Experimental study to enhance photovoltaic efficiency in arid climate. An innovative method of cooling using humidified air in Aswan, Egypt.

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Abstract—While the benefits of humid air in boosting photovoltaic cell performance are well known, this research introduces a method to further enhance PV cell efficiency, specifically tailored for arid regions like Aswan, Egypt. The innovative aspect of this study is the use of pre-cooled humidified air, a technique never tried before. This study evaluates the effectiveness of this cooling method and its potential to reduce the temperature of photovoltaic cells, thereby increasing their efficiency. The experimental setup included two 250 W polycrystalline photovoltaic panels: one cooled with pre-cooled humidified air and the other serving as a reference. The cooling system utilized an evaporative cooler is used to cool and humidify the air before directing it through an insulated duct behind the photovoltaic cell. The cooling was applied intermittently to conserve energy. The cooling method led to a maximum reduction in temperature by 26 °C, with an average decrease of 7 °C. This resulted in a power output increase of up to 7.5%, with efficiency improving from 12.8% to 13.77%. Additionally, there was an average daily increase in energy production of 2.2%. These findings encourage a practical approach to enhancing photovoltaic efficiency in hot and dry climates

Keywords— PV cooling, evaporative cooling, solar energy, Efficiency.

introduction

Fossil fuel energy production has had a disastrous impact on the environment recently, causing serious problems like acid rain, air pollution, global warming, and climatic fluctuations. As a result, there has been a strong movement in favor of renewable alternatives like solar energy. Photovoltaic (PV) panels are one of the main uses for directly producing electricity from solar power. However, several variables can greatly impact their performance including high temperatures, dust, wind speed, frontal layer permeability, panel coatings, and solar radiation. In fact, during peak hours, the temperature of solar PV cells can rise to over 65 °C, which causes a decrease in their output capacity. For each degree of temperature increase, crystalline silicon photovoltaic cells' efficiency can drop by up to 0.5% [1]. Therefore, there is a pressing need to explore various cooling methods to mitigate this issue, including water cooling, air cooling, phase change materials, and heat sinks. Among these methods, evaporative cooling stands out as an effective solution, particularly in hot, arid regions like Aswan. This makes it an enticing approach for cooling solar panels in such locales.

Scientists have conducted numerous studies and proposed various methods to enhance electricity generation from photovoltaic cells through different cooling approaches, whether by using water, air, or humidified air Suresh et al [1] studied the results of applying evaporative cooling in a confined area with a cooling pad. The PV panel was cooled by the wet air

that was forced through the wetted cooling pad by means of a fan. The pad was moistened by the capillary effect of a water tank, and the humidity was increased by an upper glass cover. Chandrasekar et al [2] employed a straightforward passive evaporative cooling system, attaching a wet cotton wick rolled into a disc to the rear of the photovoltaic panel. created a passive EC technique to regulate the PV panel's temperature rise. Alami [3] The panel's reverse was covered in an artificial clay layer for the study, which let a thin layer of water evaporate. 19.1% was the highest power increase. Bahaidarah et al [4] investigated the operation of a photovoltaic module with active water cooling at its rear surface during hot weather In Dhahran, Saudi Arabia. According to the test results, cooling caused the PV module's temperature to drop by about 20 °C and increased power generation by 9%. Niˇzeti´c et al [5] employed water spraying on a photovoltaic module to lower its temperature and explore its capacity for self-cleaning in a Mediterranean environment. According to the test results, the water spraying caused the module's temperature to drop from 54 °C to 24 °C and increased the overall generated power by 16.3%. Soliman et al [6] attached a heat sink to the rear surface of a photovoltaic module to conduct an experimental investigation into forced-air and natural cooling. By using these techniques, the temperature of the PV modules dropped by about 5.4% and 11%, respectively, and the electrical yield increased by about 16%. Amr et al [7] created a photovoltaic module with fins fastened to the back that act as a heat sink to lower the module's temperature. As the number and height of the fins increased, this temperature dropped by about 4-5 °C, improving electrical power efficiency. Murtadha and Hussein et al [8] utilized copper tubes and plates fixed to the back surface of photovoltaic panels for cooling by Al_2O_3 nanoparticles with water as the working fluid. When compared to the standard unit, the nanofluid at a 3-weight per cent concentration could increase the output power by 13%. Li et al [9] The study focused on the energy-saving potential of selective spectral, passive radiative, and combined cooling methods for passive PV module cooling. The experiments were carried out in China with an air mass of 1.5, ambient temperature of 36 °C, and average wind speed of 2 m/s. The findings indicated that the three cooling methods increased the electrical efficiency by 0.98%, 2.4%, and 4.55%, in that order. Bayrak et al [10] conducted experiments on PV cooling using three different approaches: aluminum fins with different layouts, PCM ($CaCl_2.6H_2O$), and thermoelectric materials. Under the same experimental conditions, the PV cooling with fins produced the highest power production (47.88 W), while the cooling with PCM and thermoelectric materials (TEM) produced the lowest electricity output (44.26 W). Sun et al [11] examined a PV cooling technique in the climate of Chiang Mai using PCM RT42, which is 50 mm thick and attached to the back surface of a PV panel. The highest temperature of the PV modules dropped from 76 °C to 64 °C while power generation increased by 4.3%. Ziˇzak et al [12]conducted an experiment where water was supplied to the backside of the PV panels. This resulted in a successful drop in the panel's operating temperature of over 20 °C and a 9.6% increase in power output compared to the non-cooled panel. Haidar et al [13] installed a photovoltaic panel on the open duct's top. On the lower side of the duct, a piece of cloth was wet. Using a fan, the air was pushed into the duct in the same direction as the water flow. PV panels' temperature was lowered by 10 °C while their power increased by 5%. Mahmood et al [14] suggested a new design for the evaporative cooling system that incorporated the evaporative cooling system below the photovoltaic panels and the PV panels themselves. A cellulose cooling pad with three different thickness values (50, 100, and 150 mm) and three different water flow rates (1, 2, and 3 Lpm) was used to test the cooling system. The PV panel efficiency of the designed system with varying thicknesses could be improved by 7.4%, 10.5%, and 11.2% in comparison to the standard PV module without a cooling system. Alktranee et al [15] evaluated the cooling capabilities and thermal characteristics of evaporative cooling and rectangular aluminum fins. The findings indicated that although the aluminum case's temperature decreased by just 6.7%, evaporative cooling managed to achieve a 22.3% temperature drop. K. Srithar et [16] al addressed the efficiency drop in photovoltaic panels due to temperature rise by combining evaporative cooling with a solar still. The cooling system uses a jute sack soaked in water, which cools the rear side of the panel via capillary action. The solar still also produces water by condensing vapor on a glass surface. This method increased output power by 5.6%, boosted electrical efficiency by 14.51%, and reduced surface temperature by 8°C. Additionally, the system produced 550 ml of water after seven hours of sunlight. Siwakorn Jirapongphatai et al [17] presented a method of evaporative cooling for photovoltaic (PV) modules to mitigate efficiency losses caused by high temperatures. Specifically, it focuses on a floating-type module utilizing a hydrophilic pad made of polypropylene mixed with synthetic fiber, which is attached to the rear surface of a 320 W mono-crystalline module. The system employs a small pump to supply water to the pad at various flow rates and inlet temperatures. Installed in Chiang Mai, Thailand, at an 18° inclination facing south, the module's temperature was monitored, and a set of heat and mass transfer models was developed to analyze temperature effects on electrical performance. The results indicated that the maximum temperature of the PV module could be reduced from 73.2 °C to approximately 46 °C on clear days, leading to a 10% increase in total electrical power generation. Furthermore, higher water flow rates and lower inlet temperatures enhanced module performance. The study revealed that during summer months, the evaporative cooling system could achieve an increase of 6.5% to 11.1% in net electrical energy compared to configurations without evaporative cooling, particularly when the feed water temperature was maintained between 20–30 °C.

It is clear from the above discussion that humid air is important in enhancing the efficiency of the cells. In all previous studies of cooling using evaporative cooling, porous materials are used to absorb water and are placed directly behind the cell, then air passes over them and the cell is cooled. However, in this study, the novelty lies in pre-cooling the air by evaporative cooling and then it is blown into the cell's jacket for cooling. This investigation will be conducted in the arid climate of Aswan, where hot and dry conditions prevail.

Table.1 Electric properties of PV modules (Manufacturer's data).

Electrical characteristics at STC	Values
power (P_{max})	250 W
Voltage open circuit (V_{OC})	36 V
Current short circuit (I_{SC})	9.16 A
Module efficiency	14.9 %
Maximum power voltage (V_{max})	30 V
Maximum power current (I_{max})	8.33 A
All technical data are at STC (standard test condition) solar radiation= 1000W/m^2 and $T_{ambient}$= 25 °C	

Table.2 Different measuring instruments and their measuring range and accuracies.

Instruments		The function	Measuring Range	Accuracy
Infrared thermometer		Surfaces temperature measurement	-50 °C - 600 °C	±2%
Solar power meter		Solar radiation measurement	2000 W/m2	±10 W/m2
Wind speed meter		Wind speed measurement	.3 m/s – 30 m/s	±5%
Avometer	DC voltage	Panel output voltage	200 mV - 600 V	±.8%
	DC current	Panel output current	2 mA – 10 A	±1.2%

Experimental setup

The test device consists of two identical 250-watt polycrystalline photovoltaic panels with the dimensions of 1.63 m × .92 m. the electrical properties of the PV module are shown in Table 1, one of them is cooled using humidified air, and the other is the reference panel without cooling for comparison purposes. Both are equipped with the necessary measuring devices. as indicated in Table 2 The photovoltaic units have been installed on a flat surface, facing south at a tilt angle of 23.5 degrees. They were tested under hot and dry conditions with an average wind speed of 3 m/s through the day in Aswan, Egypt. One of these units was cooled, while the other was used as a reference unit without cooling for comparison purposes. In this study, the photovoltaic cell was cooled using evaporatively cooled air extracted from the

evaporative cooler. The air was directed to pass through a flexible tube and then through an air passage to enter the rear channel of the photovoltaic cell.

The passages for the cooled air were insulated to prevent cooling loss, and an outlet was provided at the end of the cell to expel the heated air after absorbing heat from the cell, thus facilitating its cooling as shown in the figure.1.

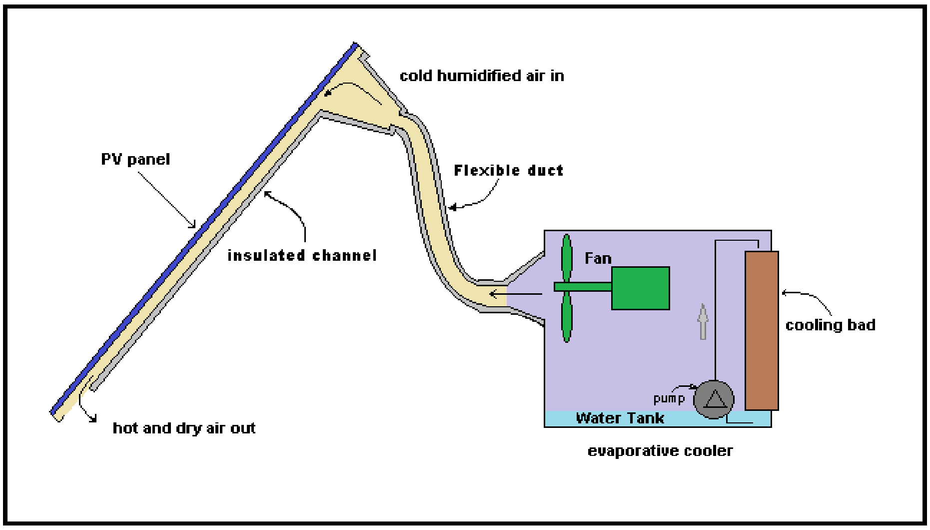

Fig. 1. schematic diagram for humidified air-cooling design

Fig. 2. humidified air-cooling design

The humidified air is produced from an EC with a capacity of 1/3 HP and dimensions of 860 mm in width, 860 mm in depth, and 900 mm in length, which operates by utilizing a small water circulation pump and fan powered by an AC motor. The water is drawn from a tank located at the bottom of the cooler and then directed through a porous pad with a high water-holding capacity inside the cooler. Whereas the fan or blower draws the air from the outside through the water-soaked pad, resulting in the water being evaporated, leading to a drop in the air temperature due to the heat absorbed during the evaporation process which converts some of the sensible heat of the air into latent heat. In hot and dry climates, the evaporative cooling technique is more effective due to the process's dependence on low humidity levels and dry air's capacity to contain more moisture Because the evaporative cooling process depends on low humidity levels and dry air's ability to hold more moisture, it works best in hot, dry climates[18], [19]. Then, using a sheet metal air diffuser, the fan drives cold, humid air through an isolated flexible duct to cool the cell.

The evaporative cooler cools and humidifies the air, with the incoming air temperature and relative humidity being approximately 40 degrees Celsius and 23%, respectively. The air exits at a lower temperature and higher relative humidity, around 25 degrees Celsius or lower, with relative humidity rising to about 66%. The cooled and humidified air is then pushed through the insulated channel positioned behind the cell for cooling. Subsequently, the air temperature rises and the relative humidity decreases again after partially absorbing heat from the cell to enhance its efficiency. To conserve energy used by the evaporative cooler, the operation is intermittent, with specific intervals to maintain an acceptable range of cell temperatures.

The uncertainty analysis

Measurement errors are resulted from various causes such as, instrument calibrations, the data set finite statistics, and the methods used. In fact, we do not know the exact value of the measured parameters. There are two main types of errors; systematic error and random error. The main difference between systematic and random errors is that, random errors lead to fluctuations of measured value of instrument around the true value. Systematic errors; lead to predictable and consistent deviation from the true value due to a problem related to equipment calibrations.

- Uncertainty analysis helps in describing the interval about the measured value within which one can suspect that the true value must fall with a stated probability. Uncertainty analysis is the process of identifying, quantifying, and combining the errors.
- The level of uncertainty associated with each dependent variable is assessed by considering all potential sources of error, as outlined in Heywood's [20]. The following equation describes the estimated uncertainty (U_R); where R is the dependent variable determined by measuring the independent variables (x_1, x_2, …, x_n) and their corresponding Accuracies (U_1, U_2, …, U_n).

$$U_R = \sqrt{\left(\frac{\partial R}{\partial x_1} U_1\right)^2 + \left(\frac{\partial R}{\partial x_2} U_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} U_n\right)^2}$$

➢ Uncertainty in measuring the output power

Pout put = $\frac{FF}{ɲ}$× (Isc × Voc)

Where (Isc) is the short-circuit current and (Voc) is the open-circuit voltage (FF) is the fill factor and (ɲ) is the efficiency of the measurement instrument.

$$U_P = \frac{FF}{ɲ}\sqrt{(Isc\ u_V)^2 + (Voc\ u_I)^2}$$

- At full power condition (P = 217 kW), the error in measuring is ± 0.316 %.
- At low power condition (P = 1 kW), the error in measuring is ± 0.29987 %.

Uncertainty in measuring the efficiency

$$panel\ efficiency = \frac{P}{G * A} * 100\ \%$$

Where G is the solar radiation, A is the panel surface area.

$$U_P = \frac{1}{A}\sqrt{\left(\frac{-p}{G^2}\ u_G\right)^2 + \left(\frac{1}{G}u_P\right)^2}$$

- The error in measuring the efficiency is ±1.2 %.

Results and discussion

The experiments were carried out in an arid and hot climate conditions of Aswan, Egypt, in June 2022, temperature variations, voltage differential, current intensity, and solar radiation were all measured during the day. To determine the power generated by photovoltaic cells, the short-circuit current (Isc) and the open-circuit voltage (Voc) must first be measured. By multiplying these two values the maximum power output of the cell is calculated. To obtain the actual power generated, this product is then multiplied by the fill factor (FF).

$$Poutput = FF \times (Isc \times Voc)$$

So, it's important to identify the factors affecting these variables.

The short-circuit Current

The amount of solar radiation was measured all day long. It was noted how sunlight affected the current. It was observed that the current increased until the afternoon, indicating that it is influenced by variations in solar radiation intensity, as indicated in figure 3. After that, it began to decrease until the end of the day.

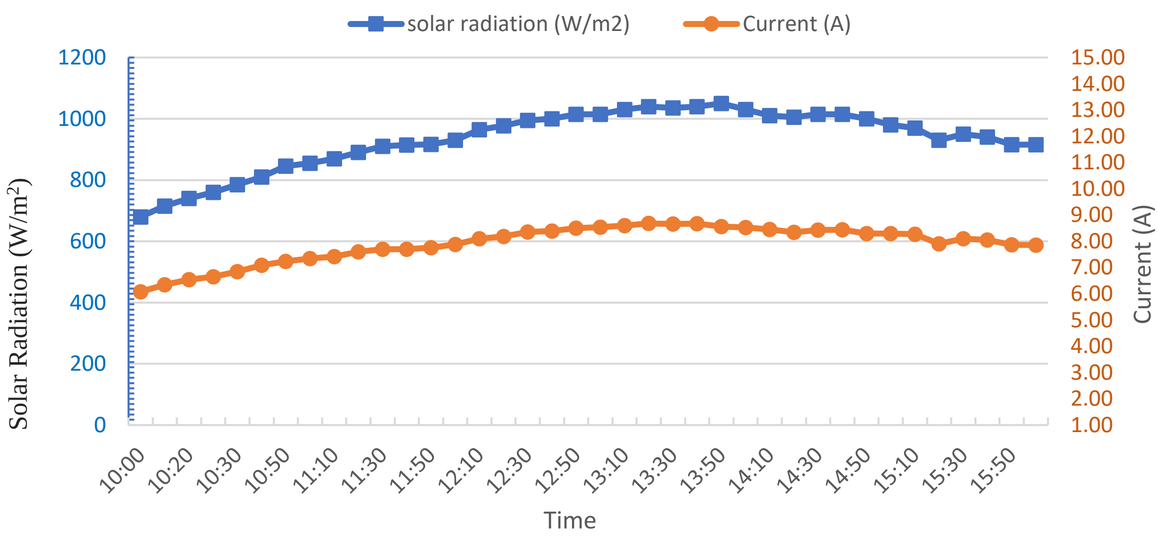

Fig. 3. solar raditon effect on short circuit current.

The open-circuit voltage

It is noted from the presented figure (where T_1 is the reference cell temperature, T_2 is the cooled cell temperature, V_1 is the generated voltage at the reference cell and V_2 is the generated voltage at the cooled cell) that with the cooling process, the temperature of cell T_2 decreases, which leads to an increase in the voltage generated in cell V_2 compared to the cell without cooling, due to its high-temperature T_1, which leads to a decrease in the generated voltage difference. Since the cooling process is intermittent, when the cooler is turned off, the temperature rises again, causing the generated voltage V_2 to decrease. However, it is also observed that during cooler shutdowns, temperatures rise to higher-than-normal levels, exceeding those in the reference cell. This is due to the presence of the

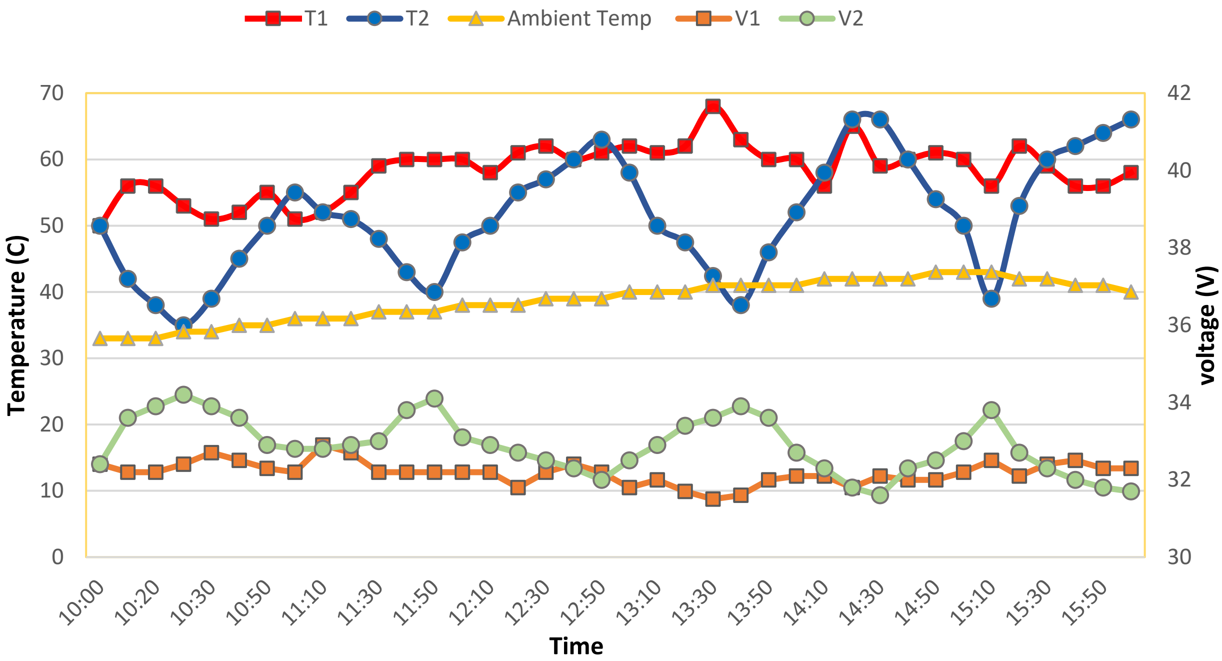

Fig.4. temperture and voltage change in both panels with cooling and without

insulated channel behind the cooled cell, which may prevent heat transfer and convective heat loss from the back surface of the cell, regarding voltage difference, it depends on the cell's temperature. Higher temperatures negatively impact the voltage generated across the cell terminals, whereas lower temperatures lead to an increase in voltage. Consequently, the power generated by the cell increases during temperature drops compared to the reference cell, which operates without cooling, under the same solar radiation and climatic conditions as in figure 4.

In contrast to that in the reference cell due to the absence of obstruction or the insulation behind the cell.

The output power

Since the power generated by the cell is the product of the voltage and the current generated by the cell, we will compare the power generated in the cooled cell with the power generated in the reference cell in the following curve, Figure 5.

From the previous figure, (where P_1 is the reference cell output power, P_2 is the cooled cell output power). it is evident that cooling the cell increases the generated power. However, during periods of cooler shutdown, a decrease begins due to the rise in temperature again. When the generated power decreases, it may even drop below that of the reference cell. This is attributed to the presence of the insulated channel behind the cell, which prevents heat transfer from the rear side of the cell. Consequently, the cell's temperature increases more than the reference cell, leading to a decrease in the voltage generated, thus reducing its generated power at that moment. However, the power increases again with cooling when the temperature decreases, increasing the generated power.

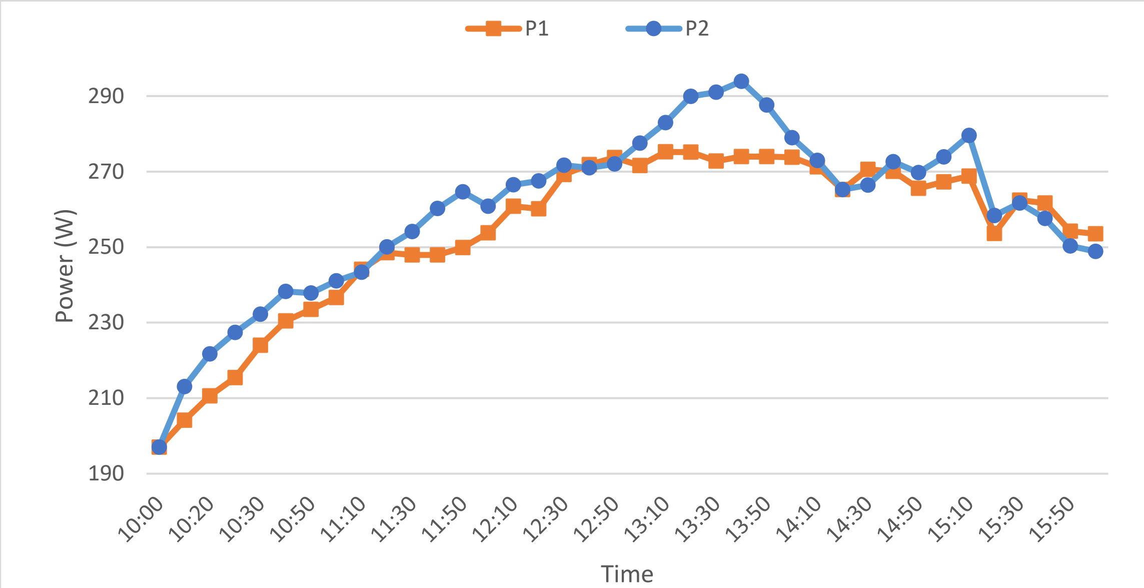

Fig.5. comarison of the output power from the cooled and refernce cell

From the previous results, it was found that the maximum cooling temperature difference reached 25.6 °C, with an average decrease of 7 °C. resulting in a 7.5% increase in the cell's generated power compared to the reference cell with efficiency improving from 12.8% to 13.77%. However, at times, the generated power was lower than that of the reference cell due to elevated temperatures. Ultimately, the average increase in generated power throughout the day was 2.2%.

Conclusion

- The results show that when this cooling method was employed that:
- The maximum increase in cell-generated power was around 7.5% compared to the output power of the reference cell, with an average increase of 2.2% throughout the day.
- The maximum cooling was achieved with a temperature difference of 26 degrees, with an average of 7 degrees throughout the day.

The improvement in efficiency was from 12.8% to 13.77%.

It is evident from these results that cooling using humidified air is a highly effective method in hot and dry areas such as Aswan, Egypt. However, there is an issue when using the insulated channel behind the cell, which may lead to higher temperatures than the reference cell, particularly during cooler shutdown periods.

Future studies should build on this research by investigating a cooling method that utilizes humidified air without disrupting the natural heat loss processes. This could involve cooling the front surface of the cell while avoiding barriers that hinder heat dissipation. Exploring the feasibility of continuous cooling could help maintain stable temperatures, preventing the efficiency drops associated with intermittent cooling.

Performing a cost-benefit analysis to evaluate the economic viability of implementing cooling systems on a larger scale.

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