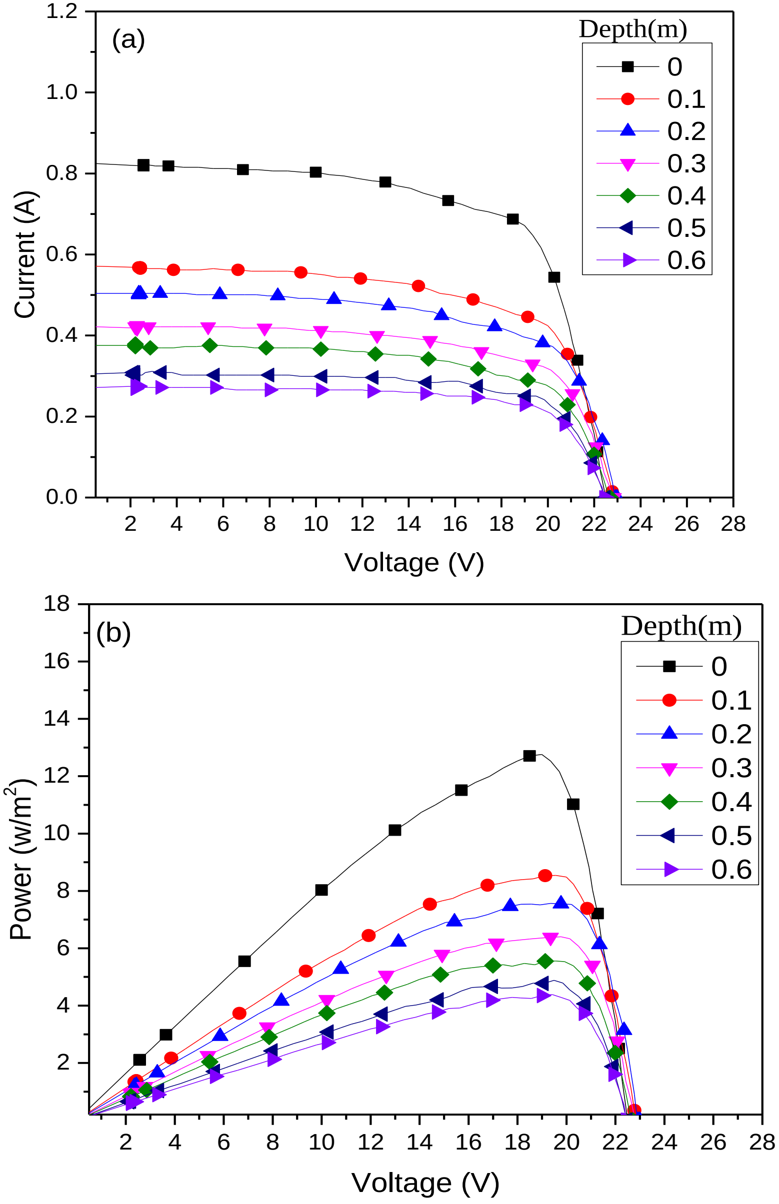

Figure 5. The variation of current of current and voltage (a) power and voltage (b) for the solar panel at various water depths

The power generated by the solar panels decreased with water depth as shown in figure 6 below. The decrease was attributed to the reduction of short-circuit current and solar irradiance to the PV panels as the water depth increased, an observation that is consistent with previous discussion and observation. In week 3, power generated reduced from 12.73 W to 4.46 W (rate of 0.14 W/cm, a 65.0% decrease) while in the 2nd week, the power generated varied from 18.81 W to 7.14 W which was 0.19 W/cm giving a 62.1% decrease. Finally, for week 1, it declined from 6.70 W to 2.16 W at the rate of 0.076 W/cm indicating a reduction of 67.8%. Similar findings were observed by Hahn *et al.* (2019). The purpose of this exploratory research study was to create a first-order analytical relationship between the performance of solar PV panel and their operating water depth. It was noted that, despite the decrease in power, the solar PV panel was able to generate power that can power low rated devices like active sonar sensors and magnetic anomaly detectors.

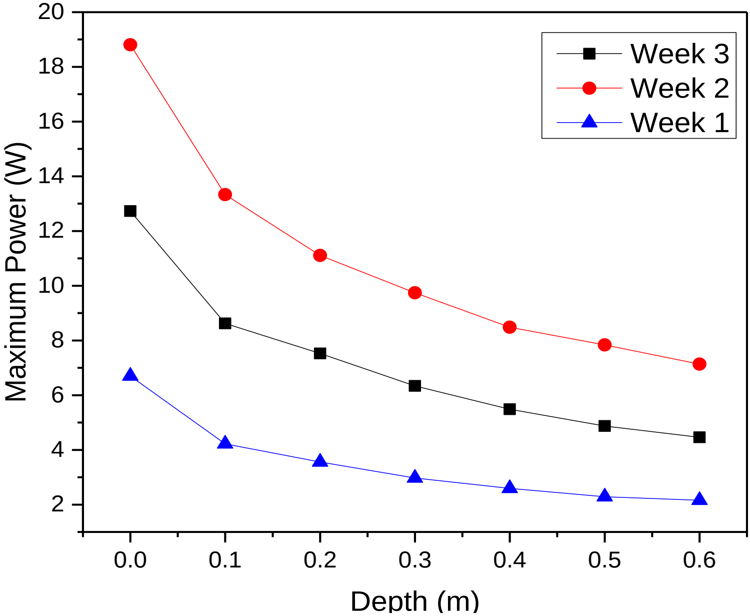

Figure 6. Graph of maximum power (Pmax) versus panel depth for the three weeks.

Figure 7 shows the trend of the effect of water depth on the power conversion efficiency (PCE) of submerged solar panels for week 3 (main graph) to week 1 (inset on the right). PCE is a measure of photon to electrical conversion efficiency of the panels or the ration of power input to output. The study computed the PCE for underwater solar panels where it was observed that for instance in week 3, at 0.0 m the PCE recorded was 16.7 % while at 0.6 m deep it was 15.0% (a reduction of 0.03%/cm) demonstrated by the fit equation

$$y = -3.15x+16.76$$

In week 2, the PCE was ranging from 18.3% to 15.2% making the reduction to be 0.05%/cm and finally in week 1, the PCE was varying from 19.4 % when the panel was floating and 15.4% when it was immersed at 0.6 m deep which gave 0.07%/cm reduction with both having the fit equations

$$y = -5.12x+18.25$$

$$y = -6.96x+19.15$$

respectively. The general trend showed that as the solar panels' immersion depth increased, the power conversion efficiency reduced. Submerged PV solar panels at 0.0 m recorded an average of 18.1% of the PCE while at 0.6 m deep the average PCE recorded was 15.1% which was 0.05%/cm drop. The reduction was attributed to less incident solar irradiance on the solar panel when the water depth increased. Throughout the three weeks period, it can be deduced that the trend and PCE value was within the expected value 14-22% obtained by (Sugianto, 2020) and (Rosa-Clot *et al.*, 2010).

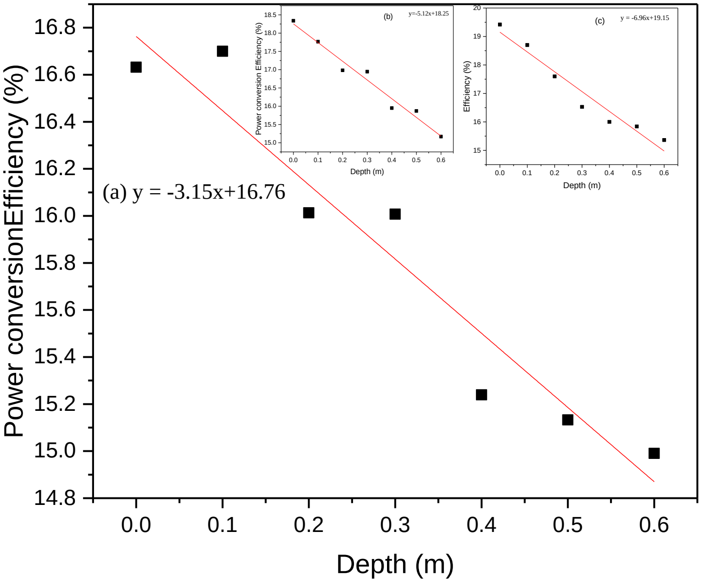

Figure 7. Graph of conversion efficiency with depth week 3 (a), week 2 (b) and week 3 (c).

The variation in power conversion efficiency with water depth was highly influenced by the panel temperature and the light intensity falling on the surfaces of the panel at a specific depth. Variation in PCE values for various water depths was as a result of a trade-off between the temperature drops and light absorbed. From figure 8, PCE for depths less than 0.6 m can be estimated using the fitting equation in the graphs above.

CONCLUSION

The experimental study of underwater PV panels has been investigated. The power output, panel temperature, incident irradiance and power conversion efficiency were obtained and their behavior was observed to decrease with respect to water depth. The panel temperature reduced at a rate of 0.062 °C/cm and on average by 15.48% as the depth increased from 0 m to 0.6 m. The power output decreased from about 12 W/m^2 on the surface to about 3 W/m^2at 0.6 m, a decrease of about 75% at a rate of 0.15 W/cm. At Isc, the photocurrent dropped from about 0.82 A at 0 m to about 0.27A at 0.6 m while the maximum power P_{max} decreased by about 64.92% over the same depth. The power conversion efficiency also dropped from about 16.7 % to about 15%, a less than 2% decrease. This study provided a preliminary understanding on the performance behavior of underwater photovoltaic and based on the results obtained with water depth up to 0.6 m. Despite few challenges and limitations, the results obtained showed an enormous possibility to harness power for underwater solar PV technology.

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ABBREVIATIONS

CV- Cross validation
I_{SC} - short-circuit current
I-V- Current-Voltage
LOOCV- Leave-one-out
G_a- Solar irradiance
MAE -Mean absolute error
OOB- out-of-bag
P_{max-} maximum output power
PCA- Principal Component analysis
PCE- power conversion efficiency
PMMA- polymethylmethacrylate

P-V - Power-Voltage
RF- Random Forest
RMSE -Root mean square error
R^2 -Determination coefficient
SVM- Support vector machine
SVR- support vector regression
T_a- Ambient temperature
V_s -wind speed
V_{oc}- open-circuit voltage,
UW- underwater
WPVS- water-based photovoltaic

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