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Research Paper

Electricity Generation Performance Test of Bare and Cooled Photovoltaic Panels

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Abstract

Electric generation using solar photovoltaic (PV) panels is promising for most locations because solar energy is abundant, clean and inexhaustible. However, the solar electricity generation ability of solar PV drops significantly below the nominal efficiency values as a result of higher operating temperatures, particularly in hot locations. The drop in efficiency of solar panels can be enhanced by convectively cooling solar panel surface. This paper reports the comparative electric generation performances of two identical PV panels of electric power ratings of 60 W with efficiency of 12% and photon absorption area of 0.945 m × 0.55 m. The tests were conducted by exposing both panels to the sun in parallel, one panel bare (non-cooled) and the other being cooled for three cases of cooling arrangements: continuous water cooling, intermittent water cooling, or continuous air cooling. The electric generation performance was determined in terms of electric power output and efficiency after measuring surface temperatures, voltages, and currents of both solar panels from 9 am to 3 pm. For the bare PV panel, the average surface temperature, current, voltage, power, and efficiency over the test period were found to be 46.0ºC, 2.5 A, 18.2 V, 30.6 W, and 7.96% for bare panel and 34.8ºC, 2.76 A, 19.2 V, 35.81 W and 9.69% for panel cooled by water continuously. 17.02 & 21.73% day average increment of power and efficiency was attained due to cooling. These transient engineering performance data are needed for the sizing and economic viability study of PV plants in Adama City.

1. Introduction

Electricity is clean and high-grade energy that is commonly generated by hydroelectric power, fossil-thermal, nuclear, wind power, geothermal, solar -thermal and solar PV plants. Among these plants, Ethiopia generates electricity primarily using hydro and wind power plants and to a certain extent using diesel (fossil-thermal) and geothermal plants. The economic activity, population, and demand for electric energy in the country is rapidly increasing. To satisfactory supply energy to industries and the people, the country has to diversify its energy generation capabilities by utilizing different technologies particularly solar thermal power and solar electricity, in addition to the expansion of the existing electric generating plants. In this regard, there are indicative studies that suggest the use of standalone PV systems, energy mixes such as biomass, and the challenges & opportunities of renewable energy use in Ethiopia (Benti et al., 2023a, 2023b, 2022 & 2021; Girum et al., 2021, Yedilfan, 2021). Among these indicative suggestions, solar electricity is very promising for the country since it is green energy technology and can be effectively designed for utility-scale or micro-scale, or individual house-scale plants for both urban and rural areas. Electricity generation from this type of installation is growing over the globe. For instance,

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the government of India has the intention of generating about 100 GW of electricity from solar PV power plants (Berwal et al., 2017). The abundance of sunlight throughout the years in Ethiopia is still untapped & underutilized despite the country has a lot of potential areas (e.g. Adama, Afar, etc.) that can generate electricity from the sun using solar PV plants.

Solar PV plants are commonly installed as standalone, arrays, or solar farm sizes that could be connected to the grid or used for off-grid applications. The solar-to-electricity conversion efficiency of solar panels is normally low since the current (I) and Voltage (V) or I-V characteristics of the cells depend on several operating parameters such as solar flux intensity, ranges of spectral absorption, dust accumulation on the absorber surface, and the operating temperature (Singh, 2013; Dwivedi 2020). But among the environmental parameters, the key parameters that affect the performance of a solar PV system are the solar radiation flux and surface temperature of the cell (Dwivedi, 2020). Electricity production of bare PV systems is directly proportional to solar flux and inversely proportional to panel surface temperature. Solar panel efficiency in the field depends on the quantity or type of semiconductor used for the construction of the cell which is monocrystalline, polycrystalline, and amorphous silicon (Biwole et al., 2011; Attari, 2011). Test of the I-V characteristics of solar PV cells on the field under different climatic conditions is recommended for selecting plant location, sizing the appropriate panels, and prediction of future performance of solar PV power plants (Bansal et al., 2021; Attari, 2011). Photovoltaic (PV) panels utilize photoelectric conversion semiconductors, called solar cells, which directly convert absorbed sunlight into electric power (Arifin et al., 2020). During this energy conversion process, these cells only convert part of incoming solar radiation into useful power output while the remaining is lost as waste heat. The waste heat raises the cell temperature. The rise in surface temperature of a photovoltaic panel causes a significant reduction in electric power generation and efficiency due to reduced open-circuit voltage and short-circuit current outputs of the solar panels (Baloch et al., 2015). The panel voltage output linearly decreases with an increase in cell temperature by approximately 2.2 mV per every 1 °C rise in temperature and the electrical efficiency decreases approximately by 0.5 %/℃ (Yesilyurt et al., 2018). Cooling of the surface temperature of solar photovoltaic panels enhances their electric generation capacity and efficiency. Bare (non-cooled) PV plants operating outdoors generate less electricity and degrade (Bansal et al., 2021) whereas surface-cooled cells generate better electricity. I-V characteristics of cells is commonly tested when the PV plant operates bare (non- cooled) and when cooled.

Bansal et al., (2021) presented a techno-economic, degradation, and performance test of a 5 MW grid-connected utility-scale solar PV power plant composed of 21,740 polycrystalline modules over seven consecutive years. Power generation loss and micro-cracks on the panel surface were observed due to hot spots and uneven heating of the solar cells. Charfi et al., (2018) conducted a field performance test of a titled PV system installed in white and gray soils for three consecutive days under a climate of Tunisian Saharan and measured the I-V characteristics. Kandil et al., (2011), conducted outdoor experimentation on a photovoltaic module made of copper-indium-diselenide to assess the efficiency through measurement of I-V characteristics under different climates in Kuwait, whereas Ilham et al., (2018) studied the field performance of monocrystalline, polycrystalline and amorphous PV panels under the climatic condition of Morocco and found out that monocrystalline panel has better energy yield compared to the others. Dhass et al., (2015) tested monocrystalline, polycrystalline, and black solar cells. Khalid et al., (2018) indicated that dust, humidity, and temperature affect the performance of solar panels negatively after conducting a comprehensive literature review on the environmental and operational factors that affect the energy conversion capacity of PV systems.

Several techniques are used by researchers to cool photovoltaic panels back or frontal surface temperature. The state-of-the-art review on parameters that affect the operation of photovoltaic panels and cooling techniques classification was reported by Dwivedi et al., (2020). The cooling system can be an active cooling system that utilized the flowing of air or spraying of water or using water sprinklers & wipers over the panel surface or the use of heat pipes and refrigerant cooling systems (Amelia et al., 2016; Prajapati et al., 2017; Ibrahim, 2018; Moharram et al., 2013; Bhakre et al., 2021). Passive cooling systems like the use of phase-changing materials to conduct heat away from the panel surface, bare aluminum fin or fin embedded in phase-changing materials, or immersion of the solar photovoltaic panel in water were used to cool solar photovoltaic panels (Chandrashekar et al., 2020; El Mays et al., 2017; Firoozzadeh et al., 2019; Khanna et al., 2018); Mehrotra et al., 2014).

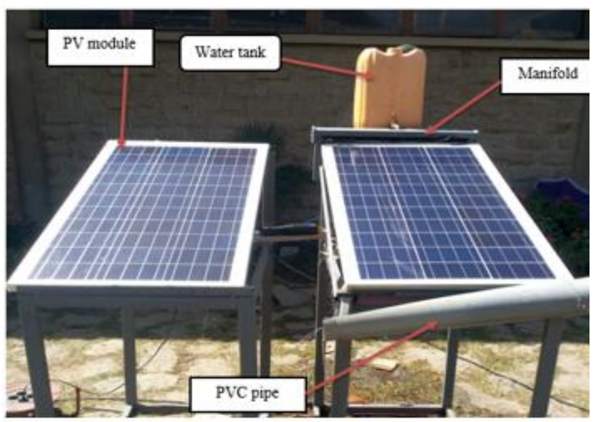
Accumulation of dust on the photovoltaic panel reduces the photon absorption for instance by 16% and the use of water as a cooling technique also has the advantage of cleaning the top surface of the photovoltaic panel from dust (Aldihani et al., 2014). The common research methods used to identify the enhancement of the electric generation capacity of photovoltaic panels through cooling are numerical, numerical & experimental, and experimental studies (Elbreki et al., 2020; Kim et al., 2020; Aldihani et al., 2014). The experimental study is more common and the performance is evaluated in terms of voltage, current output, and power output. Experimental field performance tests of photovoltaic panels were carried out under different environmental operating conditions such as Kuwait, Nigeria, Bangladesh, and Cairo (Aldihani et al., 2014; Ale & Rotipin, 2019; Arefin et al., 2019 and Abdelrahman et al., 2013). Milind et al., (2017) investigated experimentally the performance of a polycrystalline solar panel with a 60 cm × 60 cm solar area using free front water-cooling and found that the power generated increased from 5% to 19.05% due to the cooling. Abdelrahman et al., (2013) have experimentally investigated three different cooling mechanisms of a 40 W monocrystalline solar module for their power output compared to non-cooled panels. They reported that front cooling, back cooling, and back & front cooling of the panel resulted in power generation enhancement of up to 22, 29.8, and 35%, respectively compared to the non-cooled panel. Experimentally, Ale and Rotipin, (2019) have studied the voltage, current, and power output of a 150 W horizontally paced monocrystalline PV panel of size 1480 mm by 670 mm from 8 am up to 6 pm cooled by water. The experiments were done during the hottest period in Nigeria. The results showed that the water cooling has a significant effect on the efficiency between 11 am to 4:30 pm and it has no significant effect between 8 am to 10:30 am. The output power of the water-cooled panel increases maximally by 9.83 % and average by 5.2%. Arefin et al., (2019) have evaluated the performance of a 20 W solar panel of areas 0.5 m x 0.44 m from 10 a.m. up to 4 p.m. when cooled by water numerically and experimentally. Top surface cooling of the solar photovoltaic panel was able to increase the electrical efficiency by almost 1.5% which significantly reduce the surface temperature. Govardhanan et al., (2020) compared the experimental performance of water-cooling and a non-cooled (bare) photovoltaic panel with a capacity of 25 W with dimensions of 54 cm × 47 cm.

Purchase and installation of imported solar photovoltaic panels in Ethiopia are increasing from time to time for different uses, but field performance tests research findings on the diurnal voltage & current characteristics, power output, and efficiency of commercially available solar panels are rare in contrast to the recent research trend in this field. There are some studies on the sizing and economic feasibility of a standalone PV system for rural or urban areas in Ethiopia. These studies were theoretical that uses analytical or software tools for the prediction of the solar–to–electricity conversion capacity of PV systems (Benti et al., 2023a, 2023). This type of research effort on PV plant project sizing and economic feasibility prediction can be made more reliable if it bases on field performance I-V characteristic data under actual operating conditions with electrical load in Ethiopia for cooled or non-cooled PV systems. This research aims to experimentally investigate the diurnal electric power generation characteristics (or I-V) of bare and cooled PV panels with electrical load (bulbs) in the Adama city environment which is dusty & hot with high solar electricity generation potential. The study also compares efficiency enhancement that can be achieved by cooling photovoltaic panels continuously or intermittently with water or air compared to bare performance. The research finding is useful in assessing the solar electricity generation potential of the city both by bare or cooled solar panels that can be used for sizing and evaluating the levelized cost of electricity production from PV arrays or solar farm projects.

2. Materials and Methods

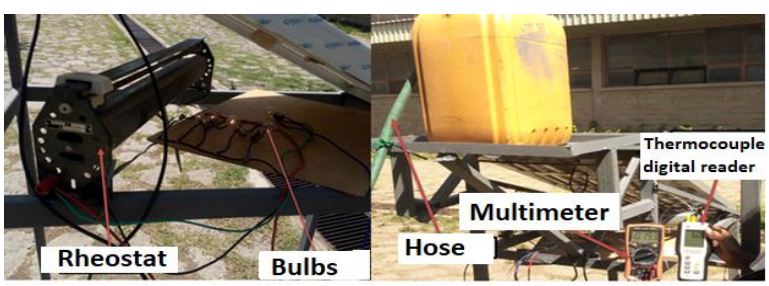
2.1. Experimental Setups and Instruments

The experimental setup was composed of two 60 W power rating photovoltaic panels of solar collecting areas 0.945 m x 0.55 m, 23.5^o tilted metal stands for the panels, office fan or water tank connected to a tap (Figure 1) and 60 W bulbs loads with electrical wiring connected with a potentiometer or Rheostat (Figure 2a). Figure 1a and Figure 1b shows the bare and cooled PV panel, respectively. According to the manufacturer manual, the solar panels' cell used in this study was made from polycrystalline silicon, and its electrical characteristics were specified at the standard test conditions (STC) of 1000 W/m^2 solar intensity and 25 ℃ module temperature. The characteristics of the solar panels as specified by the manufacturers were Peak power (Pmax) of 60 W, Fill factor (FF) of 0.68, Power tolerance of 0-3 %, Voltage (Vmp) of 18.0 V, Current (Imp) of 3.33 A, Open circuit voltage (Voc) of 21.5 V, Short circuit current (Isc) of 4.25 A and maximum system voltage of 1000 VDC. The experimentation was conducted by exposing both panels to the sun in parallel while one of the panel's top surfaces is either cooled by water or air (Figure 1b) and the other without cooling or bare (Figure 2a). The current & voltage output and the ambient temperature & surface temperatures of the solar panels were measured using a digital multimeter and K-type thermocouple wire connected to a digital reader, respectively as shown in Figure 2b. The uncertainty in measuring current, voltage, and temperature was 0.5% of a reading, 0.8% of a reading, and 1 ºC, respectively. The irradiance striking the solar panels was determined using the sunshine hour recorded by the East Shoa Zone National Meteorology Station, Adama. The data on the electric generation performances of each solar panel were studied from 9 am up to 3 pm with data measurement every 15 minutes.



a) b)

Figure 1. The parallel solar panels' experimental setup (a) Bare, (b) Water cooled



a) b)

Figure 2 a) Wiring & installation of the DC bulbs & rheostat b) Voltage & temperature measuring instruments (15 May 2021)

Solar photovoltaic panels are flat plate solar collects that collect both components of solar radiation: beam radiation , I_b(W/m^2) and diffused radiation, I_d (W/m^2) to generate electricity. The general formula of total hourly solar radiation incident on a tilted solar collector I_T is given by (Duffie and Beckman, 2013).

$$I_T = I_b \frac{\cos\theta}{\cos\theta_z} + I_d\left(\frac{1+\cos\beta}{2}\right) + (I_b + I_d)\rho\left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

$$\cos\theta = \cos\varphi\cos\beta\cos\delta\cos\omega + \sin\varphi\sin\beta\cos\delta\cos\omega + \sin\delta(\sin\varphi\cos\beta - \sin\beta\cos\varphi) \ldots\ldots\ldots\ldots(2)$$

$$\cos\theta_z = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta \ldots\ldots\ldots\ldots(3)$$

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \ldots\ldots\ldots\ldots(4)$$

Where: I_T - Total hourly irradiance on a tilted surface (W/m^2), I_b -Hourly beam irradiance (W /m^2), I_d-Hourly diffuse irradiance (W/ m^2), θ_z -Solar zenith angle (o); θ- Angle of incidence (o); $\beta = \varphi + 15^o$ – Tilt angle from the horizontal(o); φ -Latitude(o); ω -Hour angle(o); δ- Declination angle (o); $\rho = 0.2$ –Ground reflectivity (-).

The latitude (φ), longitude, and elevation above sea level for Adama city are 8.558^o N, 39.28^o E, and 1648 m, respectively. The solar energy incident on the panels was determined after calculating the global solar radiation, beam radiation and diffused radiation on horizontal solar panels using the geographical and sunshine duration data collected from Adama Meteorology Station and using the procedure develop for Adama City (Venkatachalam et al., 2019). The results for the test period of the solar panels are depicted in Figure 3.

2.2. Energy Performance Analysis

The primary data collected to evaluate the solar panels' performance were the short circuit current, open circuit voltage outputs, and surface temperatures of the bare and cooled solar panels. These current-voltage characteristics of the photovoltaic module were used to calculate the photovoltaic module efficiency. The solar photovoltaic module converts part of the incident solar radiation directly into electric power after absorbing a fraction of the photon of the solar irradiance striking its absorber area (Duffy & Beckman, 2013). The overall energy conversion efficiency of a photovoltaic module can be expressed by the equation

$$\eta_e = \frac{P_{out}}{I_T A} \ldots\ldots\ldots\ldots(5)$$

Where P_{out} is the electric power generated by a solar panel (W), P_{in} is the solar energy incident on the solar panel (W). The electric power output from the photovoltaic module can be calculated from

$$P_{out} = I_{SC} \times V_{OC} \times FF \ldots\ldots\ldots\ldots(6)$$

Where: I_{sc}-Short circuit current (A), V_{OC}- Open circuit voltage (V), FF- Fill factor (-)

The solar energy incident on the tilted photovoltaic panel can be found by multiplying the total incident solar radiation intensity I_T (W/m^2) in Adama city by the solar collection area A (m^2) as

$$P_{in} = I_T A \ldots\ldots\ldots\ldots(7)$$

As shown in Figure 3, the hourly variation of irradiance falling on the tilted solar panels was more or less similar for the continuous water and air-cooled experimental days. The solar irradiance variation, for intermittent cooling by water test day, was a maximum of 20% at the starting and ending time of the experiment but close to the value of irradiance for continuously cooling experimentation days between the start and end of the experiment as seen in Figure 3. This trend has the advantage of identifying the effect of temperature on the current and voltage characteristics as a result of cooling the panel surface by air or water on the electric power generated since the effect of irradiance variation for these days can be considered marginal.

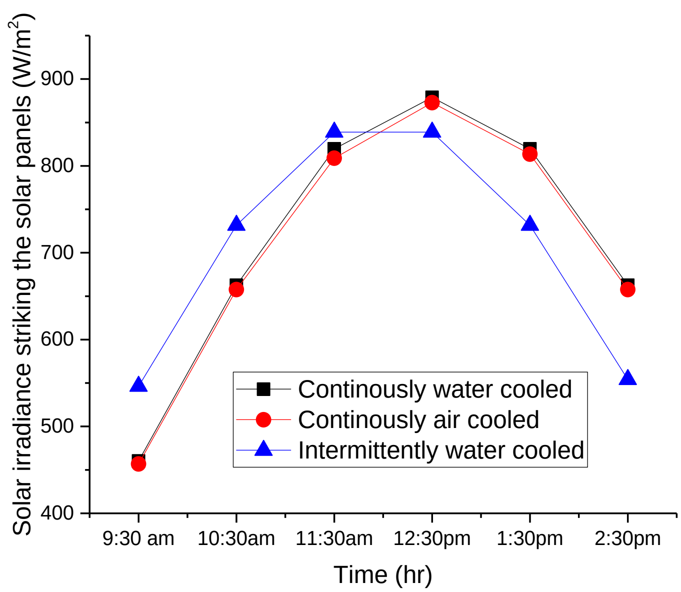


Figure 3. The incident solar radiation on the tilted solar panels

3. Results and Discussion

The electricity generation performance of a solar panel decreases when the ambient temperature increases. In this study, the electricity generation performance of the two identical solar panels inclined at 23.5° from the horizontal and facing the sun in the south direction with zero surface azimuth angle was investigated experimentally in May. The hourly estimated solar radiation incident on the tilted solar panels for the days of the experimentation is shown in Figure 3. The month of May was selected for the experimentation since it is the hottest season with maximum ambient air temperature compared to the other months. The performance of the solar panels in May was a good indicator of the electrical performance of solar panels in Adama City compared to other months. During experimentation, a bare solar panel and another either cooled by water or air were exposed to the sun in parallel on the same day from 9 am up to 3 pm. Three different solar panel cooling techniques were used to test the experimental electricity generation performance of the solar panels: intermittent water cooling, continuous water cooling, and continuous air cooling. The top surface temperature of the solar panels was measured at two points on the top & bottom surfaces of the solar panels and the average values were taken as the temperature of the panels. The short circuit current, voltage, and surface temperature of the solar panels were collected to evaluate the electricity generation performances of the bare (non-cooled) and the cooled solar panels.

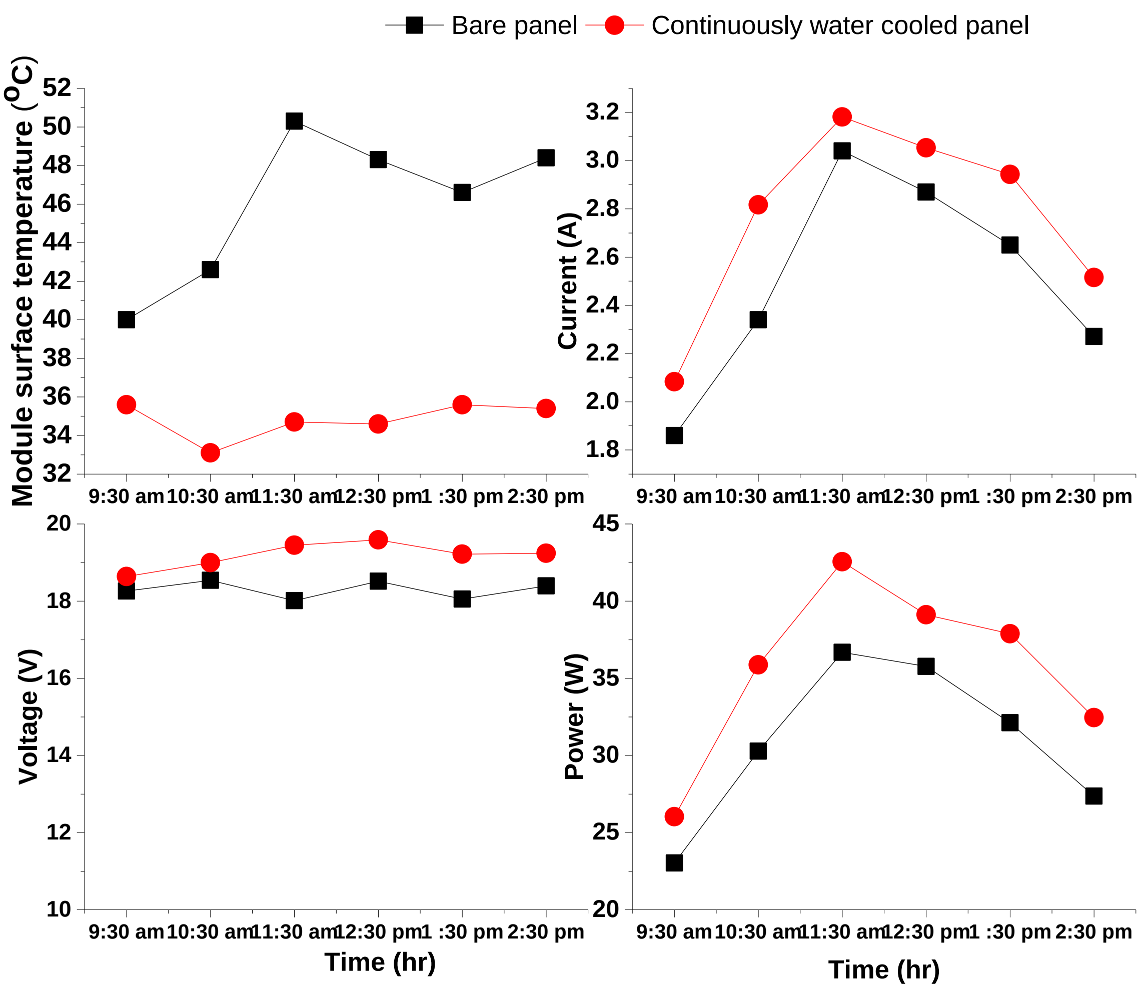


Figure 4. Electricity generation performance of bare and continuously water-cooled solar panels (15 May 2021)

The effect of convective cooling of the solar panel surfaces was studied by continuously flowing water with a mass flow rate of 0.23 kg/min and air with a volume flow rate of 0.0457 m^3/min on the power output and efficiency of the solar panels. The intermittent cooling was done by opening the tap and randomly flowing water over the solar panel for a few seconds. The surface temperatures and the electrical characteristics of the bare and cooled panels were measured for the three cases of cooling arrangement: continuous flow water cooling versus bare panel (Figure 4), intermittent water cooling versus bare panel (Figure 5), and continuous flow air cooling versus bare panel (Figure 6) over time. As shown from the figures, the voltage characteristic of both cooled and bare solar panels was more or less flat concerning time but the surface temperature variation of the solar panels was considerable. The flat or more or less constant voltage output is due to the connection of the solar cells in parallel in manufacturing the panel. The electric current and surface temperature of solar panels varies similarly with the variation of the solar intensity over time.

The electricity generation performance of the solar panels from 9 am up to 3 pm was calculated in terms of the electric power generated and the efficiency for the three cases of cooling arrangement are indicated in Figure 4, Figure 5, and Figure 6, respectively. As seen in Figure 4, the voltage characteristic of both the cooled and bare solar panels are more or less flat concerning time. The maximum voltage, current and power output of the bare (non-cooled) and continuously water-cooled panels were 18.05 & 19.5V, 3 & 3.2 A, and 36.6 & 42.5 W, respectively. The day average increment in current, voltage, and power were 0.26 A, 0.89 V, and 4.77 W, respectively due to 11.2ºC day average decrease in surface temperature of the panels with a day average solar flux of 717.2 W/m^2.

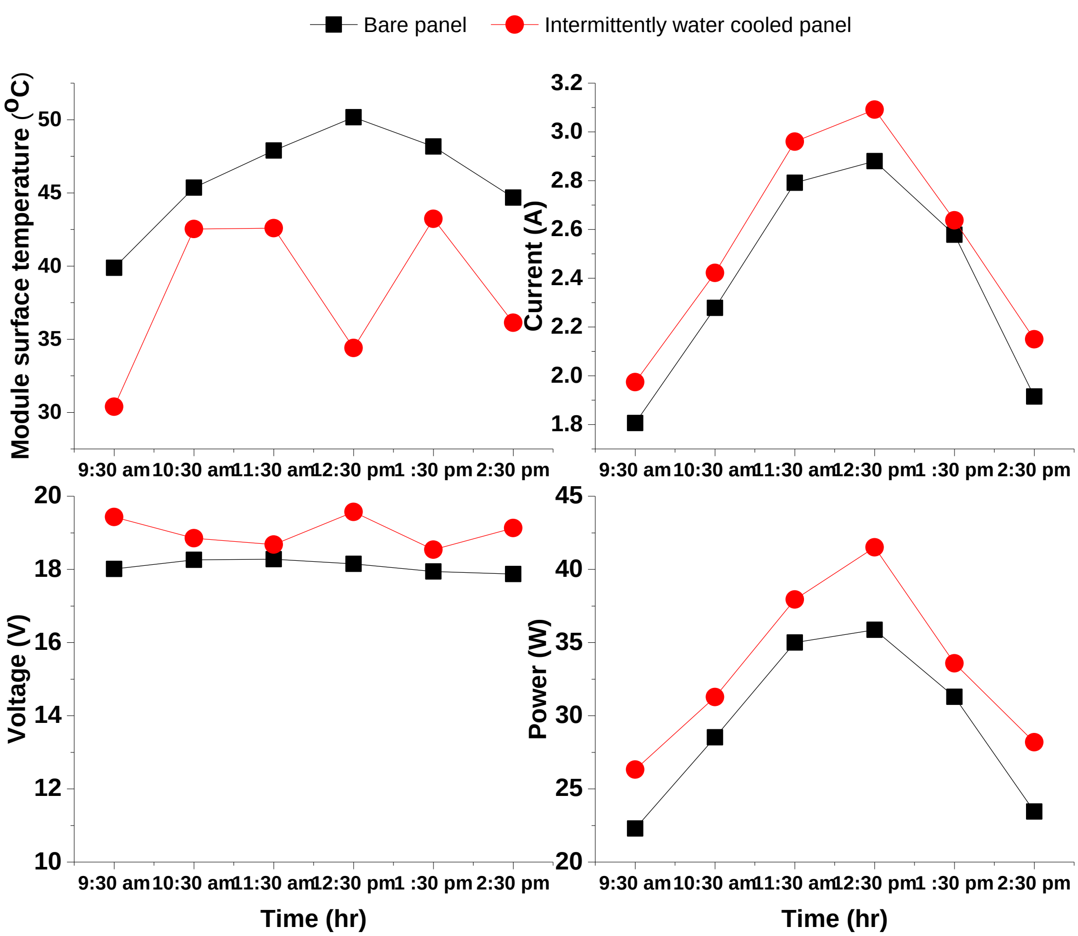


Figure 5. Electricity generation performance of bare and intermittently water-cooled solar panels (May 19, 2021)

Figure 5, depicts the electricity generation performance of the continuously air-cooled solar panel with peak values of the voltage, current and power output of the bare (non-cooled) and continuously air-cooled panels were found to be 18.5 & 18.8 V, 3 & 3.04 A and 37.3 & 39.0 W, respectively. The day average decrease in surface temperature of the panels and the solar flux for this case were 7.81ºC and 706.9 W/m^2. The day average gain in current, voltage, and power as a result of the cooling was 0.16 A, 0.94 V and 3.7 W, respectively. Figure 6, shows the electricity generation performance of the intermittently cooled solar panels compared with the bare panel. The peak values of the voltage, current and power output of the bare (non-cooled) and intermittently water-cooled panels were found to be 18.1 & 19.5 V, 2.8 & 3.0 A, and 35.8 & 41.5 W, respectively. The power output of bare and cooled solar panels was much less than the 60 W power output rating as tested by the solar panel manufacturer. Day average increment in current, voltage and power were 0.15 A, 0.5 V and 2.92 W, respectively due to 6.6ºC day average decrease in surface temperature of the panels with a day average solar flux of 711.1 W/m^2.

Figure 7 shows the calculated efficiency of the solar panels for continuous air-cooled, intermittently water-cooled and continuously water-cooling cases compared to the bare solar panel. The peak values of the electrical efficiency observed were 8.2 & 8.6%, 8.2 & 9.5% and 9.6 &10.8 %, respectively which are way below the nominal efficiency of the solar panel as tested by the manufacturer. The results clearly show that cooling the solar panel surface has enhancement on the power generation and efficiency of the solar panels.

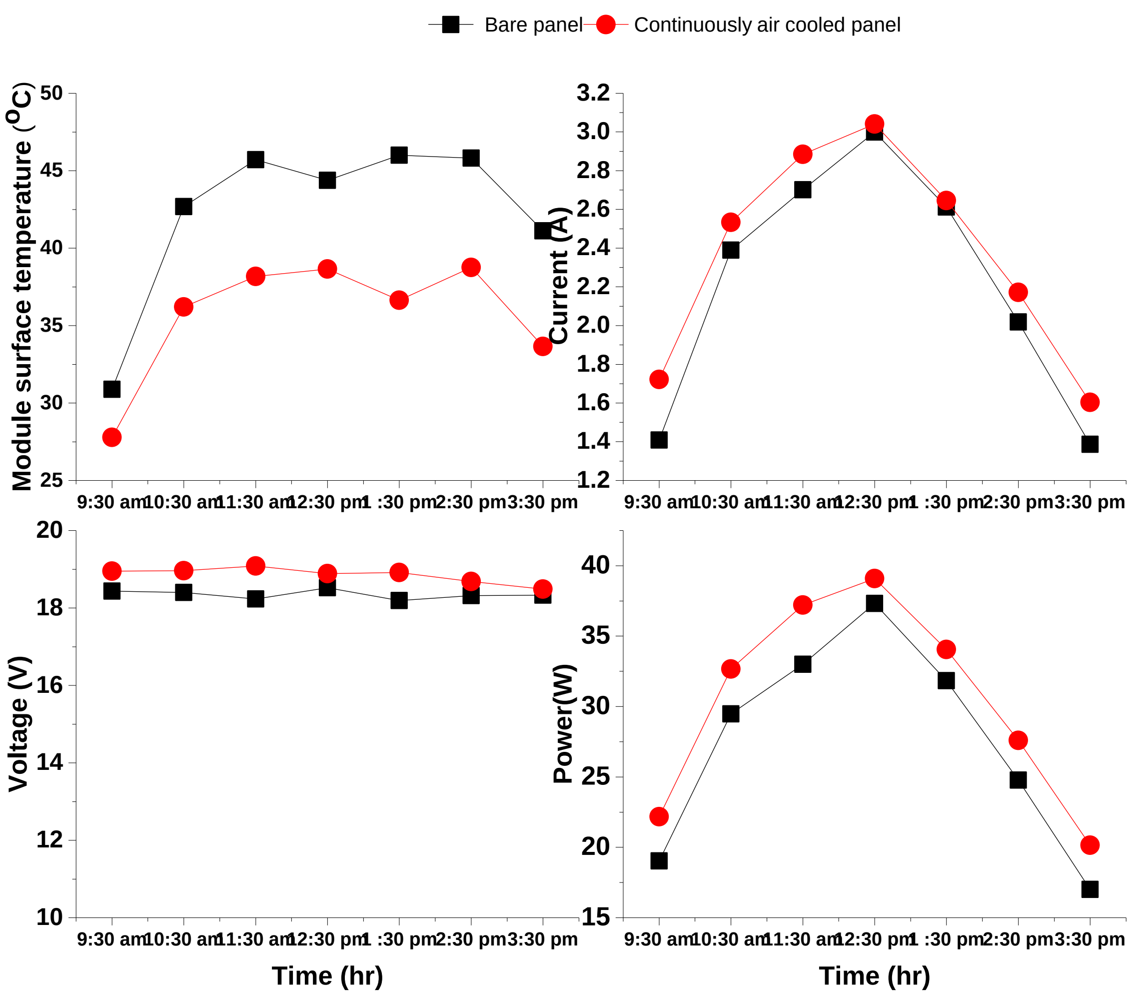


Figure 6. Electricity generation performance of bare and continuously air-cooled solar panel (May 22, 2021)

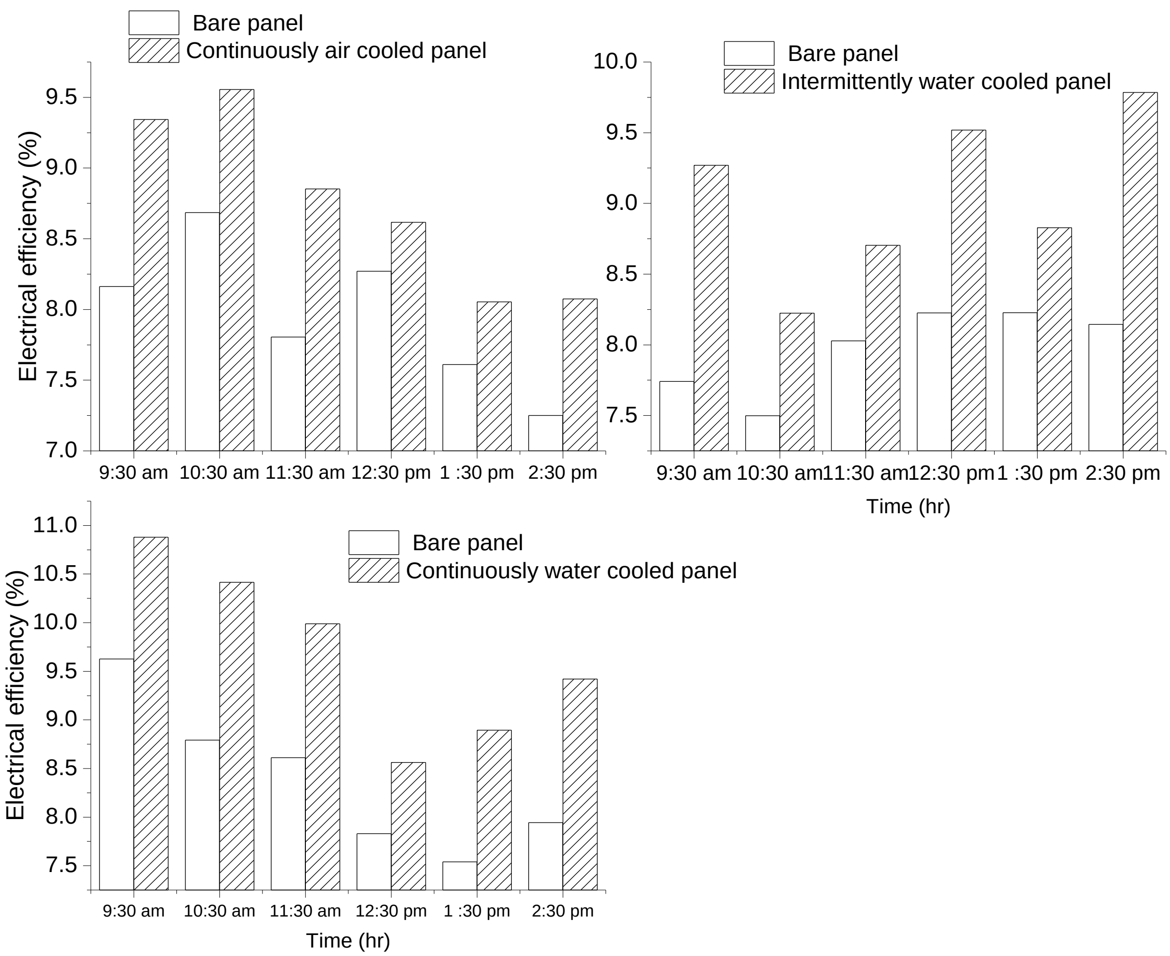


Figure 7. Electrical efficiency of the continuous air, intermittently water, and continuously water-cooled solar panels

The standard way of operating solar PV plants is bare (non-cooled). The transient I-V, temperature and efficiency test data on bare PV systems are important in making design decisions of array arrangement, in series or parallel or conjugate, to meet the design requirement of solar PV plant installation. The average diurnal efficiency of the bare solar panels under Adama weather conditions was found to be in the range of 7.76 to 8.3 % which is approximately equal to 66.3 to 69.9% of the ideal 12% efficiency specified by the manufacturers at standard test conditions as shown in Figure 4, 5 and 6. There is a considerable mismatch between the experimental performances of the tested PV panels in real climatic conditions compared to the performance test results of the manufacturer. The peak surface temperature observed in Figures 4, 5 and 6 for the bare PV panel tilted at 23.5^{o} is approximately 50^{o}C which is double the standard test temperature. This peak temperature fluctuation caused voltage and hence power drop. The peak temperature observed is relatively low compared to 80^{o} the peak surface temperature observed in the dusty city of Mekka, Saudi Arabia for a bare PV tilted at 21.5^{o}C, a country outlined as a promising solar installation site (Hassen et al., 2022). The influence of the surface temperature of the solar panels can also be further researched for its effect on the optimum electrical performance of the PV panels at different tilt angles (Bosnjakovic, et al., 2021). Compared to this temperature Adama has a better prospect of solar installation from the point of view of environmental stress and degradation on the PV panel.

Cooling solar panels is essential not only for enhancing efficiency but also for protection from a temperature gradient that causes micro-cracks in the cell due to uneven heating and degradation and failure of the panels (Bansal, 2021). Active cooling by water and air is a simple technique whereas passive cooling is self-operable, more reliable and cost-effective than active cooling methods. However, the use of Tea-light candle phase-changing materials was also found to be inefficient for PV cooling (Nicholas et al., 2017). Active cooling of solar panels is also more reliable, particularly with solar cogeneration: production of electricity and hot water or air for heating and drying applications (Abdullah et al., 2019; Bandaru et al., 2021).

4. Conclusion

In this work, experimental performance of bare (non-cooled) and cooled photovoltaic panels were tested during electricity generation using 60 W rated bulbs as load over a day. Two commercial photovoltaic panels made of polycrystalline materials with 60 W power output and 12% efficiency at 1000 W/m^2 & 25ºC with a solar aperture area of 0.945 m × 0.55 m were tested. The electricity generation performances of these two solar panels when operated bare and cooled by air or water were determined in terms of voltage, current, power output, surface temperature and efficiency. Experimental measurements indicated that the voltage generated is more or less flat over the day but the measured current varies considerably over time with a trend similar to the solar intensity. The average electric power and efficiency observed for the bare & cooled solar panels were 30.8 & 35.6 W, 27.4 & 30.4 W and 29.4 & 33.1 W, and 8.3 & 9.6 %, 7.8 & 8.7 % and 7.9 & 9.0 %, with a temperature difference of 11.2, 6.6 and 7.8 ºC, respectively for continuously water cooled, continuously air cooled and intermittently water cooled panels. Continuous water cooling of the solar panels by water results in better enhancement of electricity generation than intermittent water and continuous air cooling means. Further research is required to identify improvements in energy efficiency and electricity developed by solar panels for various mass flow rates of water and using other cooling techniques for different solar panel sizes. The following are recommended for future works:

- Performance test of the three main types of PV panels with different sizes and power ratings in the market: monocrystalline, polycrystalline & amorphous silicon cells side by side at various tilt angles.
- Conduct experimental investigation on the passive cooling of PV panel by confining a thin film of water in a box between the PV panel surface and an additional glass cover sealed at its sides & bottom but open at the top. Similar research can also be carried out using opaque material at the back.
- Conduct diurnal and season bare experimental solar-to-electricity conversion performance of micro solar PV plant with complete system components (inverter, battery, etc.) for representative days of each month in a year or over the year.

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